

Predicting forest dieback in Maine, USA: a simple model based on soil frost and drought

Allan N.D. Auclair, Warren E. Heilman, and Blondel Brinkman

Abstract: Tree roots of northern hardwoods are shallow rooted, winter active, and minimally frost hardened; dieback is a winter freezing injury to roots incited by frost penetration in the absence of adequate snow cover and exacerbated by drought in summer. High soil water content greatly increases conductivity of frost. We develop a model based on the sum of z-scores of soil frost (December–February) and drought in summer (May–September) that accurately predicts timing and severity of dieback on sugar maple (*Acer saccharum* Marsh.), *Betula* spp., *Fraxinus* spp., and red spruce (*Picea rubens* Sarg.) in Maine, USA, during 1920–1995. Discrepancies between predicted and actual dieback relate largely to tree population dynamics. Extraordinary levels of dieback on *Betula* during 1935–1950 occurred under low stress but in mature populations; under high climate stress during 1951–1975, younger surviving *Betula* proved resistant and showed little dieback. Severe dieback in *Acer* stands during 1975–1995 may relate to extensive partial cutting, leaving stands open to frost and high water tables. Widespread use of forwarder feller/buncher and wheeled skidders after 1960 commonly left hummocky, irregular surfaces subject to pooling and accelerated frost penetration. Silvicultural applications include modifying harvesting practices to minimize frost complications and use of the model to track and map climatic risk to avoid conditions and locales subject to dieback.

Résumé : Les racines des feuillus nordiques sont peu profondes, actives en hiver et à peine endurcies au froid; le dépérissement est le résultat de dommages aux racines dus au gel hivernal qui pénètre dans le sol à cause d'un couvert nival insuffisant et ces dommages sont aggravés par la sécheresse estivale. Une teneur en eau élevée dans le sol augmente grandement la conductivité du gel. Nous avons élaboré un modèle basé sur la somme des écarts réduits du gel dans le sol (décembre à février) et de la sécheresse estivale (mai à septembre) qui prédit correctement le moment et la sévérité du dépérissement d'érable à sucre (*Acer saccharum* Marsh.), de *Betula* spp., de *Fraxinus* spp. et d'épinette rouge (*Picea rubens* Sarg.) dans le Maine de 1920 à 1995. Les divergences entre les dépérissements prédits et réels sont surtout reliées à la dynamique des populations d'arbres. Un dépérissement très sévère de *Betula*, de 1935 à 1950, est survenu dans des conditions de stress léger mais dans des populations matures. Dans des conditions de stress climatique sévère, de 1951 à 1995, de jeunes tiges de *Betula* qui ont survécu se sont avérées résistantes et ont subi peu de dépérissement. Le dépérissement sévère dans les peuplements d'*Acer*, de 1975 à 1995, est possiblement relié aux nombreuses coupes partielles qui ont rendu les peuplements plus vulnérables au gel et favorisé la remontée de la nappe phréatique. L'usage généralisé des abatteuses porteuses ou groupeuses et des débusqueuses à roue après 1960 a fréquemment laissé des surfaces irrégulières, avec des bosses et des creux, sujettes à l'accumulation d'eau et à la pénétration plus rapide du gel. Les applications sylvicoles incluent la modification des pratiques de récolte afin de minimiser les complications reliées au gel et l'utilisation de modèles pour détecter et cartographier les risques climatiques dans le but d'éviter les situations et les endroits sujets au dépérissement.

[Traduit par la Rédaction]

Introduction

Dieback in US northern hardwoods is associated with root mortality caused by soil frost (Pomerleau 1991). Soil frost events typically relate to lack of adequate snow cover at the time of intense cold. The effect of root kill is to exacerbate the effects of drought in the following growing season (Auclair et al. 1992).

No model has yet been developed to signal when a forest is at risk of dieback. Understanding the causes and being

able to predict dieback is important to forest health managers who need frequent, updated assessments on which to base operational decisions. Although of greatest public and scientific concern in the 1980s, dieback remains a continuing threat under shifts to warmer winters and more variable precipitation (Allen and Breshears 2007). It is logical to expect future episodes that will be as extensive and severe as those in the past.

Our objective is to model the severity of forest dieback on four tree species (sugar maple (*Acer saccharum* Marsh.),

Received 9 March 2009. Accepted 19 January 2010. Published on the NRC Research Press Web site at cjfr.nrc.ca on 14 April 2010.

A.N.D. Auclair¹ and B. Brinkman. United States Department of Agriculture, Animal and Plant Health Inspection Service, Policy and Program Development, Riverdale, MD 20737-1236, USA.

W.E. Heilman. United States Department of Agriculture, Forest Service, Northern Research Station, 1407 S. Harrison Road, Room 220, East Lansing, MI 48823, USA.

¹Corresponding author (e-mail: allan.auclair@aphis.usda.gov).

Betula spp., *Fraxinus* spp., and red spruce (*Picea rubens* Sarg.) in Maine, USA, using estimates of soil frost and drought over the 1920–1995 period. A related objective is to verify our model using actual levels of dieback and to examine statistical properties of the model.

In the early 1950s, Pomerleau (1991) successfully induced crown dieback on birch and maple in a set of soil frost experiments. He hypothesized that the sudden, widespread dieback over Quebec and adjacent regions in the 1940s and 1950s had been incited by cold winter temperatures at a time of little or no snow cover. He noted that crown dieback was proportional to the length of exposure of roots to frost in the laboratory (Pomerleau 1991) or to rooting depth of trees on plots cleared of snow (Pomerleau and Lortie 1962). He separately experimented with the effects of soil moisture on dieback (Pomerleau 1991), noting that recovery is frequently associated with “a greater amount and better distribution of rainfall”. Pomerleau’s work remained unpublished until 1991. It is only recently that the effect of frost on root kill has been quantified (Cleavitt et al. 2008).

Our hypothesis is that severe crown dieback in northern hardwoods is caused foremost by soil frost injuries to tree roots, subsequently exacerbated by drought; conversely, dieback will rapidly subside as these extreme stresses diminish.

Material and methods

Study area

Maine in the northeastern-most United States was chosen as a test case, since it has both a varied topography and climate and an unusually high incidence of dieback (Auclair 2005). The State has consistent annual forest condition surveys (Maine Department of Conservation 1920–1995), long-term meteorological records (US NCDC 1920–2007), and forest health plot measurements for 1990 to the present (USDA Forest Service 2002).

Definition of dieback

Dieback is “the 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). Crown damage incited by an insect, disease, mechanical injury, or extreme weather such as icing, frost kill, hail, high winds, or hurricane is excluded. Damage caused by drought or frost is included, since these are known to incite dieback.

Dieback data

Crown condition data were accessed for sugar maple, white ash (*Fraxinus americana* L.), red ash (*Fraxinus pennsylvanica* Marsh.), black ash (*Fraxinus nigra* Marsh.), white birch (*Betula papyrifera* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and red spruce. Species of ash and birch are not consistently differentiated in the pathology reports and are analyzed only at the generic level.

Reconstruction of dieback on each species was possible due to consistent detailing of canopy condition and a wealth of information on weather, diseases, insects, cutting, fire, or other agents (Maine Department of Conservation 1920–1995). Routine USDA Forest Service (1950–1995) reports were accessed from 1950; additional sources included doctoral theses, scientific journal articles, reports of state and

federal resource agencies, and overviews on dieback across northern hardwoods (e.g., Millers et al. 1989; Walker et al. 1990).

Numeric index (NI) of dieback

We quantified the level of dieback using a method previously developed, tested, and refined by the senior author (Auclair 2005) as follows.

(1) We first identified key words and phrases in the annual survey reports (and other literature) in terms of extent and severity.

(2) Area extent was scaled 1–10: “one, two, or few individual locations” rated 1, “many areas or localities” rated 5, and “all of commercial forest in region” rated 10.

(3) Severity of dieback was the sum of symptom, intensity, and cover type codes divided by 2: symptom severity (0–10) included “crown dieback” (weighted 8), “epicormic sprouting” (weighted 5), “leader mortality” (weighted 4), etc. Intensity (1–5) included a gradient from “a few trees” (coded 1) to “many trees” to “unusually severe” to “rapid deterioration and death” (coded 5). Cover type (1–5) expressed the effect of climate stress, considered greatest when dieback occurred in protected locations such as natural forest, sugar bush, and rural woodlots (coded 5) and least in exposed cutover, plantation, and roadside locations (coded 1).

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

(5) A panel of forest scientists critiqued the proposed methods, complete with actual data. Two significant changes were made: we excluded leaf symptoms, since there was no evidence that these led to crown dieback, and we excluded minor episodes to distinguish actual episodes from “background” levels.

(6) Reconstruction was done on a species-by-species, year-by-year, and decade-by-decade basis repeated for the full 1920–1995 interval.

(7) Numeric codes in each 10-year period were plotted to identify any gaps; cross-referencing and verification were applied until we were certain that the patterns quantified were accurate.

Meteorological stations and data treatment

One meteorological station was located in each of the five major USDA Plant Hardiness Zones (USDA ARS USNA 2003) of Maine. In total, five stations were identified along north–south and coast–inland gradients to represent the considerable forest cover and climatic variation across the State (Table 1). The Caribou Municipal Airport is north of and Jackman is within the Longfellow Mountains (peak elevation 1605 m). Farmington is in the southeastern foothills of the White Mountains (i.e., inland but oceanic aspect). Portland and Bangor are on or near the coast east of these mountains and under strong maritime influence.

Daily minimum and maximum temperature, daily total precipitation, and daily snow-depth records were acquired for the 1 January 1920 through 31 December 2007 period at each of the five meteorological stations (US NCDC 1920–2007, www.ncdc.noaa.gov/oa/ncdc.html [accessed 1 December

Table 1. Identity and coordinates of five meteorological stations used in the analysis of annual soil frost and drought conditions in Maine during 1920–2007.

Station	Station identification No.	Latitude and longitude	Elevation (m)	AWHC (cm)
Caribou Municipal Airport	171175	46°52'N, 68°01'W	190.2	25.8
Jackman	174086	45°37'N, 70°15'W	362.7	24.4
Bangor	170350	44°48'N, 68°48'W	18.0	24.6
Farmington	172765	44°41'N, 70°09'W	128.0	21.1
Portland International Jetport	176905	43°39'N, 70°18'W	13.7	21.2

Note: Daily temperature, precipitation, and snow depth records were accessed at the US National Climate Data Center (US NCDC 1920–2007). Available water-holding capacity of soil (AWHC) at each station was obtained from the US National Drought Mitigation Center (2008).

2008]). At each location, an alternative station was identified within a 75 km radius to serve as a substitute in the event that the principal station contained minor data gaps. The standard procedure was to use, on any day, temperature and (or) precipitation data from the substitute station to fill a gap.

Snow depth was typically reported daily over the October–May period every year. In the minority of days where daily snow depth was not measured (indicated by a “99999” code in the NCDC meteorological record), we used the routinely recorded snowfall for that day and added this to the prior day snow depth. In rare cases where neither the daily snowfall nor the daily snow depth was reported, we simply interpolated between successive days of recorded snow depth. Where a trace level of daily snow depth was reported (coded “T” in the NCDC record), we replaced this code by 0.0254 cm snow depth.

Soil frost and drought estimates

Soil frost was assumed to occur when daily snow depth was less than 25 cm and minimum air temperature was less than -10°C ; the daily degree-days of soil frost below these thresholds were summed for each winter month (December–February) over the 1920–2007 period.

We judged that, while our choice of 25 cm of snow and -10°C was arbitrary, it provided a reasonable approximation of conditions on the forest floor for continuous snow cover insulation on an irregular surface (with fallen logs and other irregular debris) and frost sufficient to cause damage to fine roots (Cleavitt et al. 2008). The level of drought over the growing season was estimated using the Palmer drought severity index (PDSI); to achieve this, the web-based US National Drought Mitigation Center (2008) version for the self-calibrating PDSI algorithm, including station available water holding capacity (Table 1), was obtained at <http://drought.unl.edu/> [accessed 10 July 2008]. We computed monthly self-calibrated values of PDSI for May–September of each year for the 1920–2007 period. The PDSI scale ranges from -5 (dry) to $+5$ (wet). Since we sought a measure of drought, we reversed this scale and used the term “drought index” throughout the text.

Dieback risk index (DRI)

DRI is the average of the degree-days of soil frost of the most severe month in winter (December–February) and the drought index of the most severe month of the growing season (May–September). An intermediate DRI was computed by first computing z -scores for annual values of soil frost

and drought of their respective timeseries (1920–2007) and then adding the two z -scores of these variables.

Dieback is known to be affected by the age or maturity of the tree population (Manion 1991). Ideally, we would have included the age or percent nearing “maturity” in the tree population as a term in the DRI but lacked access to this kind of data for long time series. As an alternative, we included a lagged-response term, namely the level of actual dieback in the prior year. The response-lagged DRI (DRI_{lag}) is the same as DRI above but has the prior year ($t - 1$) actual dieback included as a third term.

Three steps were used in developing a final DRI (and DRI_{lag}) for comparison with actual dieback. First, we weighted actual dieback, soil frost, and drought values at each station by “net volume of growing-stock trees on timberland” of each of the four forest types (Griffith and Alerich 1996) in counties represented by a station. In each case, we computed yearly values of the standard error of the mean (SE). The resultant was a time series of weighted DRI representative of Maine as a whole. This step was essential, since there was only one dieback time series on each tree species to represent the variation in climate and vegetation across the State. As one might expect, tree abundances varied widely and had a proportionally large effect on final weighted DRI values. For example, the net volume of growing stock per unit area of timberland in birch, sugar maple, and red spruce is three- to fourfold greater in the north (Caribou station) than in the south (Farmington station). Ash is the exception with the greatest net volume in the center of the State (Bangor station).

Ideally, we would have weighted using time-adjusted net volumes of growing stock over the entire 1920–1995 period; this would have been very difficult given that systematic 7-year forest inventories in Maine were first completed in 1958.

Second, the weighted actual dieback, soil frost, and drought values were differenced by subtracting year t from year $t - 1$ (hereafter referred to as “first differences”). Our use of first differences was to facilitate achieving stationarity in the data set, a necessary precondition to correlation and other statistical analyses where periodicity (i.e., high autocorrelation) is evident.

Third, we applied point-centered 7-year averaging to all of the original and net tree volume weighted annual data (actual dieback, soil frost, and drought). In an additional step, we reapplied 7-year averaging to the previously averaged data, a technique known as the double-averaging method (e.g., Righetti 2008). This extreme form of

“smoothing” is used in cases where original data show extraordinary variability or turbulence (i.e., extreme noise) to help envision overall or general trends (hereafter referred to as “general trends”).

Stepwise linear regression (SLR) model

SLR modeling is used as a test of whether we could adequately treat the very high levels of autocorrelation evident in the data. At issue is the development of an SLR model with acceptable levels of stationarity and autocorrelation of residuals.

The marked periodicity in soil frost, drought, and actual dieback time series poses a particularly difficult statistical challenge. We approached the issue of autocorrelation in the data sets by experimenting with a set of data transformations. We compared the R^2 and autocorrelation of residuals between test SLR models run (i) with no transformation in the original data (i.e., high levels of autocorrelation), (ii) with first-difference data (improved stationarity), with (iii) first-difference data including a lagged dependent variable (i.e., actual dieback in year $t - 1$), and (iv) with first-difference data including the lagged dependent variable (i.e., actual dieback in year $t - 1$) and lagged independent variables (i.e., soil frost and drought, both in year $t - 1$). At each stage of data transformation, we tested the autocorrelation in residuals using the Durbin–Watson statistic (Durbin and Watson 1951) or the Durbin h statistic in models where a lagged-response variable was applied (Pindyck and Rubinfeld 1997). Residual autocorrelation probability estimates (P_r) were calculated in each Durbin- h test.

Time series plots

Trends of net timber volume weighted soil frost, drought, and derived DRI and DRI_{lag} were plotted as first differences over the entire 1920–2007 period for the mean of all species combined and for the four species separately. Trends involving actual dieback were limited to 1920–1995. For each trend, the 7-year average and general trend were plotted.

Verification of DRI and SLR models

The climate-based predictions of dieback based on the DRI and SLR models were compared with the actual dieback reconstructed from field observations during 1920–1995. Any discrepancy was noted and interpreted and, where indicated, methods were explored to improve the accuracy of the DRI.

Note that the DRI model, based exclusively on meteorological information, is completely independent of the survey-based biological data. This is also true of the SLR model where only soil frost and drought are used as independent variables. The autoregression SLR model (see Table 2), by contrast, uses the prior-year observed dieback; in this sense, the prediction of current-year dieback is not strictly an independent verification of the response variable in the equation (as is implied by the term “autoregression” using year $t - 1$ values).

Results and discussion

Trends and variation in actual dieback

The NI shows three conspicuous features: marked in-

crease over the century, high interannual variability, and a regular, rhyming recurrence of dieback (Fig. 1).

The NI increased eightfold from 0.8 in 1920 to 6.7 in 1995. Initially, ash was the only tree species affected; three episodes affecting birch, then ash and red spruce, and finally ash, birch, maple, and spruce followed (Fig. 1a; see Fig. 5a). The fact that DRI decreases slightly over the same period (see Fig. 4a) suggests that the large number of tree species affected recently accounts for much of the trend in Fig. 1a. In addition to its primary purpose of achieving stationarity, first differences have the additional effect of detrending the dieback time series (Fig. 1b). The 7-year average and the general trend clearly show a strong periodicity (Fig. 1c). The four successive dieback events in Maine averaged about 22 years duration and were notably more regular and more pronounced than in the Appalachian and Midwest regions of northern hardwoods (Auclair 2005).

Trends and variation in soil frost and drought

Soil frost shows especially high year-to-year variability and long-term increase (Figs. 2a and 2b). The 7-year average and general trend clearly show a cyclical pattern, notably a 12- to 15-year periodicity after 1955. The regression trend increases 30% from 205 degree-days C in 1920 to 265 degree-days C in 2007. Individual years with greater than 350 degree-days C of frost are 1925 and 1929 but only become relatively common in and after 1962 (Fig. 2c).

The two variables used to calculate soil frost also show conspicuous change. The regression trend of annual winter snow depth decreases 44% from 45.7 cm in 1920 to 25.4 cm in 2007; deep snows in peak years of 1920, 1923, and 1934 (88.9, 96.8, and 75.4 cm average winter snow depth, respectively) decrease by roughly two thirds to 29.0 cm average winter snow depth in 2003, the most recent “peak” year. Conversely, the regression trend of the average temperature less than -10 °C in the coldest winter month rose 42% from -0.95 °C in 1920 to -0.55 °C in 2007.

Drought index decreased from neutral (+0.1) in 1920 to moist (-1.3) in 2007 (Fig. 3a) or 14% relative to the full range (-5 to $+5$) of the index. This is consistent with a 7.3% increase in growing season monthly total precipitation (from 3.58 to 3.84 cm) and a decrease in mean growing season temperatures from 61.1 to 59.5 °C across the State during 1920–2007. Drought exhibits frequent, but uneven peaks varying from 1 to 6 years duration (Figs. 3a and 3b). Periodicity is especially obvious in the 7-year average and general trend; these show recurrent episodes of elevated drought lasting 12–22 years (Fig. 3c).

Trends and variation in DRI

DRI shows a slight (6%) decrease over the century (Fig. 4a), consistent with a rise in soil frost (Fig. 2a) but a decrease in drought (Fig. 3a). The year-to-year changes in DRI show conspicuous variability (Fig. 4b). A regular if uneven periodicity in DRI is evident in the 7-year average and general trend; the 1920–2007 regression trend decreases only slightly (Fig. 4c).

The two components of DRI covary, but with some notable differences. Soil frost is highly variable relative to much more consistent episodic trends in drought. Yearly acute soil frost immediately precedes and occurs multiple times within

Fig. 1. Actual dieback levels in Maine during 1920–1995: (a) original annual values with standard error of the mean, (b) annual first differences, and (c) first-differences 7-year average and general trend (heavy line). The linear regression is shown in each case.

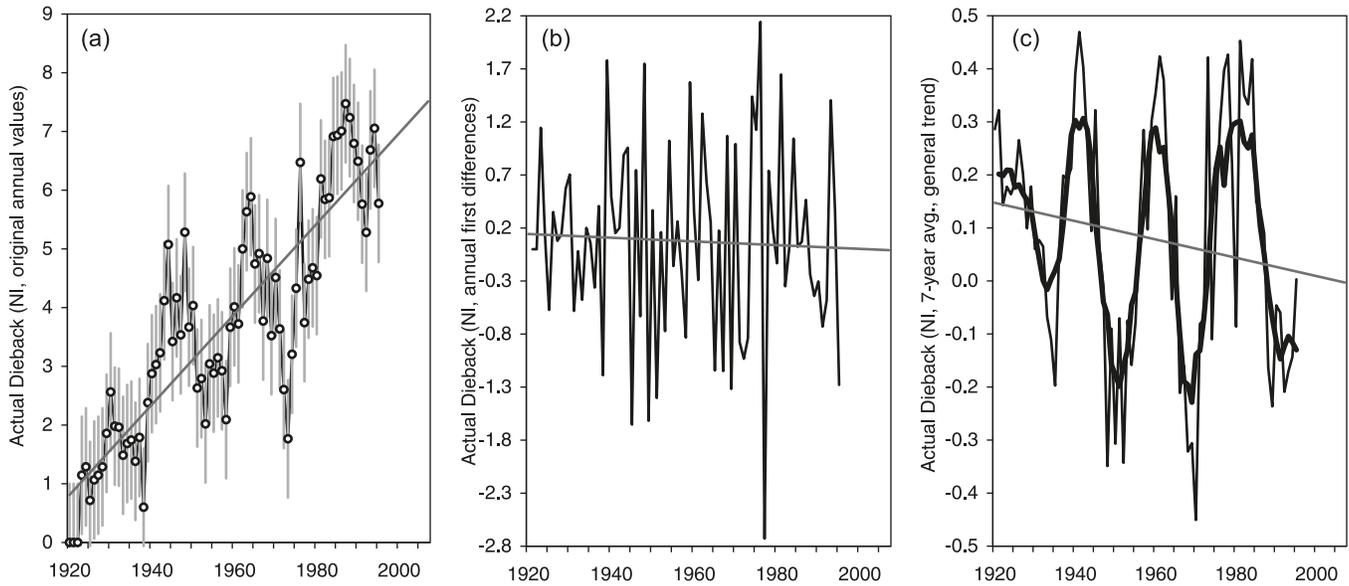
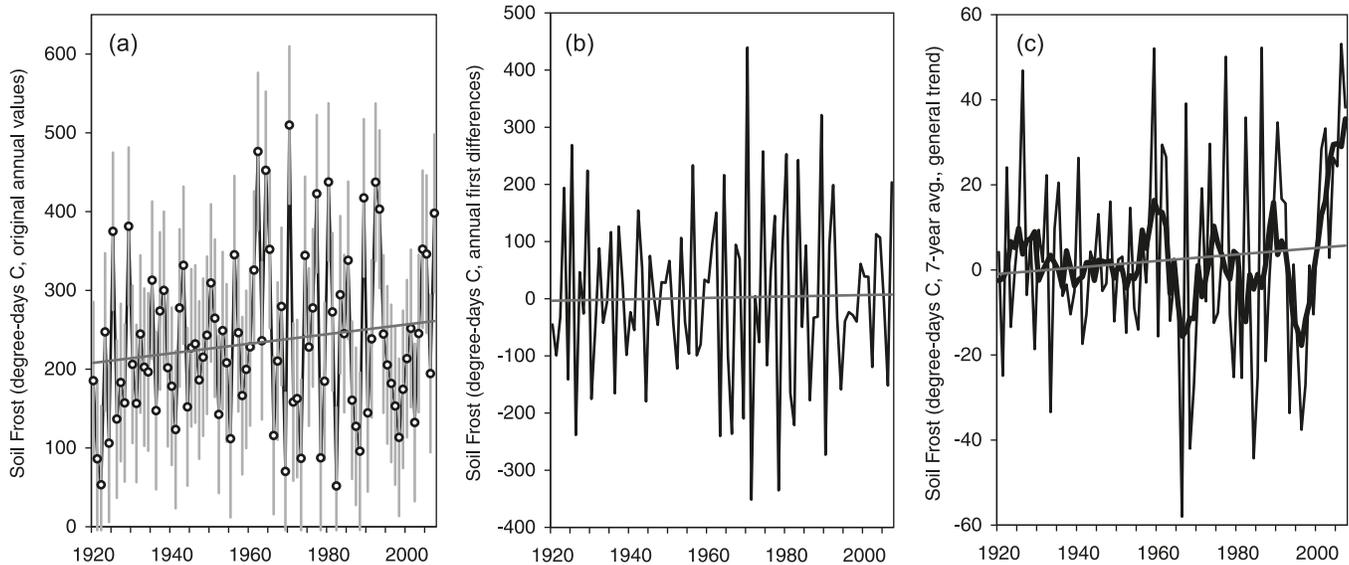


Fig. 2. Soil frost levels in Maine during 1920–2007: (a) original annual values with standard error of the mean, (b) annual first differences, and (c) first-differences 7-year average and general trend (heavy line). The linear regression is shown in each case.



each major episode; it also occurs occasionally between major episodes. Three years of extreme soil frost are 1987, 1988, and 1989 (Fig. 2) in the absence of drought (Fig. 3), hence, relatively low DRI in these years (Fig. 4). We note that, in this exceptional situation, elevated dieback occurs on the three hardwoods but not on red spruce (see DRI models of individual tree species below).

Verification: DRI versus actual dieback

Yearly changes in climate stress (DRI) result in instantaneous increases and decreases in actual dieback (Fig. 5a). The same close climate–dieback interaction is evident using the general trend (Fig. 5b).

A necessary caution in graphing first differences as in Fig. 5 is that dieback, if severe, will continue even as differ-

enced values drop to zero or slightly negative (i.e., no or little decrease from a prior peak year of severe dieback). The vertical boxes in Fig. 5a demarcate the duration of severe, persistent dieback well above that attributable to background variability or “noise” (Auclair 2005). The purpose is to identify differences between episodes (e.g., duration, level of severity, and species affected) and to examine the coincidence of dieback onset/subsidence with stress.

Five features are noteworthy. (i) Each episode involves an increasing duration and expanding cadre of tree species (Fig. 5a). (ii) Severe dieback (NI > 4.0) occurs in 60 of the 76 years or 79% of the 1920–1995 interval (Fig. 5a). Severe climate stress (DRI > 0.4 based on non-differenced, 1-year values) occurs in 68% of this period, suggesting that dieback and associated climate stress are the normative forest

Fig. 3. Drought levels in Maine during 1920–2007 based on the drought index: (a) original annual values with standard error of the mean, (b) annual first differences, and (c) first-differences 7-year average and general trend (heavy line). The linear regression trend is shown in each case.

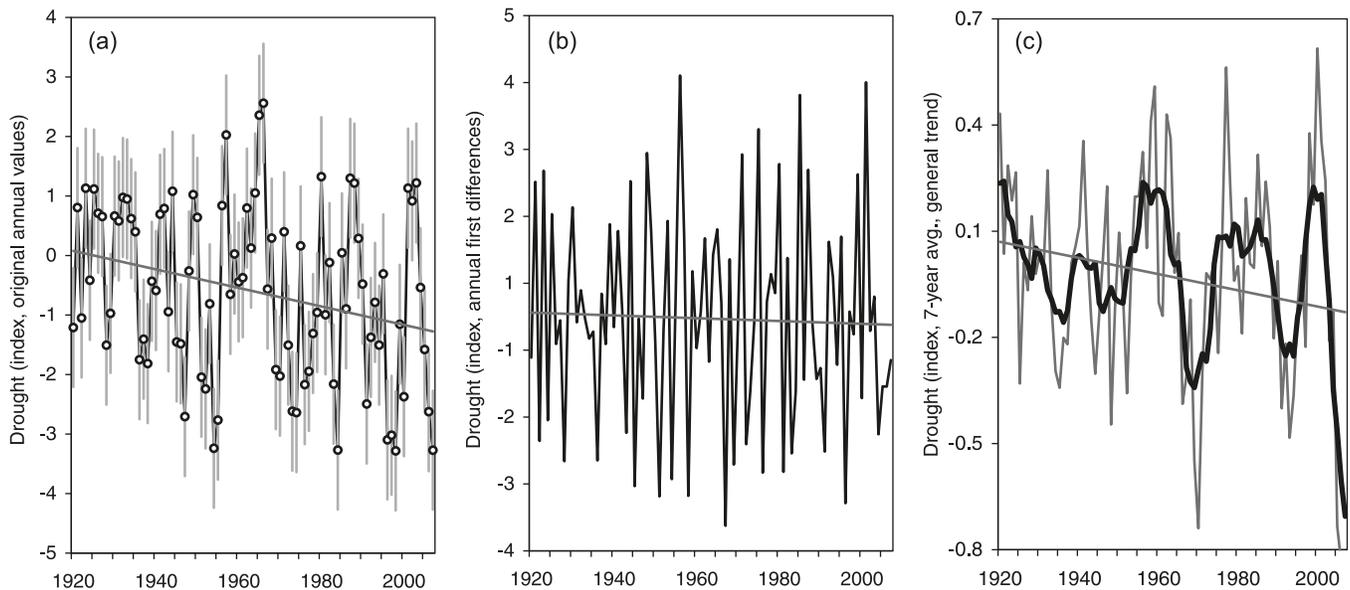
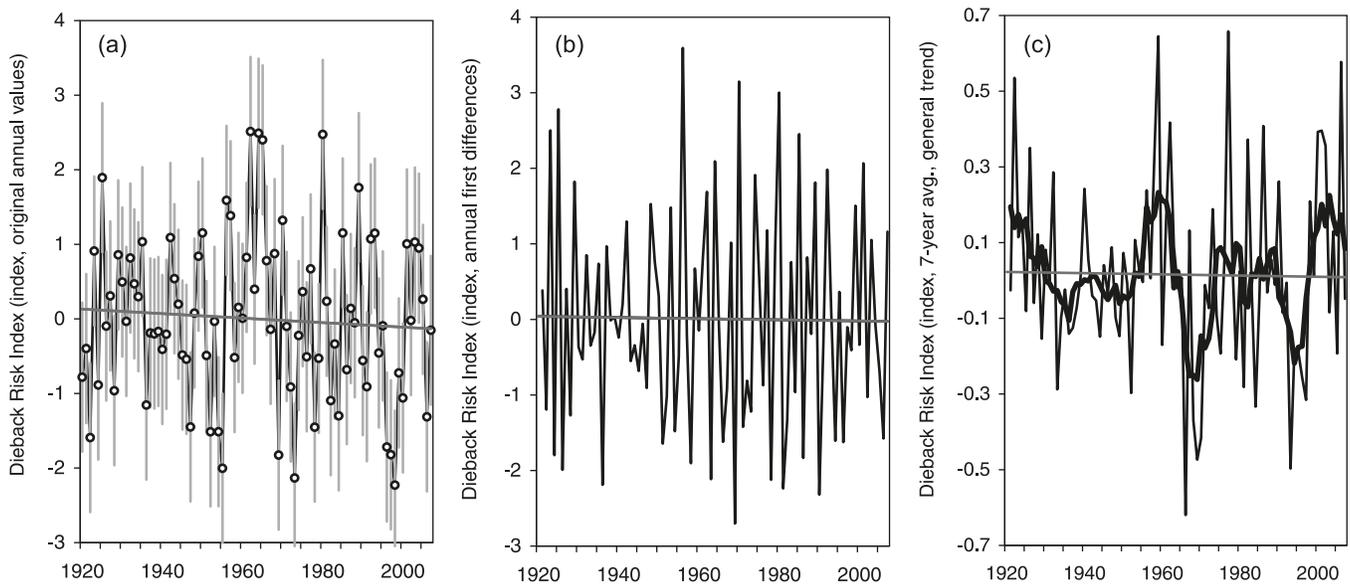


Fig. 4. Dieback risk index estimates in Maine during 1920–2007: (a) original annual values with standard error of the mean, (b) annual first differences, and (c) first-differences 7-year average and general trend (heavy line). The linear regression trend is shown in each case.



condition. (iii) The onset of dieback is closely linked to climate stress; subsidence or “recovery” immediately follows a drop in climate stress (Fig. 5). (iv) The exception is white birch during 1939–1951. Although the average DRI is relatively low over this 13-year period, we note that soil frost, drought, and DRI peaked sufficiently in individual years to cause injury from 1935 on and notably during 1943–1944 and again during 1949–1951 (Figs. 2b, 3b, and 4b). This dieback episode is by far the largest in the historic record in terms of volume of tree mortality (Auclair 2005). The discrepancy between DRI versus actual dieback in the 1976–1995 period relates to the additive number of mature tree populations affected; severe dieback first occurred on sugar maple (1976)

and then on birch (1979), ash (1981), and red spruce (1984); once initiated, dieback continued unabated on all species through 1995. (v) A prominent feature of the general trend in Fig. 5b is a more or less regular cycle of stress and dieback but also high variability (Figs. 1–5). Variability is characteristic of all diebacks worldwide that show typically great variation in crown and trunk symptoms, marked shifts over the landscape in species, sites, and geographic areas affected, and sudden “on-off” changes year to year (Auclair et al. 1992).

Verification: DRI_{lag} versus actual dieback

The response-lagged DRI model greatly improves the pre-

Fig. 5. (a) Dieback risk index (heavy line) versus actual dieback (light line) in Maine; both variables are 7-year averages of annual first differences. The linear regression of the dieback risk index for 1920–2007 is shown. Predominant tree species and duration of the four major dieback episodes in Maine are shown. (b) Dieback risk index (DRI) (heavy line) versus actual dieback in Maine; both variables are general trends first differences. The linear regression of the dieback risk index for 1920–2007 is shown.

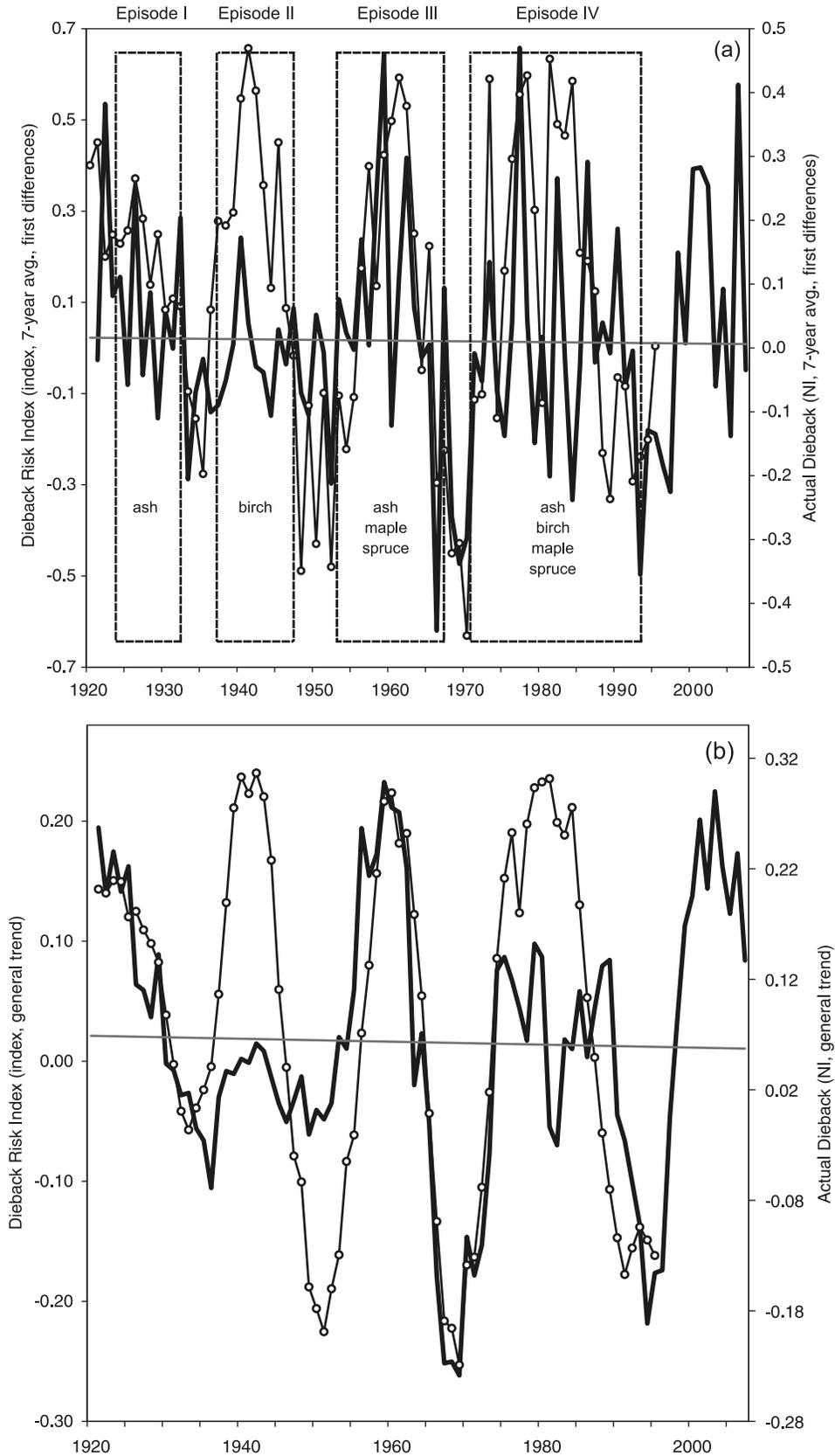
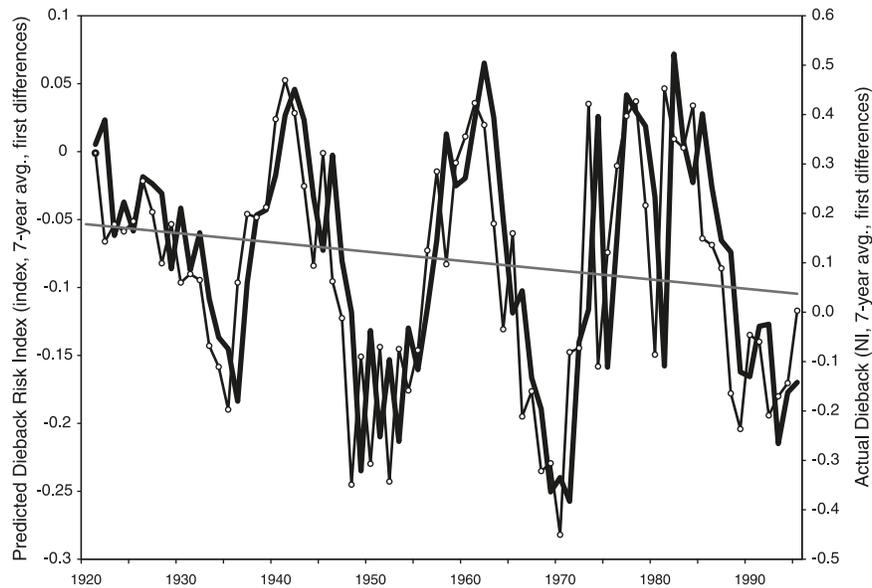


Fig. 6. Response-lagged dieback risk index (DRI) (heavy line) versus actual dieback (light line) in Maine during 1921–1995; both variables are 7-year averages of annual first differences. The linear regression of the dieback risk index for 1921–1995 is shown.



diction of actual dieback (Fig. 6). It differs from the non-lagged DRI model (Fig. 5a) in showing little discrepancy in the 1939–1951 and 1976–1995 episodes. The advantage of the nonlagged DRI model is its simplicity and the ability to envision climatic impacts directly, uncomplicated by the effect of prior years' dieback.

DRI models of individual tree species

Comparison among the four species enables us to address three questions. (i) How do the four species differ? For example, birch is unique among the four species in being an early pioneer and shows marked cohort senescence (Mueller-Dombois 1986). (ii) What is the role of tree population dynamics? The perception that trees are increasingly vulnerable as they age (Manion 1991) is now supported by research showing that pit membranes of older vessels become brittle and rupture easily under stress (Sperry et al. 1991). Hence, recovery from extensive cutting/clearing after 1860 and differing ages among species at biological "maturation" are important hallmarks indicating when a species is at risk to extreme stress. Young populations may be relatively unaffected at a time when older populations are severely impacted. (iii) What can we learn about species-, site-, and management-specific mechanisms inciting dieback?

Dieback on red spruce

Red spruce shows a close relationship to freezing/drought stresses in Maine. From 1950 on, the timing of episodes coincides precisely with changes in DRI; the magnitude of the stress also coincides except for some differences in the 1970s and early 1980s (Fig. 7a).

Prior to 1950, there is little apparent response to climate stress. We ascribe the absence of dieback through the 1920–1950 period to especially high red spruce loss to spruce budworm (*Choristoneura fumiferana* Clemens) dur-

ing 1912–1920 (Royama 1984) and hence a relative lack of mature red spruce.

After 1950, extensive dieback coincides with elevated stress. Especially high red spruce mortality occurred during 1871–1885 (Johnson et al. 1986) and extensive clear-cutting during 1870–1895. By the 1950s or about 80 years after extensive mortality/logging in the State, populations of mature red spruce were common and especially vulnerable to dieback (Fig. 7a).

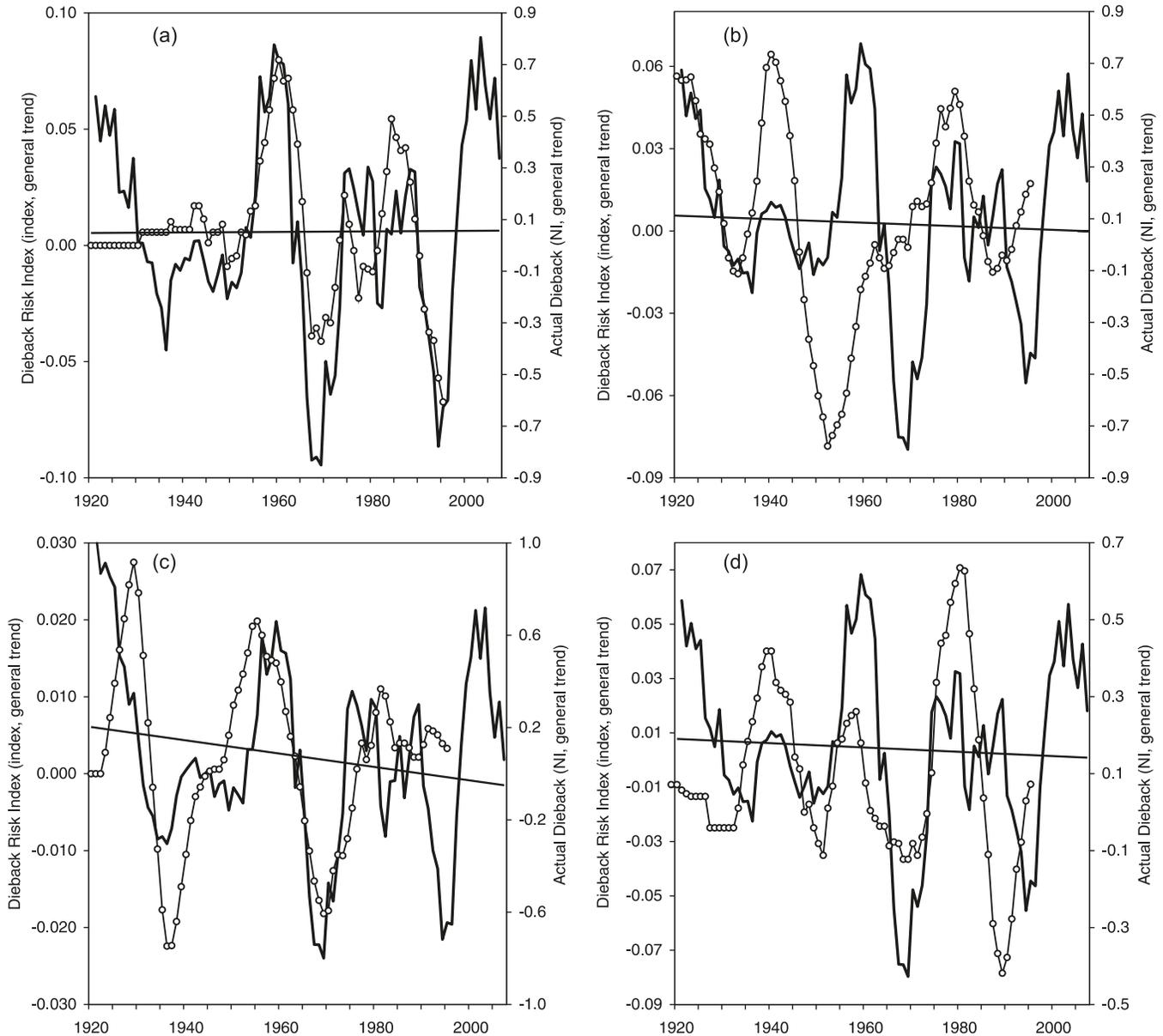
The sensitivity of red spruce current-year foliage to extreme cold is well documented. DeHayes et al. (1999) noted that "the direct link between freezing injury and red spruce decline in northern montane regions of the species geographic range is so strong that the decline is widely attributed to freezing." Region-wide freezing events have increased over the past 40 years. This is significant in that current-year foliage is especially susceptible, having about 10 °C less freezing resistance than 1-year foliage.

Exposure of red spruce seedlings to acidic cloud water at ambient levels is shown to significantly lower concentrations of Ca and Mg and reduce cold tolerance in current-year foliage by an average of 6–7 °C. Chronic N deposition also lowers Ca foliage concentrations, enhances electrolyte leakage, reduces cold tolerance, and results in greater freezing injury (DeHayes et al. 1999).

Johnson et al. (1986) reported that all six periods of extensive red spruce mortality during 1820–1985 in the Appalachians of New York show anomalously high late-summer temperatures and unusually cold December and January conditions. They postulated that the mechanism of decline "might involve adverse effects of temperature on C budgets and/or on winter hardiness".

We infer from our observations (Fig. 7a) and those above that red spruce is vulnerable to frost through at least three independent mechanisms.

Fig. 7. Dieback risk index (heavy line) versus actual dieback (light line) in Maine: (a) red spruce (*Picea rubens*), (b) birch (*Betula* spp.), (c) ash (*Fraxinus* spp.), and (d) sugar maple (*Acer saccharum*). Both dieback risk index and actual dieback are general trends first differences. The linear regression of the dieback risk index for 1921–2007 is shown in each case.



Dieback on white birch

White birch also shows a close, but more complicated relationship to freezing/drought stresses. Dieback episodes coincide precisely with changes in DRI over the 1920–1950 and 1970–1986 periods but not over 1951–1969 and 1986–1995 (Fig. 7b).

In Maine, white birch pioneered broadly on areas clear-cut of red spruce, reaching maturity in the 1920s–1930s. The spectacular dieback of 1935–1950 is synchronized senescence (Mueller-Dombois 1986). DRI over this interval is up but low compared with severity of dieback; it is likely that these populations on soils degraded by fire and erosion were unusually sensitive to stress (Fig. 7b).

The notable dissynchrony during 1951–1975 between high stress but low dieback likely relates to a paucity of

mature, vulnerable white birch. Elevated dieback in the mid-1970s and 1980s probably involves resurgent birch that reseeded from stressed and dying populations in the 1920s and on. Dieback during 1989–1995 (Fig. 7b) occurs under exceptionally high soil frost but low drought.

Birch is shallow rooted and sensitive to moisture and freezing stress. K. Greenidge’s work (see Walker et al. 1990) on birch over the 1950s in New Brunswick showed that dieback is proportional to fine root mortality and to the extent of air embolism of sapwood. He failed to demonstrate convincingly that drought was the inciting stress and ceded the possibility of frost-induced injury (see Walker et al. 1990). Clark and Barter (1958) concluded that drought alone could not explain the dieback. Conversely, dieback was demonstrated to be proportional to the duration of frost

(Pomerleau 1991) and to depth of frost penetration on plots cleared of snow (Pomerleau and Lortie 1962). Cox and Malcolm (1997) showed that white birch subjected to >60 degree-days thaw >4 °C followed by freezing died back. They concluded that “winter thaws, and its close correlation with irreversible losses of xylem conductivity due to embolisms, coupled with the inability to refill the xylem because of root damage, may be key factors in initiating birch decline”. Thaw–freeze models simulated accurately the extent of birch dieback over eastern Canada during 1930–1960 (Bourque et al. 2005). In stands of mountain paper birch (*Betula cordifolia* Regel) along the Bay of Fundy, acidic fog with pH as low as 3.0 is linked to birch foliar browning, leaf cuticular erosion, and early leaf loss followed by invasion of *Septoria betulae* Pass. fungus (see Mohan et al. 2009).

Dieback on ash

Ash shows an especially close relation to freezing/drought stresses in all four major episodes. Dieback coincides precisely with DRI throughout 1920–1995 (Fig. 7c). Elevated dieback during 1990–1995 on black ash (Livingston and White 1997) coincides with severe soil frost.

White ash typically occurs as a minor component of sugar maple forests. Black ash can dominate stands along rivers and on lowlands. In 1993, ash dieback extended across 50 000 ha or over much of the 65 000 ha of elm – ash – red maple forest type in Maine. Large losses due to dieback are occurring over the Northeast, for example, on 43 000 ha in New York and on 11 000 ha in Minnesota (Ward et al. 2009). Dieback has been widespread on European ash (*Fraxinus excelsior* L.) since the early 1990s (<http://archives.eppo.org/EPPOReporting/2007/Rse-0709.pdf> [accessed 20 October 2009]). Spread of emerald ash borer (*Agrilus planipennis* Fairmaire) into Maine is likely, so total ash losses could be considerable.

Ash is especially shallow rooted and exquisitely sensitive to soil moisture and nutrients conditions. It has one of the largest vessel structures of any ring-porous hardwood, suggesting narrow limits for moisture calibration. White ash occupies well-drained mesic sites and is rarely found on crests or on low-lying slope positions. Leaf stomata are unable to completely close under drying conditions so that excessive transpiration occurs. Agents such as mycoplasma-like organisms reportedly stunt root growth.

Ash dieback is pronounced on poor sites. Black ash growing on wet sites (with standing water or saturated soils) has five times greater dieback and mortality (25% dead) than trees growing on mesic sites (5% dead) (Ward et al. 2009).

Hibben (1978) concluded that in New York, water stress followed by invasion by canker fungi is the primary cause of ash dieback. Conversely, in a study of severe ash dieback during 1942–1957 and 1962–1980 in New York, Castello et al. (1985) found severe drought in only half of the onset years and concluded that additional factors were involved.

Recently, Pokomy (1995) noted that widespread dieback on green ash in several midwestern States is independent of mycoplasma-like organisms (ash yellows) but is related to drought in 1980–1981 and 1988–1989 and to severe cold in 1994. Ward et al. (2009) noted that the cause of black ash decline is unknown but thought to be related to drought

(see Livingston and White 1997), subfreezing winter temperatures with little snow cover, or late spring frost.

Few studies have focused on the effects of acidic rain or cloud water on ash, but ash is widely recognized as one of the most sensitive trees to elevated ozone levels; white ash is a bioindicator of excessive ozone in US forest health surveys.

Dieback on sugar maple

Dieback on sugar maple occurs in three of four major episodes, starts rapidly at onset of climate stress (DRI), and also subsides rapidly (Fig. 7d).

Three patterns are unique to sugar maple. (i) Within each episode, the subsidence of dieback precedes a drop in frost/drought stress by 3–6 years. A possible interpretation is especially rapid infection/infestation by secondary and decay organisms in the relatively humid coastal climate of Maine. Sugar maple has a particularly large array of primary pathogens (e.g., *Verticillium* spp. and *Ceratocystis* spp.) and second-order insect defoliators (Houston 1999). (ii) The maximum severity (Fig. 7d) occurred recently (1970–1993) (Fig. 5a). Since the 1960s, high grading has occurred extensively throughout Maine. The impact of opening the stand and considerable soil disturbance by mechanized equipment leaving irregular surfaces and pooled water increases the likelihood of soil frost (see Soil frost and soil saturation section below). (iii) Dieback increased markedly during 1989–1995. Extreme soil frost during 1987–1989 suggests a high level of root mortality.

Dieback during 1928–1932 (Fig. 5a) was low but unequivocally did occur at severe levels (1935–1950) in Maine before the 1950s, in contrast with the general perception (e.g., Houston 1999). Severe dieback during 1935–1950 at a time of moderate DRI and low dieback at a time of especially high DRI during 1950–1965 is similar to the pattern in birch (Fig. 7b), suggesting synchronized senescence. By 1975 or fully 100 years after extensive logging and (or) cropland reversion in the State, populations of mature sugar maple were common and vulnerable to dieback.

Sugar maple is moderately shallow rooted and grows best on soils that are deep, rich in nutrients, and moist but moderately coarse textured and well drained. The species is sensitive to both drought and excessive soil moisture, forms vesicular–arbuscular mycorrhizal associations readily impacted by soil acidity, freezing, and drought events, is among the most sensitive of tree species to mineral (especially Ca and Mg) deficits common on acidic soils, and is readily impaired by elevated ozone known to significantly alter nutrient acquisition (St. Clair et al. 2008).

Sugar maple is an important benchmark species and the focus of intense monitoring by the North American Sugar Maple Decline Project (NAMP) (Allen et al. 1999). An overview of NAMP studies indicates that severe drought and heavy defoliation did not lead to unusual levels of mortality. Rather, mortality is within normal bounds for hardwood forests. Most declines are explained by acute stress factors such as defoliation, drought, or winter soilfreezing combined with knowledge of land-use history (Allen et al. 1999).

If atmospheric deposition is affecting sugar maple, the effects across NAMP plots in the United States and Canada are subtle and not reflected in crown condition or mortality.

On some sites, soil acidification, when augmented by acidic deposition, may significantly affect growth and tree resistance to stresses and opportunistic organisms (Houston 1999).

On unglaciated, acidic, nutrient-imbalanced soils low in Ca and Mg receiving elevated acid rain, declining maple stands have unusually high foliar Mn, extremely low foliar Mg (<700 mg·kg⁻¹), and two or more moderate to severe defoliations (Horsley et al. 2000). St. Clair et al. (2008) hypothesized that by exacerbating nutrient imbalances, acidic deposition impairs primary metabolism and reduces C gain, such as high starch reserves in roots, which correlates with greater vitality and ability to resist stress and defoliation.

Frost induction experiments in sugar maple show that soil freezing results in cellular injury of first- and second-order roots in the organic horizon that are critical to water and nutrient uptake. Repeated freezing damage and new production of fine roots represent a potentially significant C drain on the tree followed by decreased growth and increased tree mortality (Cleavitt et al. 2008). Soil freezing results in very high pulses of NO₃⁻ release to the soil, further accelerating soil acidification (Groffman et al. 2001). Soil frost and, in nutrient-limited conditions, soil pH effects on fine roots are seen as critical factors in sugar maple decline.

The SLR model

The initial stepwise linear regression of original (i.e., non-differenced) data showed a high first-order autocorrelation of residuals ($r_a = 0.789$). Transformation of original data to first differences approximately halved this level ($r_a = 0.408$) but was insufficient to meet 5% significance in the Durbin–Watson test for autocorrelation levels in the residuals. Including a lagged dependent variable (i.e., actual dieback lagged at $t - 1$) greatly improved R^2 and lowered the first-order autocorrelation of residuals ($r_a = -0.160$) but did not meet the 5% Durbin h test of no significant autocorrelation of residuals. The probability (P_r) of no significant autocorrelation of residuals was <0.018; this compared with an acceptable minimum $P_r < 0.050$. Including lagged independent variables (i.e., soil frost and drought, both lagged $t - 1$) in addition to the lagged dependent variable only slightly increased R^2 , slightly lowered the first-order autocorrelation of residuals ($r_a = -0.145$), but again failed to meet the 5% Durbin h test (Table 2).

The SLR models with data transformed to first differences and with lagged variables show moderate to high residual autocorrelation. While acknowledging its statistical limitations as a test model, SLR with lagged dependent variable (model 3, Table 2) shows good agreement between predicted and actual dieback throughout the 1920–1995 period. Including lagged soil frost and lagged drought independent variables (model 4, Table 2) adds complexity but does little to improve the model. It is noteworthy that in a separate test set of SLR models based on individual tree species (versus the average of all four species), we obtained models for birch, sugar maple, and red spruce (but not for ash) that met the 5% Durbin h test ($P_r < 0.226, 0.085, 0.063,$ and 0.0001 , respectively) for residual autocorrelation but that had only moderate R^2 (0.678, 0.476, 0.386, and 0.733, respectively).

Table 2. Stepwise linear regression models tested using successive degrees of data transformation.

Test model	R^2	First-order autocorrelation	Durbin–Watson or Durbin h statistic	DI (or $P_r < h$)	Du (or $P_r < h$)
1. Original data with no transformation	0.444	0.789	0.377 (Durbin–Watson)	1.571	1.680
2. Data differenced	0.299	0.408	1.183 (Durbin–Watson)	1.571	1.680
3. Data differenced with lagged response variable	0.490	-0.160	-2.096 (Durbin h)	$P_r < 0.018$	$P_r < 0.018$
4. Data differenced with lagged response, lagged soil frost, and drought independent variables	0.498	-0.145	-2.096 (Durbin h)	$P_r < 0.018$	$P_r < 0.018$

Note: All models based on 7-year averages of annual data ($n = 75$); inclusion of all variables is forced. R^2 , first-order autocorrelation, and the Durbin–Watson or Durbin h test statistic are given. The lower (DI) and upper (Du) bounds of these tests for 5% significance are shown. $P_r < h$ is the probability that there is no significant autocorrelation in the residuals when using the Durbin h test.

General discussion

Importance of the Pomerleau studies

Pomerleau (1991) was not only the first to successfully induce tree and stand dieback in a set of field experiments, his hypothesis on the central importance of soil frost as the foremost mechanism of dieback in northern hardwoods remains the most cogent, compelling, and consistent explanation to date.

One of the best ways of testing a scientific hypothesis is to make predictions. Using a simple model, we demonstrate that Pomerleau's (1991) conclusion applies equally over time (four successive major dieback episodes), to species other than maple and birch (i.e., to ash and red spruce), and to other regions of northern hardwoods, namely Maine, arguably the foremost "epicenter" of severe and recurrent dieback in the eastern United States. In 1991, it was virtually unknown how widespread soil frost was as a mechanism outside the one laboratory and one field site (in southern Quebec), within other species, and over variants of the northern hardwoods.

The 1991 publication of the Pomerleau experiments spawned a remarkable number of snow-removal experiments both in Canada (e.g., Bertrand et al. 1994; Pilon et al. 1994) and in the United States (e.g., Groffman et al. 2001; Decker et al. 2003; Hennon et al. 2006; Cleavitt et al. 2008). These studies have elucidated a wealth of factual details and much is now known on the effects of soil frost on tree physiochemical response to stress (Bertrand et al. 1994), on the nature and extent of root damage (Cleavitt et al. 2008), on soil nitrification, mycorrhizal and microbial changes, and on the selective impacts on forest species (Groffman et al. 2001).

Root freezing and other stresses

Dieback in northern hardwoods is a winter injury to roots incited by erratic winter weather. Tree roots in northern hardwoods are extraordinarily vulnerable to freezing, since they only minimally frost harden in the cold season. They are by far the least frost hardened of any tree tissue and can freeze at as little as $-1\text{ }^{\circ}\text{C}$ (Sakai and Larcher 1987). Rapid decomposition of leaf litter in fall and winter elevates soil temperature and nutrient release; there is strong selective advantage for hardwood species to remain highly active to ensure replenishment of nutrient loss in leaf-fall. Moreover, trees are notably shallow rooting, with over 90% of fine roots in the upper 30 cm (e.g., Skilling 1964). In this condition, they depend foremost on protection from freezing provided by deep, persistent snowpack from late November through early March. Severe thaw is lethal in situations where snowpack melts and exposes roots to deep frost.

In addition to root kill, Auclair et al. (1992) identified at least three other frost mechanisms leading to dieback: aboveground tissue (e.g., ray parenchyma, leaf buds) mortality due to extreme winter cold, cold following winter thaw sufficient to rehydrate trunk, branch, or bud tissues followed by freezing, and irreversible xylem cavitation induced by thaw-freeze. Winter period anomalies associated with dieback in the literature include incidence of low snowfall/low snow accumulation, winter rain and (or) thaw resulting in meltdown of snowpack, severe frost in fall and spring, effects of warm fall weather on frost hardening (and dehardening

in the case of winter thaws), among others. Roots are also injured by flooding.

In this study, we develop a first-generation, region-level model of dieback based on extreme climate events. We recognize, in retrospect, the great importance of species- and site-specific information. A second-generation model would benefit by including (i) tree population dynamics (e.g., tree age distribution, age to biological maturity), (ii) soil water content and other terms affecting soil thermal conductivity, (iii) site variables impacting on root frost resistance (e.g., acidic deposition, insect defoliation) and drought resistance, (iv) root vulnerability and recovery from frost injury (e.g., rooting depth, inherent frost hardiness, capacity for recovery), and (v) there is a need to recognize the importance of natural mortality events (e.g., insect defoliation, wind or ice damage) and silvicultural practices (e.g., high grading) that open the stand. These conditions have the effect of both increasing the likelihood of extreme frost due to subfreezing air temperatures and heightening the water table (i.e., by reducing tree evapotranspiration) that then act as a conduit for rapid soil frost penetration.

Soil frost and soil saturation

We initially used mean soil frost of the winter season (December–February) and mean drought levels of the entire growing season (May–September) in computing DRI but observed only poor simulation of dieback levels. In adopting frost and drought of the most severe 1 month, values of DRI showed greatly improved correlation with actual dieback. This is consistent with extremes of weather (not seasonal averages) causing injury. Soil frost and drought show marked periodicity and tend to co-occur within episodes and hence have an amplifying effect on dieback.

In this study, a straightforward if somewhat arbitrary index of soil frost was used. Using a thermodynamic model such as SHAW (simultaneous heat and water model; www.ars.usda.gov/SP2UserFiles/Place/53620000/ShawUsersManual.pdf [accessed 20 October 2009]) has the advantage of including soil thermal conductivity terms (e.g., soil moisture content, organic content, soil texture) that strongly impact on rate of frost penetration; the model also quantifies the duration, depth, and severity of the freeze and timing and rate of soil thaw.

Soil water content has rarely been identified as pivotal but is key to understanding dieback in northern hardwoods, since it strongly conditions the sensitivity to and rate of soil freezing. For example, thermal conductivity (k) (watts per metre kelvin) of liquid water ($k = 0.6$) is 20–30 times greater than air ($k = 0.02\text{--}0.03$), while dry snow is insulating ($k = 0.1$) and ice ($k = 1.6\text{--}2.2$) is three to four times more conductive than liquid water and, once formed in the soil, acts to accelerate soil frost penetration. Other components such as wood ($k = 0.04\text{--}0.4$), soil ($k = 0.17\text{--}1.13$), and stone (e.g., granite: $k = 1.73\text{--}3.98$) have widely varying coefficients (http://en.wikipedia.org/wiki/List_of_thermal_conductivities [accessed 20 October 2009]) so that fine versus coarse texture, organic content, and rock content are important terms conditioning how fast freezing (and thawing) will occur. We note that dieback is most severe in Maine where humidity and precipitation are high relative to Appalachian and midwestern states (Auclair 2005). Dieback was first observed on lowland sites

(e.g., black ash dieback in Quebec 1925 (Pomerleau 1991); yellow cedar decline in coastal Alaska (Hennon et al. 2006)), and is associated with winter thaw/winter rain meltdown of the snowpack leading to saturation of the soil profile (Auclair et al. 1992) or with flooding. Black ash dieback is five times greater on wet than on mesic soils (Ward et al. 2009).

Applications of DRI and future directions

Contribution to evolving dieback/decline theory

Dieback phenomena are controversial. Since the 1960s, several contrasting theories have been proposed to explain the primary cause of extensive forest dieback/decline in North America, Europe, and elsewhere (e.g., Australia). Four prominent theories include the host-stress-saprogen model (e.g., Houston 1999), the “natural” or cohort senescence theory (Mueller-Dombois 1986), the Ulrich acid rain theory (see DeHayes et al. 1999), and the climate change theory (see Allen and Breshears 2007; Mohan et al. 2009).

Houston (1999) noted that “understanding of cause–effect relationships and underlying mechanisms is increasing”. His update on inciting stresses (e.g., defoliation, drought, winter freezing), amplifying factors (e.g., soil acidification), and the role of secondary-action organisms in sugar maple declines applies equally to many tree species.

Here, we emphasize soil freezing as a key mechanism of root-kill, i.e., provide a “root-centric” interpretation of how dieback works in northern hardwoods. We propose a realignment of the Houston (1999) framework to include the following nine key perceptions: (i) tree roots in northern hardwoods are extraordinarily vulnerable to freezing, (ii) soil water content is key to understanding dieback, since it strongly affects the rate, depth, and duration of soil freezing (and is critically impacted by modern silvicultural practices), (iii) exceptional variability is characteristic, conditioned by high spatial/temporal variability of soil water and snow cover and differences in species sensitivity to stress, (iv) diebacks recur cyclically at decadal and regional scales, (v) diebacks are universal and are known to have occurred worldwide and over the 19th, 20th, and 21st centuries, (vi) diebacks are the “normative” condition and not the exception; inciting stresses and symptoms exist for 70%–80% of the time, (vii) at the century scale, biological maturation/cohort senescence is a critical factor determining when a host population is sensitive to dieback, (viii) trees rapidly recover as soon as stresses diminish, a condition that fits the definition of “dieback” (Manion 1991) as distinguished from “decline”, and (ix) dieback is both manageable and strongly impacted by silvicultural practices that damage trees, impede soil drainage, and open the stand to frost.

Climate change

Several researchers have suggested that dieback will increase under continued climate change (e.g., Allen and Breshears 2007; Mohan et al. 2009). This is a critical area needing investigation and not a moot point regarding dieback in Maine, considering that temperature shifts are expected to be large in northern regions and in the winter season.

Snowpack is crucial to sustaining northern hardwoods; this point emphasizes the need to quantify long-term

changes in soil frost and drought and to identify what areas geographically are affected as climate changes. Some mountain ranges in Europe and the western United States, for example, have experienced a 50%–75% decrease in snowpack in recent decades (Monson et al. 2006). Lemke et al. (2007) mapped large areas in the United States, Canada, and Eurasia with snow cover decreases of 16%–36% between the 1967–1987 and 1988–2004 periods; this included much of the US area in northern hardwoods.

Our caution in overgeneralizing the likelihood of a dieback – climate change response (Mohan et al. 2009) is the very high variability evident in precipitation and in acute soil frost events that mask long-term trends and the presence of trade-offs between variables such as snow cover, soil frost, and summer drought. Our findings of a slight decrease in stresses inciting dieback over the century apply to Maine, but high region-to-region variation is expected.

It is worth emphasizing that even in the absence of climate change, severe dieback events are likely in the future. As forest types in US northern hardwoods continue to mature, they become increasingly vulnerable to erratic climate. In contrast with models of incremental forest change under future climates, dieback events in northern hardwoods are extremely abrupt and severe. Extraordinary levels of tree mortality have been recorded in events over the century, yet the full magnitude of loss to dieback is generally underappreciated in the forestry and scientific communities and needs to be revisited. For example, red spruce during 1871–1885 experienced dieback over the Adirondacks, Vermont, New Hampshire, and Maine with losses estimated at “one-third to one-half of the fully grown spruce timber (see Johnson et al. 1986, p. 323). Surveys on white birch in Quebec, New Hampshire, and Maine showed “not less than 80% of the merchantable birch was dead by 1945” (e.g., Clark and Barter 1958). Krist et al. (2007) estimated mortality losses to 42 insect and disease agents across all US forests over the next 15 years (2005–2020); in aggregate, projected losses to decline exceed any other single category including loss to pine beetles (*Dendroctonus ponderosae* Hopk. and *Dendroctonus frontalis* Zimm.), root diseases (all), and gypsy moth (*Lymantria dispar* L.).

Baseline for comparison

Trends developed for Maine provide a baseline on dieback and climate stress and a practical tool against which to interpret “spot” events as well as long-term trends (i.e., global warming). Ward et al. (2009) studied dieback on black ash in Minnesota in part to establish a baseline ahead of the wave of ash mortality likely upon arrival of emerald ash borer from adjacent states.

The concept of a climate–dieback link has received increased attention across North America and in the wider global community. A cursory overview, for example, indicates that dieback in northern Europe is currently observed on numerous tree species, including those in all genera of our study (i.e., Norway maple (*Acer platanoides* L.), European white birch (*Betula pendula* Roth), European ash (*F. excelsior*), and Norway spruce (*Picea abies* (L.) Karst.)). A baseline would help identify that point at which shifts in climate are having a decisive impact on forest dieback globally.

Climate data, readily available at approximately 12 000 US meteorological stations and at over 40 000 stations worldwide, make it possible to map areas nationwide (and worldwide) at risk to dieback. Generating such a map would advance the science by differentiating frost/drought-incited dieback from other inciting factors and by identifying forest types and geographic areas resistant to or unusually sensitive to dieback as climate changes.

Required research

Several research efforts could improve our understanding of dieback: (i) foremost, there is a need to reexamine recognized dieback/declines (Allen et al. 1999, their table 9) and, in particular, those on which dieback concepts are based (e.g., Houston and Kuntz 1964; Skilling 1964); the aim is to verify that soil frost in winter is or is not the primary injury inciting dieback and to update dieback theory in line with these findings, (ii) conduct field and laboratory experiments on factors affecting root frost hardening over the fall, winter, and spring seasons, (iii) measure directly and (or) apply the SHAW model to quantify soil frost under a range of conditions where the stand has been opened to varying degrees, for example, by insect defoliation (Houston and Kuntz 1964) or by partial cutting, and (iv) reexamine the impact of modern silviculture as a factor in dieback and, where indicated, design improved harvesting practices that minimize tree damage and soil disturbance.

Silvicultural decisions

Since the 1960s, high grading of sugar maple and other hardwoods using mechanized loggers has been extensive and may have contributed to the high levels of dieback during 1970–1995 (Figs. 1a and 5a). This possibility has not been examined but merits the attention of forest managers in Maine and in other states across the Northeast.

The introduction of forwarder feller/bunchers, wheeled skidders, and other heavy equipment on-site has proven efficient but strongly impacts regeneration and site quality. Postharvest surveys in Maine show that as much as 40% of the soil surface is disturbed. Natural drainage patterns are often obliterated and the soil surface is left irregular and poorly drained (e.g., Turcotte et al. 1991). By removing trees, partial cutting promotes a high water table because of lessened evapotranspiration; together with soil disturbance that allows water to pool in hummocks, an increased incidence of soil frost is likely.

Dieback is manageable. Harvest, in particular, provides an opportunity to address issues of “overmaturity”, species selection, avoidance of tree damage, and adequate soil drainage, among others. It would be of practical interest to determine whether timely tracking of DRI and maps of DRI potential can improve operational decisions on when and where to harvest and guide tree seedling selection.

Acknowledgements

This work was supported by the Human Dimensions Research Program of the Office of Global Programs, National Atmospheric and Oceanic Administration, US Department of Commerce (Grant No. NA66GP0253). Support for the work was also received from the Forest Health Monitoring Program, Northeastern Area, Forest Service, US Department of Agriculture, under

Contract No. 01-JV-11231300-026 (2001–2002) and Cooperative Agreement No. 34-WT-03-8100-0868-IA/ALC12-40-3400. Although acquisition of the data and analysis have been funded by these programs, this paper has not been subjected to Agency peer review and does not necessarily reflect the views of the agencies and no official endorsement should be inferred. The authors are especially indebted to D. Struble and W. Ostrofsky (Forest Health Monitoring, Maine Department of Conservation, Augusta, Maine) for many helpful comments on interpretation and applications of the model. D. Struble made an invaluable contribution in providing state forest insect and disease survey reports. I. Cottingham (Department of Computer Sciences and Engineering, University of Nebraska-Lincoln) provided much assistance with the web version of the PDSI model. A. Anyamba (University of Maryland-Baltimore County and NASA Goddard Space Flight Center, Greenbelt, Maryland) added valuable insight and many contributions to developing the DRI model. The senior author is indebted to R. Pomerleau who, during a visit to his home in June 1988, kindly provided a series of manuscripts of his experiments on dieback in the 1950s; these reports and related comments were published under his name in 1991. Pomerleau, recognized as the “father of mycology in Canada”, died in 1993 (www.nrcan-rncan.gc.ca/com/deptmini/traipion/renepomerleau-eng.php [accessed 14 August 2009]).

References

- Allen, C.D., and Breshears, D.D. 2007. Climate-induced forest dieback as an emergent global phenomenon. Presented 9 August 2007. Session OOS 42-5: From Global Forest Die-Backs to Restoration in the USA. Ecological Society of America/Society for Ecological Restoration Joint Annual Meeting, San Jose, California, 5–10 August 2007. *Eos Trans. AGU*, **88**(6). doi:10.1029/2007EO470008.
- Allen, D.C., Molloy, A.W., Cooke, R.R., and Pendrel, B.A. 1999. A ten-year regional assessment of sugar maple mortality. *In* Sugar Maple Ecology and Health: Proceedings of an International Symposium, 2–4 June 1998, Warren, Pa. *Edited by* S.B. Horsley and R.P. Long. U.S. For. Serv. Gen. Tech. Rep. GTR-NE-261. pp. 27–45.
- Auclair, A.N.D. 2005. Patterns and general characteristics of severe forest dieback from 1950 to 1995 in the northeastern United States. *Can. J. For. Res.* **35**(6): 1342–1355. doi:10.1139/x05-066.
- Auclair, A.N.D., Worrest, R.C., Lachance, D., and Martin, H.C. 1992. Climatic perturbation as a general mechanism of forest dieback. *In* Forest decline concepts. *Edited by* P.D. Manion and D. Lachance. American Phytopathological Society Press, St. Paul, Minn. pp. 38–58.
- Bertrand, A., Robitaille, G., Nadeau, P., and Boutin, R. 1994. Effects of soil freezing and drought stress on abscisic acid content of sugar maple sap and leaves. *Tree Physiol.* **14**(4): 413–425. PMID:14967696.
- Bourque, C.P.-A., Cox, R.M., Allen, D.J., Arp, P.A., and Meng, F.-R. 2005. Spatial extent of winter thaw events in eastern North America: historical weather records in relation to yellow birch decline. *Global Change Biol.* **11**(9): 1477–1492. doi:10.1111/j.1365-2486.2005.00956.x.
- Castello, J.D., Silverberg, S.B., and Manion, P.D. 1985. Intensification of ash decline in New York State from 1962 through 1980. *Plant Dis.* **69**(3): 243–246. doi:10.1094/PD-69-243.
- Clark, J., and Barter, G.W. 1958. Growth and climate in relation to dieback of yellow birch. *For. Sci.* **4**: 343–364.

- Cleavitt, N.L., Fahey, T.J., Groffman, P.M., Hardy, J.P., Henry, K.S., and Driscoll, C.T. 2008. Effects of soil freezing on fine roots in a northern hardwood forest. *Can. J. For. Res.* **38**(1): 82–91. doi:10.1139/X07-133.
- Cox, R.M., and Malcolm, J.W. 1997. Effects of duration of a simulated winter thaw on dieback and xylem conductivity of *Betula papyrifera*. *Tree Physiol.* **17**(6): 389–396. PMID:14759847.
- Decker, K.L.M., Wang, D., Waite, C., and Scherbatskoy, T. 2003. Snow removal and ambient air temperature effects on forest soil temperatures in northern Vermont. *Soil Sci. Soc. Am. J.* **67**: 1234–1242.
- DeHayes, D.H., Schaberg, P.G., Hawley, G.J., and Strimbeck, G.R. 1999. Acid rain impacts on calcium nutrition and forest health. *Bioscience*, **49**(10): 789–800. doi:10.2307/1313570.
- Durbin, J., and Watson, G.S. 1951. Testing for serial correlation in least squares regression. II. *Biometrika*, **38**(1–2): 159–178. PMID:14848121.
- Griffith, D.M., and Alerich, C.L. 1996. Forest statistics for Maine, 1995. U.S. For. Serv. Bull. NE-135.
- Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.P., Fitzhugh, R.D., and Tierney, G.L. 2001. Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem. *Biogeochemistry*, **56**(2): 135–150. doi:10.1023/A:1013039830323.
- Hennon, P., D'Amore, D., Wittwer, D., Johnson, A., Schaberg, P., Hawley, G., Beier, C., Sink, S., and Juday, G. 2006. Climate warming, reduced snow, and freezing injury could explain the demise of yellow-cedar in southeast Alaska, USA. *World Resour. Rev.* **18**: 427–450.
- Hibben, C.R. 1978. Ash dieback in the Northeast: report on severity and causes. *Metro Tree Impr. Alliance Proc.* **1**: 87–96.
- Horsley, S.B., Long, R.P., Bailey, S.W., Hallett, R.A., and Hall, T.J. 2000. Factors associated with the decline disease of sugar maple on the Allegheny Plateau. *Can. J. For. Res.* **30**(9): 1365–1378. doi:10.1139/cjfr-30-9-1365.
- Houston, D.R. 1999. History of sugar maple decline. In *Sugar Maple Ecology and Health: Proceedings of an International Symposium, 2–4 June 1998, Warren, Pa.* Edited by S.B. Horsley and R.P. Long. U.S. For. Serv. Gen. Tech. Rep. GTR-NE-261. pp. 19–26.
- Houston, D.R., and Kuntz, J.E. 1964. Part 3. Pathogens associated with maple blight. In *Studies of maple blight*. Univ. Wis. Agric. Exp. Stn. Res. Bull. 250. pp. 59–79.
- Johnson, A.H., Friedland, A.J., and Dushoff, J.G. 1986. Recent and historic red spruce mortality: evidence of climatic influence. *Water Air Soil Pollut.* **30**(1–2): 319–330. doi:10.1007/BF00305203.
- Krist, F.J., Sapio, F.J., and Tkacz, B.M. 2007. Mapping risk from forest insects and diseases. Forest Health Technology Enterprise Team Rep. FHTET 2007-06. U.S. Dep. Agric. For. Serv. For. Health Prot., Washington, D.C.
- Lemke, P., Ren, J., Alley, R.B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R.H., and Zhang, T. 2007. Observations: changes in snow, ice and frozen ground. In *Climate Change 2007: The Physical Climate Basis. Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press, Cambridge, U.K.
- Livingston, W.H., and White, A.S. 1997. May drought confirmed as likely cause of brown ash dieback in Maine. *Phytopathology*, **87**: S59. PMID:18945112.
- Maine Department of Conservation. 1920–1995. Forest insect and disease survey annual reports. Forest Health Monitoring Division, Maine Forest Service, Maine Department of Conservation, Augusta, Me.
- Manion, P.D. 1991. Tree disease concepts. Prentice-Hall, Englewood Cliffs, N.J.
- Millers, I., Shriner, D.S., and Rizzo, D. 1989. History of hardwood decline in the eastern United States. U.S. For. Serv. Gen. Tech. Rep. NE-126.
- Mohan, J.E., Cox, R.M., and Iverson, L.R. 2009. Composition and carbon dynamics of forests in northeastern North America in a future, warmer world. *Can. J. For. Res.* **39**(2): 213–230. doi:10.1139/X08-185.
- Monson, R.K., Lipson, D.L., Burns, S.P., Turnipseed, A.A., Delany, A.C., Williams, M.W., and Schmidt, S.K. 2006. Winter forest soil respiration controlled by climate and microbial community composition. *Nature*, **439**(7077): 711–714. doi:10.1038/nature04555. PMID:16467835.
- Mueller-Dombois, D. 1986. Perspective for an etiology of stand level dieback. *Annu. Rev. Ecol. Syst.* **17**(1): 221–243. doi:10.1146/annurev.es.17.110186.001253.
- Pilon, C.F., Côté, B., and Fyles, J.W. 1994. Effect of snow removal on leaf water potential, soil moisture, leaf and soil nutrient status and leaf peroxidase activity of sugar maple. *Plant Soil*, **162**: 81–88. doi:10.1007/BF01416092.
- Pindyck, R.S., and Rubinfeld, D.L. 1997. Econometric models and economic forecasts. 4th ed. Irwin McGraw Hill, Boston, Mass.
- Pokomy, J.D. 1995. What is ailing your ash trees? U.S. Dep. Agric. For. Serv. State Priv. For. Rep., St. Paul, Minn.
- Pomerleau, R. 1991. Experiments on the causal mechanisms of dieback on deciduous forests in Quebec. Inf. Rep. LAU-X-96. Forestry Canada, Quebec Region, Sainte-Foy, Que.
- Pomerleau, R., and Lortie, M. 1962. Relationships of dieback to the rooting depth of white birch. *For. Sci.* **8**: 219–224.
- Righetti, M. 2008. Flow analysis in a channel with flexible vegetation using double-averaging method. *Acta Geophys.* **56**(3): 801–823. doi:10.2478/s11600-008-0032-z.
- Royama, T. 1984. Population dynamics of the spruce budworm *Choristoneura fumiferana*. *Ecol. Monogr.* **54**(4): 429–462. doi:10.2307/1942595.
- Sakai, A., and Larcher, W. 1987. Frost survival of plants. Springer-Verlag, Berlin, Germany.
- Skilling, D.D. 1964. Part 5. Ecological factors associated with maple blight. In *Studies of maple blight*. Univ. Wis. Agric. Exp. Stn. Res. Bull. 250. pp. 114–129.
- Sperry, J.S., Perry, A.H., and Sullivan, J.E.M. 1991. Pit membrane degradation and air-embolism formation in ageing xylem vessels of *Populus tremuloides* Michx. *J. Exp. Bot.* **42**(11): 1399–1406. doi:10.1093/jxb/42.11.1399.
- St. Clair, S.B., Sharpe, W.E., and Lynch, J.P. 2008. Key interactions between nutrient limitation and climatic factors in temperate forests: a synthesis of the sugar maple literature. *Can. J. For. Res.* **38**: 401–414. doi:10.1139/X07-161.
- Turcotte, D.E., Smith, C.T., and Federer, C.A. 1991. Soil disturbance following whole-tree harvesting in north-central Maine. *North. J. Appl. For.* **8**: 68–72.
- US National Drought Mitigation Center. 2008. Palmer Drought Severity Index (web version). University of Nebraska-Lincoln, Lincoln, Nebr. Available from <http://drought.unl.edu/> [accessed 10 July 2008].
- US NCDC. 1920–2007. Daily records of maximum and minimum air temperatures and total precipitation, 1910 to 1995. U.S. Dep. Commer., NOAA Satellite Inform. Serv., Asheville, Tenn. Available from www.ncdc.noaa.gov/oa/ncdc.html [accessed 1 December 2008].

- USDA ARS USNA. 2003. USDA Plant Hardiness Zone Map (web version). U.S. Dep. Agric. Misc. Publ. No. 1475, January 1990. U.S. Dep. Agric., Agric. Res. Serv., U.S. National Arboretum, Washington, D.C. Available from www.usna.usda.gov/Hardzone/ushzmap.html [accessed 1 December 2008].
- USDA Forest Service. 1950–1995. Annual reports, 1950–1995. Forest insect and disease conditions in the United States. For. Pest Manag. Div., USDA Forest Service, Washington, D.C.
- USDA Forest Service. 2002. Future direction of Forest Health Monitoring Program research. Research Work Unit SRS-4803, Southern Research Station, USDA Forest Service, Research Triangle Park, N.C.
- USDA Forest Service. 2004. Crowns: measurement and sampling. *In* Forest inventory and analysis national core field guide: field data collection procedures for Phase 3 plots. Version 2.0. Vol. 2. Internal Report on Forest Inventory and Analysis. USDA Forest Service, Arlington, Va.
- Walker, S.L., Auclair, A.N.D., and Martin, H.C. 1990. History of crown dieback and deterioration symptoms of hardwoods in eastern Canada. Parts, I, II, and III. Environment Canada, Atmospheric Environment Service, Federal LRTAP Liaison Office, Downsview, Ont.
- Ward, K., Ostry, M., Venette, R., Palik, B., Hansen, M., and Hatfield, M. 2009. Assessment of black ash (*Fraxinus nigra*) decline in Minnesota. *In* Proceedings of the Eighth Annual Forest Inventory and Analysis Symposium, 16–19 October 2006, Monterey, Calif. *Edited by* R.E. McRoberts, G.A. Reams, P.V. Van Deusen, and W.H. McWilliams. U.S. For. Serv. Gen. Tech. Rep. WO-79. pp. 115–120.