Patterns and general characteristics of severe forest dieback from 1950 to 1995 in the northeastern United States

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Abstract: US national and state forest insect and disease surveys provide plentiful information on forest dieback. These data, however, have not been quantified and analyzed systematically to address outstanding questions on the etiology of dieback. This study quantified long-term (1950–1995) trends in the severity of dieback on *Acer saccharum* Marsh., *Fraxinus* spp., *Betula* spp., and *Picea rubens* Sarg. in US northern hardwoods. A numeric index (0–10 scale) of the severity and extent of dieback was applied using key words frequently found in the surveys. The 18 episodes identified showed considerable variability among species at the local scale, yet systematic, repetitive patterns of dieback at the scale of the region and multidecadal time frame. Six dieback characteristics were evident: episodes showed abrupt onset and subsidence, endured 13.6 years on average, were cyclical, with a frequency of 22.3 years between recurrence, and averaged about two-thirds of maximum possible severity. In contrast to the perception that dieback is happenstance and chaotic, this study supports the hypothesis that, by addressing issues of spatial scale and long-term population dynamics, coherent, generic patterns emerge that are cyclic and predictable. Limitations and advantages of the approaches were discussed in terms of meeting needs of the US Forest Health Monitoring Program for innovative approaches to the analysis of the voluminous field data being assembled nationwide. By developing a quantitative database, environmental correlation and modeling of dieback now become possible.

Résumé : L'inventaire des insectes et maladies dans les forêts d'État et les forêts nationales aux États-Unis fournit beaucoup d'informations sur le dépérissement des forêts. Cependant, ces données n'ont pas été systématiquement quantifiées et analysées pour aborder les questions non résolues concernant l'étiologie du dépérissement. Cette étude a permis de quantifier les tendances à long terme (1950–1995) pour la sévérité du dépérissement chez *Acer saccharum* Marsh., *Fraxinus* spp., *Betula* spp. et *Picea rubens* Sarg. dans les forêts de feuillus nordiques aux É.-U. Un indice numérique (échelle de 0–10) de la sévérité et de l'ampleur du dépérissement a été appliqué à partir de mots-clés fréquemment utilisés dans les inventaires. Les 18 épisodes qui ont été identifiés montrent une très grande variation d'une espèce à l'autre à l'échelle locale. Malgré cela, on observe des patrons de dépérissement systématiques et répétitifs à l'échelle régionale et sur une période de plusieurs décennies. Six caractéristiques du dépérissement sont évidentes : les épisodes ont connu un début et une fin abrupts, ont duré en moyenne 13,6 ans, étaient cycliques avec une périodicité de 22,3 ans et ont atteint en moyenne environ les deux tiers de la sévérité maximale potentielle. Contrairement à la perception que le dépérissement est le fruit du hasard et chaotique, cette étude supporte l'hypothèse voulant qu'en s'attaquant aux questions d'échelle spatiale et de dynamique des populations à long terme, des patrons cohérents et génériques qui sont cycliques et prévisibles émergent. Les limites et les avantages de cette approche ont été discutés dans le contexte du US Forest Health Monitoring Program qui a besoin d'approches novatrices pour analyser la quantité volumineuse de données de terrain recueillies à la grandeur du pays. Avec la mise en place d'une base de données quantitatives, il est maintenant possible d'établir des corrélations environnementales et de modéliser le dépérissement.

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Introduction

State forest insect and disease surveys in the United States provide a wealth of information on forest dieback observed over much of the 1900s and systematically since 1950. Properly analyzed, these extensive data raise the possibility of generating new perceptions on the etiology of dieback.

The descriptive nature of the annual insect and disease reports has been a barrier to their use in numeric analysis. There is, however, a clear and continuing need for data on long-term patterns that extend over several dieback periods. Ideally these data would consist of temporally uniform, standard numeric measures of dieback such as those now being obtained annually by the US Forest Health Monitoring Program (USDA Forest Service 2004).

Most large dieback episodes in the northern hardwoods have been intensively researched, at least since the early 1950s (Walker et al. 1990), and now form the basis of the modern concepts of forest dieback (Sinclair 1964; Houston

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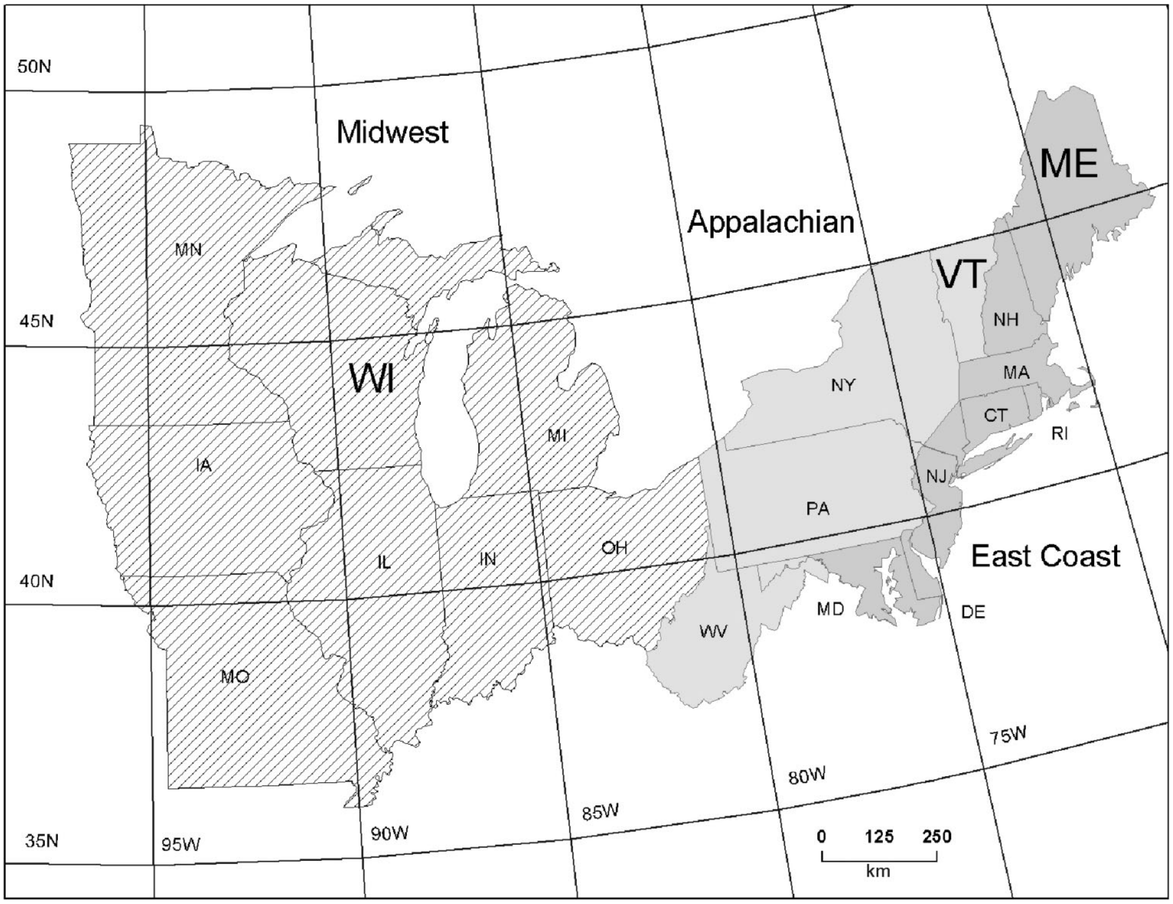
Fig. 1. Map of the Northeast US region showing distribution of the East Coast, Appalachian, and Midwest subregions. The total forest area is 13 176, 8630, and 32 465 km^2, respectively (Waddell et al. 1989). The three "lead" states used in the analysis of dieback are indicated in bold.



1981; Manion 1981, 1991). The US Northeast region remains an important focus for research on acidic deposition, and on changes in forest health associated with air pollution abatement (Mickler et al. 2000).

The objective of this study is to reconstruct and compare the patterns of dieback on several key tree species in the northeastern US that historically have experienced severe dieback. Specifically, the aim is to quantify the severity and extent of dieback on sugar maple (*Acer saccharum* Marsh.), ash (*Fraxinus* spp.), birch (*Betula* spp.), and red spruce (*Picea rubens* Sarg.) over the 1950 to 1995 period, and to then characterize important generic features of these dieback episodes.

The recent and historical literature indicates that dieback is typified by a perplexing array of symptoms, affecting different tree species unevenly; dieback usually has a patchy distribution and is sporadic, unexpected, and attributable to multiple or unexplained causes (Hinrichsen 1987). The working hypothesis in this study is that when proper attention is given to issues of spatial scale and long-term (i.e., multidecadal) population dynamics, coherent, generic patterns will emerge that are recurrent and ultimately predictable. This is in contrast to the current lack of recognition that such patterns exist and a latent assumption that dieback is happenstance and chaotic. The approach used in this study builds on and refines the efforts of early attempts (Auclair 1993*a*, 1993*b*; Auclair et al. 1990, 1992, 1996, 1997, 2002) that use both systematic reconstruction across spatial scales ranging from local to regional levels and interspecies comparisons. The ultimate goal of these studies has been to illuminate general principles of dieback etiology.

Materials and methods

General approach

The approach was to reconstruct numerically the long-term trends (1950–1995) of dieback in the Northeast United States (Fig. 1). Before this could be achieved, new methods needed to be developed to address two conspicuous problems in the available annual pathology survey records.

First, the state insect and disease survey records, and the national summaries based on the state reports (USDA Forest Service 1950–1995), are largely descriptive. The methods of survey and intensity of observation varied over time and between regions. To overcome this, I developed a standard set of codes used in the survey reports to describe external crown, branch, and bole condition and the extent of dieback. These were then converted to a 1–5 or a 1–10 numeric scale (Auclair et al. 1997).

In this study, the scanning of annual insect and disease survey reports for key words and phrases was done manually. The most recent approaches to word and pattern recognition, that is, metadata search and text and speech analysis, use computer automation (Gose et al. 1996). While a large potential exists for further dieback (and other forest disease and (or) insect infestation) applications using automated recognition and retrieval programs, these techniques are not without problems and limitations (Rath and Manmatha 2003).

Second, there was a need for a measure of dieback that could be readily integrated across broad geographic and time scales. For example, forests are increasingly at risk to dieback as they mature or senesce (Mueller-Dombois 1989, 1992) so that one to several decades of records may be needed to document the onset, progression, and subsidence of an episode. There are also subregional and regional differences in the severity and sensitivity to dieback (Barter 1953; Auclair et al. 1997).

Definition of dieback

The USDA Forest Health Monitoring Program field guide defines dieback as “recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk” (USDA Forest Service 2004). In addition the guide notes that crown dieback is only considered dieback when it occurs in the upper and outer portions of the tree. When whole branches are dead in the upper crown, without obvious signs of damage such as breaks or animal injury, it assumes that the branches died from the terminal portion of the branch. Dead branches in the lower portion of the live crown are assumed to have died from competition and shading. Dead branches in the lower live crown are not considered as part of crown dieback, unless there is continuous dieback from the upper and outer crown down to those branches.

In this study, I used the USDA Forest Service (2004) definition of dieback, ensuring that the descriptions of dieback in the insect and disease survey and literature reports accessed were consistent with the guidelines. Ciesla and Donaubauer (1994) specify that the symptoms are without obvious evidence of a single clearly identifiable causal factor such as a physical disturbance or attack by an aggressive disease or insect. Situations where it was clear that crown damage had been caused by an exotic insect (e.g., gypsy moth, *Lymantria dispar* L.), disease, or mechanical injury attributable to extreme weather such as icing, frost kill, hail, high winds, or hurricane were excluded. These forms of injury were explicitly identified in the survey reports and clearly not part of crown dieback as defined in this study. Crown dieback potentially related to drought and internal freezing injury are much more subtle and not so commonly reported. Reports of dieback associated with prior drought or thaw–freeze events were included on the consideration that their effects on the crown are known to be related to dieback (see Auclair et al. 1992, 1996; A.N.D. Auclair and W.E. Heilman, unpublished data).

Leaf anomalies were omitted on the consideration that there was no evidence that leaf chlorosis, premature leaf fall, and other commonly reported “dieback” symptoms worsened progressively into crown dieback and mortality.

Sources of data

Four principal sources were used: (1) state annual insect and disease reports on forest condition (Maine Department of Conservation 1950–1995; Vermont Department of Forests, Parks, and Recreation 1950–1995; Wisconsin Department of Natural Resources 1950–1995). Special reports such as the hardwood (Kelley and Eav 1987; Kelley et al. 1992) and spruce–fir (Weiss et al. 1985; Miller-Weeks et al. 1994) surveys in Vermont were also included; (2) USDA Forest Service (1950–1995) national annual summaries of forest insect and disease conditions; (3) over 450 scientific journal and government reports on dieback etiology; and (4) dieback overviews, including those of Millers et al. (1989) and Walker et al. (1990).

Forest dieback database

Data were sought for severe dieback on tree species in the Red Spruce – Northern Hardwood forest type of the northeastern US (Thompson and Sorenson 2000). Red spruce forest is sometimes regarded as a montane variant of Northern Hardwood (e.g., Types 30, 31 of Eyre 1980), and the term northern hardwoods (inclusive of red spruce) has been used throughout the paper.

States and regions

The Northeast and North Central units of Administrative Region 9 of the USDA Forest Service were retained, with the exception that I divided the Northeast into “East Coast” (Connecticut, Delaware, Massachussets, Maryland, Maine, New Hampshire, New Jersey, southeastern New York, Rhode Island), and “Appalachian” (western Maryland, New York, Pennsylvania, Vermont, West Virginia) subregions. The “Midwest” or North Central unit (Iowa, Illinois, Indiana, Michigan, Minnesota, Missouri, Ohio, Wisconin) was the most extensive of the three subregions (Fig. 1).

Reconstruction of forest dieback was done for a “lead” state within each of the three subregions; information from adjacent states was also evaluated if the episode was extensive. The lead (and adjacent) states included Maine (and New Hampshire), Vermont (and New York), and Wisconsin (and Michigan plus Minnesota) (Fig. 1).

Time period

I reconstructed dieback from 1950 through 1995 on the consideration that the USDA Forest Service (1950–1995) annual reports date only from 1950. This period is also the focus of a climatic analysis of dieback (A.N.D. Auclair and W.E. Heilman, unpublished data).

Tree species

Tree species with extensive or frequent dieback included sugar maple (*Acer saccharum* Marsh.), white ash, red ash, and black ash (*Fraxinus americana* L., *Fraxinus pennsylvanica* Marsh, *Fraxinus nigra* Marsh.), white birch and yellow birch (*Betula papyrifera* Marsh., *Betula alleghaniensis* Britt.), and red spruce (*Picea rubens* Sarg.). Species of ash and birch were not consistently differentiated in the pathology reports and were analyzed only at the generic level.

Numeric index of dieback

A method of quantifying the extent and severity of dieback symptoms was applied that had been previously developed, tested, and refined by the author (Auclair et al. 1996, 1997). The estimate, termed the numeric index of dieback

(NI), first identified key words and phrases in the descriptive text of the annual survey reports (and other literature), and then rated the extent and the severity of each description into a series of numeric codes on a scale of 1–5 or 1–10.

The area extent of dieback was coded on a scale of 1–10 (Auclair et al. 1997). For example, "one, two, or few individual locations" was rated 1, "many areas or localities" was rated 5, and at the other end of the spectrum, "all of commercial forest in region" was rated 10.

The severity of dieback consisted of three separate terms: a symptom code, an intensity code, and a cover type code. Symptom severity was coded 0–10, that is, twice the level of intensity and cover type codes, on the consideration that pathological condition was the most important indicator of tree and forest health. Terms referencing external crown condition included "crown dieback", weighted 8, "epicormic sprouting", weighted 5, "leader mortality", weighted 4, etc. Intensity was scaled from 1 to 5: descriptions ranged from "a few trees" (coded 1), to "many trees", to "unusually severe" and "rapid deterioration and death" (coded 5). Cover type, also scaled 1 to 5, expressed the effect of climate stress. Stress was considered greatest where dieback occurred in protected locations such as natural forest, sugar bush, and rural woodlots (coded 5); dieback in more exposed cutover, plantation, and roadside locations (coded 1) was assumed to have occurred under lower climate stress. Severity of dieback was the sum of symptom code, intensity code, and cover type code, divided by two.

To estimate the final NI, the extent of dieback (scaled 0–10) and the severity of dieback (scaled 0–10) were multiplied, and the product was divided by 10 to retain a 0–10 scale.

In previous studies, the NI had been applied to sugar maple and birch over the northern hardwoods in Canada and adjacent areas of the United States (Auclair et al. 1996, 1997). The present database of NI values differs in accessing virtually all insect and disease reports over the 1950–1995 period in lead states (approximately an order of magnitude more data), in limiting the analysis to the United States, and in including ash species and red spruce. A panel of forest scientists critiqued the proposed methods, complete with actual data. To address their concerns over questions of accuracy in the data, approaches to analysis, and interpretation of the results, two significant changes were made to exclude the extensively reported leaf symptoms on the consideration that there was no evidence that these led to crown dieback and to distinguish actual episodes from "background" levels of dieback found naturally in most stands (see next section, Summary of trends). An additional precaution was to ensure that once the data had been collected, the derivation and verification of NI values was consistently applied as the responsibility of the principal investigator.

The actual reconstruction was done on a species-by-species, year-by-year, and decade-by-decade basis, one subregion at a time. Records were assembled for one tree species, key words and phrases were highlighted, and the numeric codes determined for 1 year, proceeding though a consecutive interval of 10 years, repeated for the full 1950–1995 interval and full complement of four species. The main source of information was the state and national forest insect and disease surveys. For each 10-year period, the numeric codes derived were plotted by hand to determine whether a pattern was apparent and to identify any uncertainties in the record or gaps that required further verification. The verification process was typically time consuming but considered a critical step in ensuring that the full array of detail in available literature was accessed and context was properly interpreted. For example, the insect and disease surveys can show a bias toward recording the onset of a severe dieback event and pay less attention to the progress and subsidence of the episode. While this was true, there was nevertheless, a wealth of information on the progress of the dieback from other published sources. These sources included reports of the North American Maple Decline Project (Millers et al. 1991), Forest Health Monitoring Program (USDA Forest Service 2004), periodic state-level Forest Inventory Analysis reports (e.g., Griffith and Alerich 1996) that include mortality statistics and in many cases, direct description of the cause of growth loss and mortality, an array of doctoral theses (e.g., Greenidge 1951; Hibben 1962; Staley 1962; Ross 1964; Leblanc 1985), and over 450 scientific journal articles and in-house reports of state and federal government resource agencies, including special studies and overviews on dieback (e.g., Weiss et al. 1985; Kelley and Eav 1987; Millers et al. 1989; Kelley et al. 1992; Miller-Weeks et al. 1994; Walker et al. 1990). It is important to note that the study focused on the four species showing especially severe and widespread dieback of the approximately 50 tree species common in US northern hardwood forests. Typically there is an abundance of observations on crown condition; dieback is one of the most widely and consistently reported of any symptom of crown health (Alexander and Barnard 1992). While cross-referencing and verification using a wide range of reports proved labor intensive, I meticulously applied this approach until I had achieved reasonable certainty that the patterns quantified were accurate and reproducible.

Summary of trends

In addition to annual NI values, 5-year point-centered means were calculated and plotted over time. This convention was used throughout our work, including work in progress on climatic influences (A.N.D. Auclair and W.E. Heilman, unpublished data). The choice, compared to a running mean of the prior 4 years plus current year, was one of preference based on experimenting with different averaging techniques. An NI composite average across all forest species, episodes, and subregions was made to illustrate decadal trends on the scale of the US northern hardwoods region.

A construct was developed to identify and quantify the severity and timing of major episodes. The problem was to distinguish a genuine episode from frequent, minor, or incidental dieback (i.e., "background noise"). I identified a major episode as five or more consecutive years during which NI was 50% or more of the peak year of that episode. The years were noted, and an average NI was computed over those years (see Table 1). This method is similar to that of Auclair et al. (1997) but used a more stringent cutoff (50% of maximum NI versus 20%) to distinguish major episodes from normal or common variations in crown transparency and mortality.

Results and discussion

Trends in severity of dieback at the species level

Sugar maple

Dieback on sugar maple in the East Coast, Appalachian, and Midwest regions is illustrative of the abrupt episodic onset and subsidence pattern typical of most episodes, species, and subregions of northern hardwoods (Fig. 2). Major episodes on sugar maple are evident in and after 1955 (Table 1). The 5-year average NI trends in each subregion shows two major episodes over the 1950–1990 decades and a rough synchrony among subregions. Subsidence is marked in the early 1970s. The patterns overall show a tendency of the dieback in 1973–1995 to be more severe than over the 1951–1973 period (Figs. 2*a*, 2*b*). While this is true of sugar maple in the East Coast and Appalachian subregions, this is not evident in the Midwest (Fig. 2*c*).

Ash, birch, and red spruce

The abrupt onset and subsidence of dieback episodes in these species is as pronounced as in sugar maple (Figs. 2*d*–2*l*).

Dieback does not appear common on red spruce until the mid 1950s. Two major episodes are evident (East Coast and Appalachian subregions, species absent in Midwest) only in and after 1959 (Table 1). The 5-year average NI trend on red spruce shows a sharp but brief dieback in the mid 1970s in the East Coast (Fig. 2*j*). As in the case of sugar maple, there is a rough synchrony between subregions and a pronounced subsidence in the early 1970s. Unlike sugar maple, the episodes in the 1951–1973 and 1973–1995 periods are approximately of equal severity (Figs. 2*j*, 2*k*).

Ash shows recurrent episodes in each subregion separated by a subsidence of dieback in the early 1970s. Unlike sugar maple, there is not a consistent trend toward increased dieback in the 1973–1995 period in the East Coast and Appalachian subregions (Figs. 2*d*, 2*e*). In the Midwest, the dieback in the 1951–1973 period is less that that in the 1980s (Fig. 2*f*), and no major episode occurs until 1977 (Table 1).

Dieback patterns on birch differ notably from that of other species. The strong recovery of birch in the early 1950s in the East Coast and Appalachian subregions (Figs. 2*g*, 2*h*) follows unusually severe dieback on birch in these areas over the late 1930s and 1940s. Birch is the only species showing extensive and severe dieback at this time (Auclair et al. 1997), with an estimated mortality of 1.4 billion m^3 of commercial volume between 1940 and 1955 across the United States and Canada (Pomerleau 1991, p. 43). Although rapid subsidence of dieback was apparent by 1951, complete subsidence was not evident until the mid- to late 1950s (Figs. 2*g*, 2*h*). The lack of significant episodes on birch in the late 1950s and 1960s and only moderate dieback in the 1980s and 1990s may be partly due to the exceptionally high early (ca. 1936–1950) mortality of birch in these subregions, followed by generally younger, more resistant populations. In contrast, the 1930–1950 episode does not occur in the Midwest, and this subregion shows severe dieback episodes in both the 1954–1963 and 1977–1993 periods (Fig. 2*i*, Table 1).

In brief, individual species at the local scale show considerable variability among different periods and subregions. Overall, however, average trends at the level of the subregion and the region are consistent in showing two periods separated by a marked subsidence in the early 1970s and a tendency for dieback to be more severe over the 1973–1995 interval than earlier (Figs. 2*m*–2*o*).

Trends in major dieback episodes at the species level

A total of eighteen major dieback episodes occur in US northern hardwood forests over the 1950–1995 period on the four species in this study (Table 1). Most are prolonged (13.6 years, average) and occur notably in the East Coast (six episodes) and Appalachians (seven episodes). The Midwest, despite occupying over half (51.5%) of the total forest area (Waddell et al. 1989), has only five episodes. The Midwest is also exceptional in having no major episodes prior to 1950 (A.N.D. Auclair, unpublished data); after 1950, the average duration of the first dieback episode in this subregion was relatively short (9.5 years), whereas the second episode was relatively long (19.0 years) (Table 1).

There is a strong tendency for major dieback episodes to recur on the same species within a subregion. Two episodes occur on sugar maple, ash, and red spruce in each subregion (Table 1). The exceptions are where dieback prior to 1950 had been extensive and severe, as on sugar maple in the East Coast and on birch in the East Coast and Appalachian subregions (A.N.D. Auclair, unpublished data).

Characteristics of dieback episodes

Approaches to date rarely demonstrate the flexibility to go from one scale of dieback to another. An important aspect of the design and an achievement of this study is to address the effect of geographic (local, subregional, regional) and time (annual, multidecadal) scales in the analysis of dieback. The 18 major dieback episodes in US northern hardwoods (1950–1995), for example, show considerable variation in the incidence, duration, and magnitude at the species–episode–local level and yet consistency when trends are summarized over several decades at the regional scale. By systematically comparing these differences and commonalities, I was able to identify six general, scale-dependent properties of dieback in northern hardwoods.

Properties at scale of local episodes on individual species

(1) Onset and subsidence of dieback is rapid. A universal feature is the highly episodic nature of the dieback events. As in other forest species worldwide (Auclair 1993*a*), abrupt onset and sudden reversal of episodes is characteristic of US northern hardwoods. For example, in the severe dieback on sugar maple in the Appalachian subregion in the mid 1970s through the 1990s (Fig. 2*b*), in a single year (1976) NI increases 65% of the total rise between trough and peak and subsides 62% (of total peak to trough decrease) in a single year (1989). Average rates among all species and subregions (Fig. 3*e*) indicate NI increased 57% of trough to peak rise in the most rapid 5 years (7th–11th year) and subsides 59% (of total peak to trough decrease) in the fastest 5-year period (15th–19th year). That is, both the onset and subsidence of dieback are notably rapid.

Fig. 2. Trend of the numeric index (NI) on (*a*, *b*, *c*) sugar maple, (*d*, *e*, *f*) ash spp., (*g*, *h*, *i*) birch spp., and (*j*, *k*, *l*) red spruce in the East Coast (EC), Appalachian (AP), and Midwest (MW) subregions, and (*m*, *n*, *o*) the NI averaged across species in each subregion.

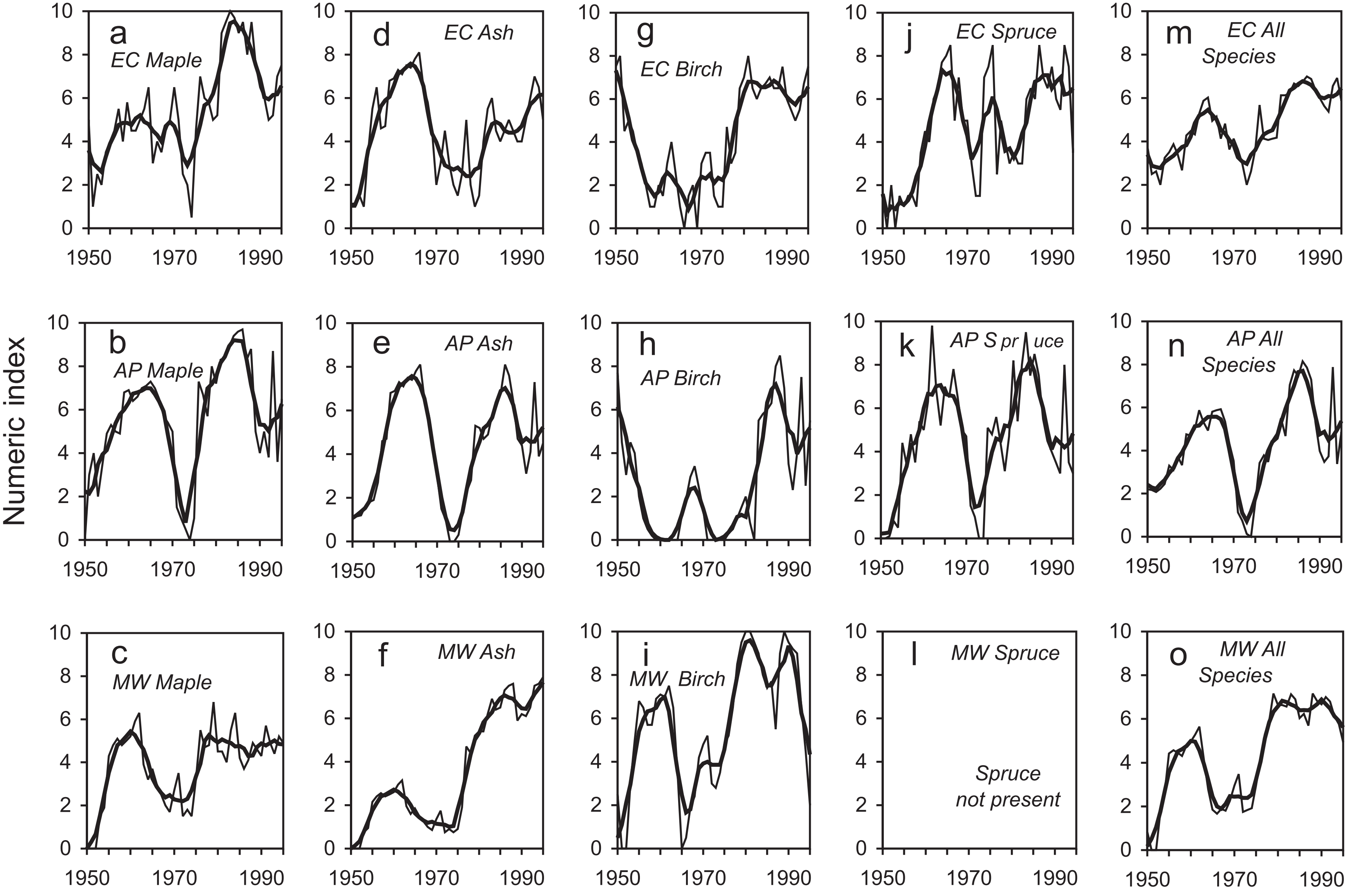


Table 1. Timing and severity of 18 major episodes of dieback in US northern hardwoods, 1950–1995.

	Sugar maple			Ash spp.			Birch spp.		
Period	Years	Peak NI	Avg. NI	Years	Peak NI	Avg. NI	Years	Peak NI	Avg. NI
East Coast									
I	—	—	—	1955–1969	8.1	6.5	—	—	—
II	1976–1995	10.0	7.4	1981–1995	7.0	5.0	1976–1995	8.0	6.5
Appalachian									
I	1955–1970	7.3	6.1	1957–1969	8.1	6.5	—	—	—
II	1976–1989	9.7	8.0	1979–1990	8.1	5.8	1983–1989	8.5	6.7
Midwest									
I	1955–1963	6.3	5.0	—	—	—	1954–1963	7.5	6.5
II	1976–1995	6.8	4.9	1977–1995	7.9	6.4	1977–1993	10.0	8.3
Mean years, NI	15.8 (1.8)	8.0 (0.7)	6.3 (0.5)	14.8 (1.1)	7.8 (0.2)	6.1 (0.2)	13.0 (2.3)	8.5 (0.5)	7.1 (0.5)

Note: Intervals I and II represent the 1951–1973 and 1973–1995 periods. Mean number of years, peak numeric index (NI), and average NI values are standard errors of the mean.

The survey records suggest that the sudden onset and equally rapid subsidence are often surprising to field observers. The implication is that events cannot be predicted by symptoms alone, and modern monitoring systems may require more than tree symptomology to successfully anticipate dieback episodes. Population age and external factors, in particular severe climatic stress (e.g., thaw freeze, drought), are most likely to drive dieback (Auclair et al. 1992, 1996; Frey et al. 2004). These factors may need to be part of the surveillance efforts if early warning and prediction of dieback is a monitoring objective.

(2) Species exhibit individuality in timing and severity of dieback. It is clear that tree species exhibit great individuality in the timing and severity of dieback (Figs. 2*a*–2*l*). I believe this is consistent with the general perception among pathologists that, at the local scale, dieback is highly variable, even chaotic. With long-term species profiles now available, the question of whether there are consistent interspecies differences can be addressed. For example, is there one tree species significantly more susceptible and hence capable of serving as a reliable early warning of a pending outbreak? I found some consistency in which the onset occurs: sugar maple > birch > ash > red spruce. Sugar maple dieback occurred first in four of the five major episodes (Table 1), and on average, 2.0 years earlier (range, 1–3 years) than the next occurring episode. Birch (2.5 years later than the first occurring episode on average; range, –1 to 7 years later; four episodes total) and ash (3.6 years later; range, 1–7 years later; five episodes) are intermediate. Red spruce occurs relatively late in the dieback cycle — an average of 4.8 years later than the first-occurring species episode (range, 3–7 years later, four episodes). Early onset also correlates with longer lasting and more severe dieback (see characteristic 3), forming a consistent timing-severity attribute that may have value in predicting the likelihood of major outbreaks.

Properties at the scale of integration of several episodes

(3) Major dieback episodes endure 13.6 years on average. The average duration of the 18 major episodes is 13.6 years (Table 1). There was, however, a three-fold range in the duration of individual episodes (7- to 20-year range). On average, episodes are longest in sugar maple (15.8 years) and ash (14.8 years), intermediate in birch (13.0 years), and shortest in red spruce (9.8 years) (Table 1). The pattern is for the earliest episodes to endure the longest and experience the highest overall levels of dieback. For example, the product of average NI × duration (Table 1) shows the sequence sugar maple > birch > ash > red spruce. The products are 99.5, 92.3, 90.3, and 66.6 NI-years, respectively. It is noteworthy that contrary to the considerable attention given to red spruce (Scott et al. 1984; Weiss et al. 1985; Johnson et al. 1986; Vogelmann et al. 1988; Miller-Weeks et al. 1994), dieback on hardwood species in the region is significantly earlier, longer lasting, and more severe.

(4) Episodes rarely exceed two-thirds of maximum severity. The NI of the 18 major episodes averages 6.5, or about two-thirds of the maximum possible extent and severity in a given area. The peak level within any episode is typically about two NI points higher (average NI = 8.2) than the mean. Individual episodes in northern hardwoods average about half (NI = 4.9) of the possible severity on sugar maple in the Midwest to over four-fifths (NI = 8.3) on birch in the Midwest, or about two times as much (Table 1).

This finding may be an important guide to the impact and eventual fate of the tree population experiencing dieback. As the population is decimated, scientists have expressed concern over the likely extinction of the species and with it the loss of commercial and cultural values. The loss of red spruce in the Adirondacks (Scott et al. 1984; Vogelmann et al. 1988), sugar maple in eastern Canada (Auclair et al. 1997), and ohia (*Metrosideros polymorpha* Gaud.) in Hawaii (Mueller-Dombois 1989, 1992) are recent examples of this phenomenon. Typically, dieback episodes subside to low levels, even in the most severe events. Generally, the mechanism of subsidence or “recovery” remains poorly understood, both at the physiological and population levels.

Properties at the scale of the US Northeast region

(5) Dieback episodes are cyclic. The trends in NI when averaged (all species, all subregions) over the 1951–1973 and 1973–1995 intervals indicate a cyclic pattern of 22 years (Fig. 3). Dieback typically increases to a peak in year 11 (somewhat earlier in ash and birch). Subsidence of the episode occurs slowly from the peak to year 15, and then drops more rapidly through the 22nd year (Figs. 3*e*, 3*f*).

Red spruce			Mean		
Years	Peak NI	Avg. NI	No. years	Peak NI	Avg. NI
1962–1970	8.5	6.5	12.0 (2.1)	8.3 (0.1)	6.5 (0.9)
1984–1994	8.5	6.9	15.8 (1.7)	8.4 (0.6)	6.5 (0.8)
1959–1969	9.8	6.5	13.3 (1.2)	8.4 (0.6)	6.4 (0.7)
1981–1988	9.5	7.5	10.3 (1.5)	9.0 (0.4)	7.0 (0.8)
—	—	—	9.5 (0.4)	6.9 (0.4)	5.8 (0.7)
—	—	—	19.0 (0.5)	8.2 (0.9)	6.5 (1.3)
9.8 (0.7)	9.1 (0.3)	6.8 (0.2)	13.6 (2.1)	8.2 (0.3)	6.5 (0.5)

shown for each species and each subregion. Values in parentheses are

Several features support the evidence of a cycle. First, although variability is high, all four species show this cyclic pattern (Figs. 3*a*–3*d*). Second, the time between onset of one major episode and the next major episode in the same species and subregion averages 22.3 years. Six of the seven onset–onset intervals endure 21 or 22 years (Table 2). And third, preliminary reconstruction of the 22-year period (1929–1950) prior to 1951 (A.N.D. Auclair, unpublished data) confirms this periodicity. Starting in 1929 and 1930, dieback on ash occurred over much of the Northeast United States (Connecticut, Massachussets, Maine, New Hampshire, New York, Pennsylvania, Rhode Island, Vermont) (Marshall 1930). An especially marked episode occurred on white and yellow birch in the 1935–1950 period; the episode ended in 1950 following one or more summers of abundant rain and lower temperatures (Fraser 1953).

In examining 40 years of records of dieback on old-growth northern hardwood trees in permanent sample plots on the Upper Peninsula Experimental Forest in Michigan, Kessler (1965, pp. 484, 486) concluded that “a cyclic pattern is involved”. From the late 1920s through the early 1960s, individual sugar maple, red maple (*Acer rubrum* L.), yellow birch, and beech (*Fagus grandifolia* Ehrh.) trees had undergone three cycles of dieback and recovery during the intervening years. Kessler (1965, 1967) did not explain the basis for this pattern, but hypothesized that “the cause or causes are environmental, involving no host-specific pathogen”. High water tables coincided with dieback in 1954 and 1962, and he suggested one theory was rootlet mortality, the dieback cycle being “a natural reaction that would bring the root–shoot ratio back into favorable balance”.

Other authors have noted the presence of dieback cycles where long-term records were available. Auclair et al. (1997) described “waves” of dieback on sugar maple and birch populations in Canadian and US northern hardwoods that were closely tied to synchronized maturation. Their explanation was that dieback, as a senescence phenomenon, affects mainly older trees (Houston 1981; Manion 1991; Mueller-Dombois 1989, 1992). Once older populations undergo a surge of mortality, the loss rates subsequently drop as the remaining younger, more vigorous trees experience less mortality. The next surge occurs as the surviving trees reach maturity; the effect is a sequence of waves in the population. In a 30-year study of changes caused by *Phytophthora cinnamomi*, Weste (2003) queried whether successive cycles of disease, dieback, and recovery may occur in infected eucalyptus stands in Australia.

As yet, there is no comprehensive treatment of dieback as a cyclic phenomenon. Alternative explanations have been found in the wide range of natural cycles operating alone or in combination. These include, among others, reproductive cycles of heavy seeding and fruiting (Gross 1972; Kessler 1969), tree population and vegetation dynamics (Sprugel 1976; Mueller-Dombois 1989, 1992; Jeltsch 2001; Worrall et al. 2005), ecosystem or biogeochemical cycles (Matson and Boone 1984; Waring et al. 1987), inherent insect and pathogen life cycles (Manion 1991), and recurrent external stresses such as hydrological cycles (Santiago et al. 2000) or low-frequency climatic variation (Wettstein and Mearns 2002; A.N.D. Auclair and W.E. Heilman, unpublished data).

An important question to the US Forest Health Monitoring Program (USDA Forest Service 2004) is whether dieback is a natural phenomenon that is a normal physiologic and population change in response to extreme stress or whether under specific conditions it leads to a persistent decrease in forest health (Alexander and Barnard 1992; USDA Forest Service 2002).

(6) “Background” levels of dieback average 16% of maximum severity. Based on the average of the first 2 years (Fig. 3), the typical cycle starts at an average NI of 1.6 (i.e., not zero), suggesting this is the approximate level of incidental dieback under natural (nonepisodic) conditions. This varies 2.5-fold, from low levels in ash (NI = 1.0), sugar maple (NI = 1.4), and red spruce (NI = 1.4) to relatively high levels in birch (NI = 2.4). This observation justifies the use of a cutoff (50% of peak value) in delimiting major episodes and also suggests that, depending on objective, the cutoff could be varied to take species differences into account.

Baseline and projection of dieback cycle

The 5-year average of the trends of all species and subregions (Fig. 2*m*–2*o*) shows a cyclic pattern over the 1950–1995 period (Fig. 4). This long-term trend can be considered a baseline of dieback changes in northeastern US forests against which other observations can be compared. It appears likely that earlier cycles may have occurred, for example, on ash and birch species over the 1929–1950 period (A.N.D. Auclair, unpublished data; Auclair et al. 1997). Very early diebacks in the Northeast region are known from the 1920s, for example, on black ash in adjacent areas of Quebec (Pomerleau 1991; Walker et al. 1990) and on red spruce in the 1871–1885 period (Hopkins 1901; Johnson et al. 1986) and over the 1880s and 1890s (Maine Department of Conservation 1890–1950). It would be a difficult but valuable study to determine whether these early dieback events conform to a 22-year pattern.

Especially apparent is the high level of dieback at the end of the 1973–1995 cycle. This persistence, that is, the failure of the cycle to return to the level evident at the start of the cycle (i.e., NI = 2.4, 1973), is consistent both with the evidence in the literature and with perceptions of survey staff. A possible explanation is the notably higher levels of climatic stress in the mid-1990s compared to levels in the early 1970s (Auclair and Heilman 2003; Auclair et al. 1996;

Fig. 3. Numeric indices of (*a*) sugar maple, (*b*) ash, (*c*) birch, (*d*) red spruce, (*e*) all species, and (*f*) all species adjusted (using linear regression of trend, $y = 0.0887x + 3.3931$, of annual values of (*e*)). Five-year point-centered mean (black) and polynomial regression trend (grey) and equation are shown in each case. The *x*-axis shows the year of the 22-year cycle derived by averaging the two 22-year periods, 1951–1973 and 1973–1995. Vertical bars are standard errors of the mean.

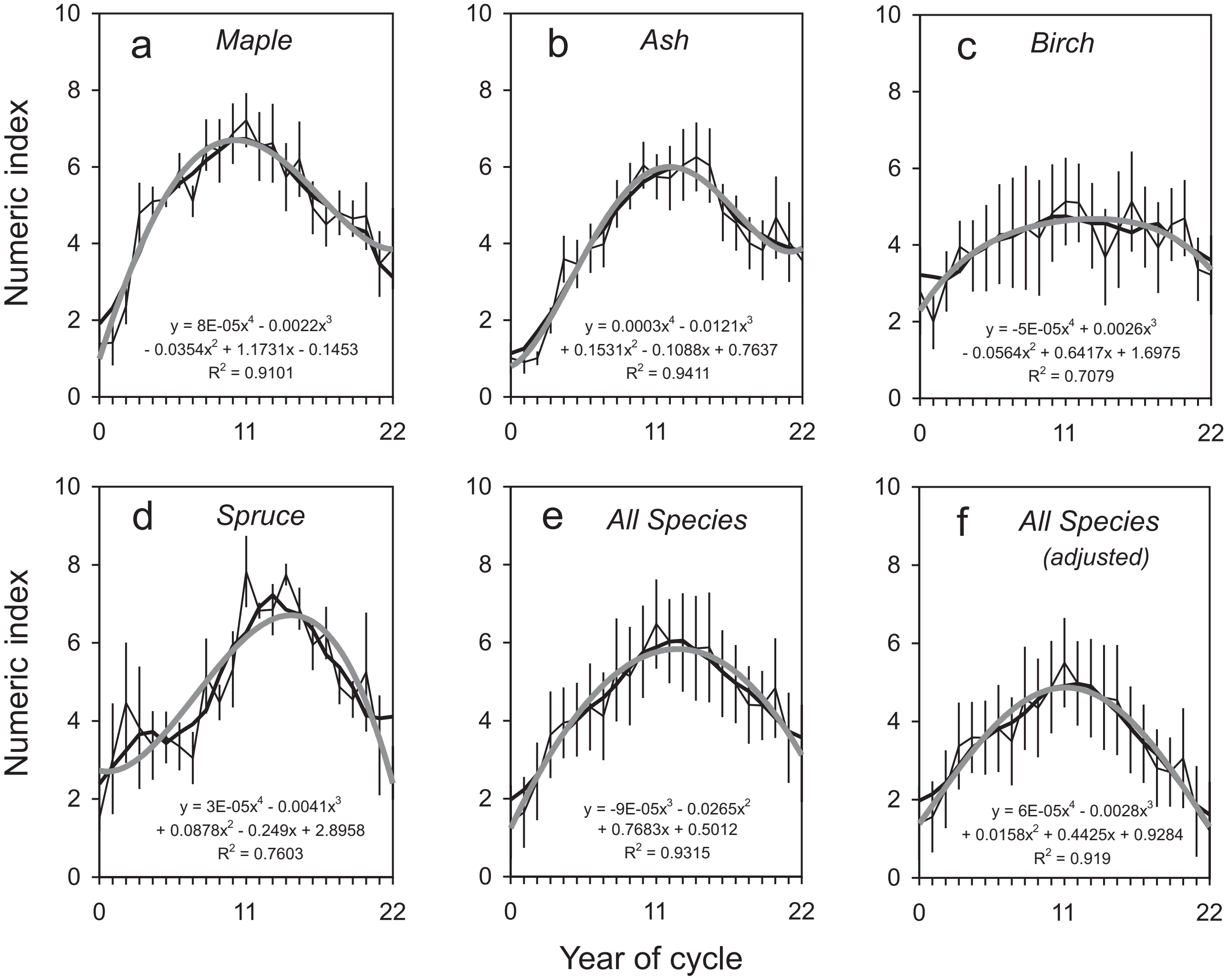


Table 2. Years from onset of a major episode to onset of subsequent episode on the same species, by subregion.

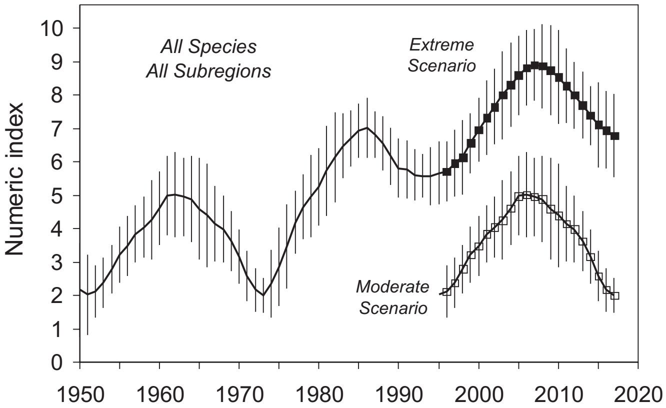
Subregion	Sugar maple	Ash spp.	Birch spp.	Red spruce	All species
East Coast	—	26	—	22	24
Appalachian	21	22	—	22	21.7
Midwest	21	—	22	—	21.5
All subregions	21	24	22	22	22.3

Wargo and Auclair 2000). In the absence of further and more recent climatic analysis, it is difficult to project with certainty the trend over the next 22-year cycle (1996–2017). Hence, I posit two contrasting scenarios for the 1996–2017 interval (Fig. 4): (*i*) a moderate scenario, assuming that the symmetric cyclic pattern of 1951–1973 would recur; this would require a marked drop in NI levels over the 1996–2000 interval; (*ii*) an extreme scenario based on the "business-as-usual" conditions represented in Fig. 3*e* of the entire 1951–1995 interval. The extreme option of Fig. 4 is considered unlikely, since by 2006 it would entail unprecedented severity of dieback over large areas. This has not been apparent to date (i.e., 2005). Expectations are that dieback will follow a cyclic pattern, reaching a peak in 2006 and decreasing through 2017, but at levels intermediate between the two scenarios in Fig. 4.

The baseline and projection of Fig. 4 is predicated on the new insight of dieback as a systematic, predictable, cyclic phenomenon. The projection to 2017 is a prediction of future dieback. It provides an expected pattern against which the voluminous stream of new Forest Health Monitoring Program dieback data can be evaluated and compared. The projected pattern may or may not materialize: the value of Fig. 4 is that there is now a baseline against which to judge observed annual changes against an expected long-term trend. One would learn a great deal if the dieback over the 1996 to 2017 period does not conform to the expected. We could ask why and reexamine our model.

Ultimately, the ability to model dieback at the landscape level will depend on understanding mechanisms controlling the timing and duration of dieback episodes. Some leads are

Fig. 4. Trends in the 5-year mean of the numeric index (1950–1995, all species, all subregions). Projected levels of dieback over the next 22-year dieback cycle, 1996–2017, are shown for an extreme scenario, based on the pattern of dieback of Fig. 3*e*, and for a moderate scenario, based on a repetition of the dieback trend of 1951–1973. Vertical bars are standard errors of the mean.



already available. For example, Auclair and Heilman (2003) noted that that the onset of dieback cycles in the early 1950s and 1970s was preceded by extreme La Niña conditions; a paired two-tailed Student's *t* test for 23 dieback episodes in US northern hardwoods showed that winter snow depth correlated with La Niña and was statistically significant in both the onset and recovery of dieback. In a different study, Auclair et al. (1996) observed as much as a two-decade difference in onset of birch and sugar maple dieback between subregions of northern hardwoods; north–south differences in timing were largely accounted for by temperature, whereas precipitation explained east–west differences. Dieback is delayed under colder and drier conditions and may partly account for the absence of major dieback episodes in the Midwest pre-1950. Similar conclusions have been reached by Frey et al. (2004) and others (Shields and Bockheim 1981). Frey et al. (2004) cite evidence that the age of onset of dieback on trembling aspen (*Populus tremuloides* Michx.) varies considerably across aspen's North American range (ca. 60 years in the Great Lakes, 80 years in Quebec, and 100 years in the western US interior), generally occurring earlier in regions with higher mean annual temperatures.

General discussion

The central issue in this paper is the potential for using the plentiful but descriptive insect and disease reports to quantify long-term historical changes in the severity of forest dieback. The author's prior experience in developing and testing a technology for quantifying dieback (Auclair et al. 1997) and its application to diebacks in Hawaii (Auclair 1993*a*), the Pacific Northwest (Auclair et al. 1990), southeastern Canada (Auclair et al. 1996, 1997), and central Europe (Auclair 1993*b*) indicated it was both feasible and a promising avenue to new insights on the etiology of diebacks. Apart from this experience, there are few studies on this topic (i.e., the quantification of descriptive records) and none on the spatial and time scales developed here on which to gauge the likelihood of success or the nature of the problems to be encountered. The alternative, that is, the failure to experiment with the quantification of descriptive records, would have left a large potential pool of important dieback information untapped.

An ancillary benefit of the NI database is to view the nature and etiology of dieback in a new light. The IUFRO (2004) Working Group on Trends in Forest Terminology is reexamining the definition of dieback, requesting from researchers new information on etiology and possible links to decreased forest health and sustainability. Is the common comingling of the terms "dieback and decline" justified? Further research on external drivers of changing NI levels in northern hardwoods, for example, may show that there are fundamentally different types of dieback. They may, for example, be labeled Dieback Type A1 (e.g., natural inherent population cycles), Type C3 (e.g., cyclic, but driven by climate and leading to persistent loss of tree health), etc. I imply here that long-term patterns of dieback covering one or more full cycles have rarely if ever been quantified and offer the possibility of a much improved understanding of dieback phenomena.

The approach

There have been literature reviews of forest diebacks in both North America (Johnson et al. 1986; Millers et al. 1989; Walker et al. 1990) and in Europe (Cramer and Cramer-Middendorf 1984; Landmann et al. 1993). The premise in this study is that key words and phrases in anecdotal text could be systematically translated into numeric codes. Prior to this study, the quantification of the long-term historical record remained one of the most weakly developed aspects of dieback research (Auclair et al. 1997).

Limitations

The process of translating forest pathology annual records and descriptive literature into numeric codes is far from ideal and not easily achieved. Ideally, the state and national survey reports would consistently contain references to all key words used here to quantify dieback. I observed early in the study that while the survey reports are an important "backbone" for the reconstruction, it is crucial to thoroughly scan a very wide array of other literature and to consistently use this to complement and elaborate on the basic survey information.

Considerable care is required to search the texts for background and context of developing or receding dieback events and to rigorously cross-reference information from adjacent years. This proved highly labor intensive. For example, the total time (including acquisition of annual reports, coding, verification, and data entry) is estimated to be approximately three 8-h days per decade for each species in each subregion, or a total of 2270 h. This had the effect of slowing the process considerably and limiting me to a few selected tree species in one region. Relative to all tree species and regions showing dieback, this study probably encompasses <5% of the total available records on dieback US wide.

Reports rarely estimate the geographic extent in detail. Measures of the statistical reliability of NI are not possible given that one annual estimate (i.e., a single data point) is derived from the state surveys and other pathology literature.

Advantages

A strong advantage of the state-level insect and disease reports is their reasonable consistency in style and uninterrupted annual reporting extending in some cases into the early 1900s. Reports for Maine, for example, are available for years extending back as far as the 1890s and describe the extensive and pronounced dieback on red spruce over Maine and adjacent states (ca. 1870–1900). It is an advantage that crown dieback is the most conspicuous and consistently reported of any pathology symptom (Alexander and Barnard 1992). The region-wide coverage of the state reports, and their century-long availability enabled me to develop the database essential to structuring an integrated view or "big picture" that has proven elusive to date. By quantifying and analyzing dieback time series, I was able to add certainty to patterns that may have been evident but lacked the conviction that only systematic comparison and contrast allow. It is also possible to identify intrinsic features evident through recurring patterns between species and among subregions and to differentiate what is general from the exceptional incidence. By developing a quantitative database, environmental correlation and modeling now become possible (Auclair et al. 2002).

Relevance to the US Forest Health Monitoring Program

The approach of selecting and coding dieback symptoms provides a measure of changes from within one or more developing and receding episodes. This has the effect of magnifying the details of the etiology of the dieback cycle far more than do area-wide surveys that include all species, forest types, and geographic areas. NI measures the collective extent and severity of "hotspots" in a subregion. Given that dieback can be limited to particular species and locales, and may affect a minor fraction of the vegetation at any one time, NI differs in important ways from general area-wide forest health surveys. The latter approaches average the magnitude and changes in dieback among damage symptoms, disease and insect symptoms, and across affected trees and unaffected healthy trees alike. This "diluting" effect can mask important details and properties of the dieback episode. An observation made of the North American Maple Project (Millers et al. 1991) was that results showing that a high fraction (e.g., 95%) of sugar maple was healthy (Millers et al. 1994) related to the broad sampling approach. Large-scale regional survey data in which results are pooled often obscure fine points in the spatial pattern (McLaughlin 1998). While appropriate for the assessment of the extent of damage to sugar maple, the North American Maple Project surveys are not effective for studying the details and dynamics of dieback episodes per se. A potential advantage of the annual plot surveys of the US Forest Health Monitoring Program is that one or a group of plots can be distinguished and followed over time.

This consideration becomes important in the proper interpretation and application of the relative scale used in the NI database. In an attempt to evaluate the actual magnitude (e.g., cubic metres per year) of losses to dieback, I compiled state-level Forest Inventory Analysis estimates of mortality across the region (1950–1995). These data, while estimating the gross tree growth (i.e., growth in diameter increment plus recruitment from sapling size classes) and losses to natural mortality (e.g., fire, extreme weather, insect and disease outbreaks) and harvesting, identify dieback separately only in rare cases. Assuming losses to dieback-related injuries are 20% of natural mortality in temperate hardwoods (ash and sugar maple) and 30% in northern or mid-elevation species (birch and red spruce), the estimated loss to dieback-related mortality averages only 2.1% of gross growth in sugar maple and 5.3% over the four species (all subregions and decades). This broad approximation using a reasonable but arbitrary mortality ascribed to dieback is consistent with the findings of the North American Maple Project, that is, a high fraction of healthy and, by inference, a low percent mortality in sugar maple and other northern hardwood forest trees.

As a matter of perspective, the North American Maple Project and US Forest Health Monitoring Program were initiated in 1988 and 1991, respectively, that is, near the end of the second 22-year period. At least another full decade of field observations beyond 2005 will be required of these programs to provide sufficient data on a complete dieback cycle.

The US Forest Health Monitoring Program is exploring new perceptions and algorithms in its analysis of the voluminous field data now being assembled across the United States (USDA Forest Service 2002). Especially valuable will be baselines that provide a yardstick for interpreting short-term observations. The mean NI trend for 1950–1995 in Fig. 4 can serve to provide this perspective. The comparison, for example, made between forest conditions in 1978–1987 versus 1968–1977, leading to the conclusion that forests are imperiled (Loucks 1998), may need to be interpreted with particular caution. The precaution is that on further examination, long-term cycles could be shown to represent largely natural, age-induced, internal population shifts unrelated to changes in atmospheric chemistry.

Conclusions

The results of this study support the outcome of earlier efforts (Auclair 1993*a*, 1993*b*; Auclair et al. 1990, 1992, 1996, 1997, 2002) that show both variability among species at the local scale, yet systematic, repetitive patterns of dieback at the scale of the region and multidecadal time frame.

It is also apparent that a consistent dieback terminology in the state survey reports, and equal attention to all phases of dieback, including the subsidence or recovery of tree health, would improve the quality and robustness of dieback data. Without this consistency, significant effort and resources are required to access a wide array of other pathology literature to cross-reference trends and add detail.

Average trends at the level of the region are consistent in showing a 22-year cycle that recurs over the 1951–1995 period. Although beyond the starting point of this study, it is noteworthy that an additional 22-year cycle may have occurred from 1929 to 1950. The new insight is that dieback in US northern hardwoods is a systematic, cyclic, and predictable phenomenon. So far, this kind of information has been conspicuously absent and an important barrier to effectively modeling dieback at the landscape level. The NI database developed here should prove valuable in exploring further the mechanisms of dieback related to inherent population changes and to climate and other external influences.

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