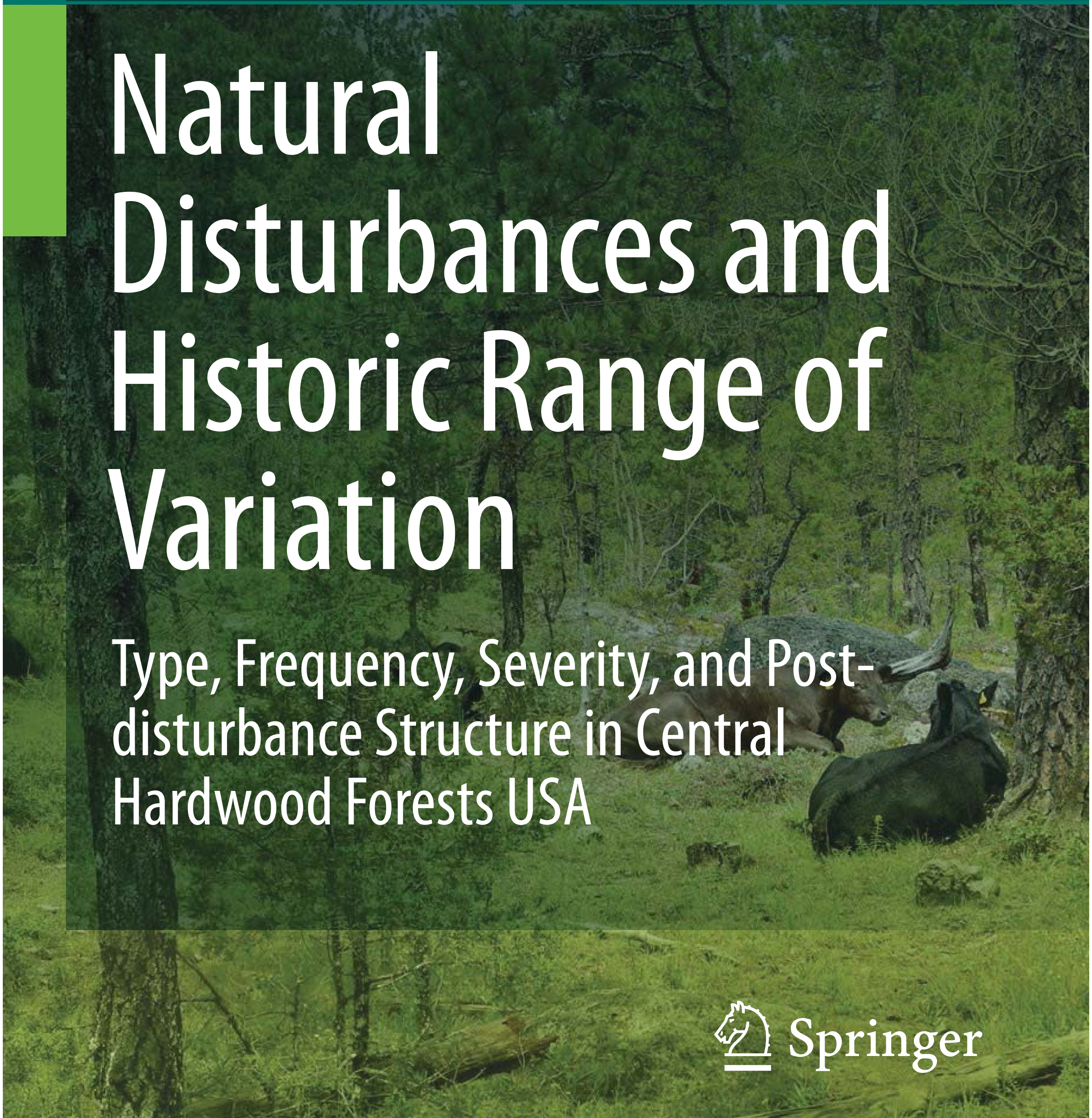
Managing Forest Ecosystems

Cathryn H. Greenberg
Beverly S. Collins *Editors*

Natural Disturbances and Historic Range of Variation

Type, Frequency, Severity, and Post-disturbance Structure in Central Hardwood Forests USA



Springer

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Volume 32

Aims & Scope

Well-managed forests and woodlands are a renewable resource, producing essential raw material with minimum waste and energy use. Rich in habitat and species diversity, forests may contribute to increased ecosystem stability. They can absorb the effects of unwanted deposition and other disturbances and protect neighbouring ecosystems by maintaining stable nutrient and energy cycles and by preventing soil degradation and erosion. They provide much-needed recreation and their continued existence contributes to stabilizing rural communities

Forests are managed for timber production and species, habitat and process conservation. A subtle shift from *multiple-use management* to *ecosystems management* is being observed and the new ecological perspective of *multi-functional forest management* is based on the principles of ecosystem diversity, stability and elasticity, and the dynamic equilibrium of primary and secondary production.

Making full use of new technology is one of the challenges facing forest management today. Resource information must be obtained with a limited budget. This requires better timing of resource assessment activities and improved use of multiple data sources. Sound ecosystems management, like any other management activity, relies on effective forecasting and operational control.

The aim of the book series ***Managing Forest Ecosystems*** is to present state-of-the-art research results relating to the practice of forest management. Contributions are solicited from prominent authors. Each reference book, monograph or proceedings volume will be focused to deal with a specific context. Typical issues of the series are: resource assessment techniques, evaluating sustainability for even-aged and uneven-aged forests, multi-objective management, predicting forest development, optimizing forest management, biodiversity management and monitoring, risk assessment and economic analysis.

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ISSN 1568-1319 ISSN 2352-3956 (electronic)
ISBN 978-3-319-21526-6 ISBN 978-3-319-21527-3 (eBook)
DOI 10.1007/978-3-319-21527-3

Library of Congress Control Number: 2015953434

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

This edited volume addresses the historic range of variation (HRV) in types, frequencies, severities, and scales of natural disturbances, and how they create heterogeneous structure within upland hardwood forests of Central Hardwood Region (CHR). The idea for this book was partially in response to a new (2012) forest planning rule which requires national forests to be managed to sustain 'ecological integrity' and within the 'natural range of variation' of natural disturbances and vegetation structure. This new mandate has brought to the forefront discussions of HRV (e.g., what is it?) and whether natural disturbance regimes should be the primary guide to forest management on national forests and other public lands. Natural resource professionals often seek 'reference conditions,' based on HRV, for defining forest management and restoration objectives. A large body of literature addresses changes in forest structure after natural disturbance, but most studies are limited to a specific site, disturbance event, forest type, or geographic area. Several literature reviews address a single natural disturbance type within a limited geographic area (often not the CHR), but do not address others or how their importance may differ among ecoregions. Synthesizing information on HRV of natural disturbance types, and their impacts on forest structure, has been identified as a top synthesis need.

Historically, as they are today, natural (non-anthropogenic) disturbances were integral to shaping central hardwood forests and essential in maintaining diverse biotic communities. In addition to a 'background' of canopy gaps created by single tree mortality, wind, fire, ice, drought, insect pests, oak decline, floods, and landslides recurringly or episodically killed or damaged trees, at scales ranging from scattered, to small or large groups of trees, and across small to large areas. Additionally, some animals, such as beavers, elks, bisons, and perhaps passenger pigeons, functioned as keystone species by affecting forest structure and thus habitat availability for other wildlife species. Prehistoric anthropogenic disturbances – fire and clearing in particular – also influenced forest structure and composition throughout much of the CHR and therefore the distribution of disturbance-dependent wildlife species. The spatial extent, frequencies, and severities differed among these natural disturbance types and created mosaics and gradients of structural conditions and canopy openness within stands and across the landscape.

A full-day symposium, organized by the editors, at the 2014 Association of Southeastern Biologists conference in Spartanburg, South Carolina, was the basis for this book. Our goal was to present original scientific research and knowledge synthesis covering major natural disturbance types, with a focus on forest structure and implications for forest management. Chapters were written by respected experts on each topic with the goal of providing current, organized, and readily accessible information for the conservation community, land managers, scientists, students and educators, and others interested in how natural disturbances historically influenced the structure and composition of central hardwood forests and what that means for forest management today.

Chapters in this volume address questions sparked by debated and sometimes controversial goals and 'reference conditions' in forest management and restoration, such as the following: What was the historic distribution, scale, and frequency of different natural disturbances? What is the gradient of patch sizes or level of tree mortality conditions created by these disturbances? How do gradual disturbances such as oak decline, occurring over a long period of time and across a broad landscape, differ in effects from discrete disturbances such as tornadoes? How does topography influence disturbance regimes or impacts? How do native biotic (insects or fungi, keystone wildlife species) and abiotic (precipitation, drought, temperature, wind, and soil) agents interact to alter disturbance outcomes? What was the diversity of age classes and gradient of forest structure created by natural disturbances alone? How might disturbance-adapted plants and animals have fared in the hypothetical historic absence of anthropogenic disturbances? How might climate change alter disturbance regimes and structure of upland hardwood forests in the future? And finally, should, and how, can land managers manage these forests within the HRV of natural disturbance frequencies, spatial extents, and gradient of conditions they create?

We sincerely thank all those who encouraged and aided in the development of this book. Each chapter was peer-reviewed by at least two outside experts and both coeditors, and we thank these colleagues for their useful suggestions: Chris Asaro, Robert Askins, Francis Ashland, Bart Cattanach, Steven Croy, Kim Daehyun, Dianne DeSteven, Chris Fettig, Mark Harmon, Matthew Heller, Louis Iverson, John Kabrick, Tara Keyser, Scott Lecce, William MacDonald, Henry McNab, Manfred Mielke, Billy Minser, Scott Pearson, Duke Rankin, Jim Rentch, John Stanturf, Scott Stoleson, Ben Tanner, and Thomas Wentworth. We also thank the Association of Southeastern Biologists for allowing us to host a conference symposium on this important topic, and the National Forests of North Carolina for assistance with travel costs for speakers. We especially thank each author for contributing, and for timely chapter revisions, which made this book possible.

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Chapter 3
Oak Decline in Central Hardwood Forests: Frequency, Spatial Extent, and Scale

Steven W. Oak, Martin A. Spetich, and Randall S. Morin

Abstract Oak decline is a widely distributed disease that results from an interacting set of factors in the Central Hardwood Region. Episodes of decline have been reported since before the turn of the twentieth century and from every state in the region. It is a stress-mediated disease that results from the interactions of physiologically mature trees, abiotic and biotic stressors that alter carbohydrate physiology, and opportunistic fungal pathogens and inner bark-feeding insects. Symptoms include reduced radial growth and slow, progressive crown dieback. Decline occurs over several years or decades, ending in death of vulnerable trees. Patterns of oak decline vary from a few trees in stands with diverse species composition and age structure, to areas covering several thousand ha in landscapes with more uniform composition of susceptible, physiologically mature red oak group species. Prolonged periods of drought that occur in combination with repeated spring defoliations by leaf-feeding insects exacerbate decline. Past disturbances have shaped current forest species composition and age structure, favoring physiologically mature stands with a large oak component, and are thus inextricably linked to oak decline vulnerability. Noteworthy examples are the functional extirpation of the American chestnut by the non-indigenous chestnut blight pathogen, combined with changing disturbance patterns, including fire suppression and reduced harvesting, during the early twentieth century. Data from extensive regional surveys have been used to develop models predicting the probability and impacts of oak decline events as part of the Forest Vegetation Simulator.

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C.H. Greenberg, B.S. Collins (eds.), *Natural Disturbances and Historic Range of Variation*, Managing Forest Ecosystems 32,
DOI 10.1007/978-3-319-21527-3_3

Keywords Crown dieback • Oak mortality • Predisposing factors • Oak decline survey • Oak decline event monitor

3.1 Historical Context for Oaks in Central Hardwood Forests

Oak (*Quercus*) forest types currently dominate the Central Hardwood Region (CHR), and oak decline is a widely distributed change agent altering species composition and forest structure throughout the region. The disease has regulated oak populations since oak species and interacting antagonists first appeared in the CHR, and that role continues to the present. Impacts of oak decline would have varied through time, as oak composition has shifted over the past several millennia with changing climate, weather, and the extent, frequency, and intensity of fire (e.g., Delcourt and Delcourt 2004). Human interventions and preferences have intentionally or unintentionally shaped forest composition and structure, either favoring or disfavoring oak populations. The expression of these preferences began with the arrival of the first aboriginal people into the region, who undoubtedly used fire to create desirable forest structures around settlements and in hunting lands (see also Greenberg et al. Chap. 1). Although managing tree species composition may not have been a primary objective, the use of fire certainly favored species well-adapted to it such as oaks, American chestnut (*Castanea dentata*), and pines (*Pinus* spp.). The extent of such landscape management increased with the human population, and accelerated with the arrival of European migrants. The introduction of destructive non-indigenous pathogens and insects continues into present decades, stimulated by increased international movement of products and people. Even though the forces shaping CHR forests operated for millennia, the relevant historical context for oak decline as observed from the mid-twentieth to the present is relatively recent. It was triggered by biological, social, and political events in the early twentieth century which altered historic disturbance regimes.

Prior to the turn of the twentieth century, forests in many parts of the CHR were dominated in composition by American chestnut and subject to frequent disturbance by fire (sometimes by natural causes, but mostly by human ignitions; see Greenberg et al. Chap. 1, Table 1.6). In 1880, 98.6 % of fires in the CHR were human caused with the top three causes attributed to land clearing, hunters and locomotives (Spetich et al. 2011). Logging to supply fuel and building materials to a pre-, and later, emerging- industrial society also was an important and widespread disturbance factor in the late nineteenth and early twentieth centuries.

Two events then occurred that had far-reaching consequences on forest landscapes. First, the chestnut blight was discovered in New York City in 1904. The cause of the disease was a non-indigenous fungal pathogen, most likely introduced with Asian chestnut varieties imported by the nursery trade to many locations in the eastern USA as early as 1876. The native American chestnut had no inherent resistance to the pathogen, and within a few decades of the discovery of the disease in New York City, the species was functionally extirpated throughout its range. Since then, it has survived only as root sprouts before once again becoming blighted and killed in a cycle that is repeated to the present day.

The second event was the 1911 enactment of the Weeks Act authorizing acquisition of land for national forests to protect headwaters of navigable streams. It was drafted in part as a response to a disastrous fire season the previous year that included 'The Great Fire of 1910' that burned over 808,000 ha and resulted in the deaths of 87 people in northeast Washington, northern Idaho, and western Montana. Though it occurred in vastly different ecosystems than those in the CHR, this catastrophe crystallized national policy and prompted the USDA Forest Service to make fire suppression a primary mission everywhere (see also Zenner Chap. 14). Further, the Weeks Act incorporated provisions for the development of federal-state cooperative fire control programs.

Prior to the Weeks Act, oaks dominated the CHR due to traits that made them more resilient to fire. The species builds large, belowground reserves of carbohydrates in root systems protected from fire. When fire killed aboveground shoots of small trees, these belowground carbohydrate reserves allowed new shoots to resprout rapidly. Large oaks also have relatively thick bark that helps reduce damage from ground-level fires. Thus, oaks had a competitive advantage over other tree species less well adapted to fire. In 1924 the Clark-McNary Act was passed, expanding the Weeks Act. Among other provisions, this Act encouraged states to form their own forestry agencies and further advanced fire suppression programs. These agencies and the laws and practices they spawned, combined with rapidly increasing efficiencies in agricultural production in the early twentieth century, gradually began to transform forests of the CHR. Open woodland conditions that had been maintained by fire, grazing and harvesting for millennia gradually became more closed as cohorts of oaks already established in the understory grew into dominant and codominant crown positions in the absence of frequent fire and other disturbance (Abrams 1992). Concurrent with these ecological changes, the USA population was growing and society was shifting from agrarian and rural, with a resource utilization ethic, to industrial and urban, with an emerging conservation ethic. By the late twentieth century, oak cohorts 80–100 years old dominated the CHR, especially on publicly owned lands not subject to development and urbanization. Table 3.1 summarizes general social and forest dynamics attributes before and after the turn of the twentieth century that help explain oak density and oak decline patterns of the more recent past.

Oak density for contemporary forests of CHR ecoregions resulting from these historic influences was determined using plots in the USDA Forest Service Forest Inventory and Analysis (FIA) Eastwide data base (Hansen et al. 1992). Data collected during the 1980s and 1990s were extracted from 26,662 plots in 20 states (Table 3.2). Overall, one third of the basal area (BA) in the CHR was comprised of oak species, with the highest average oak density values occurring in the Ozark Highlands, Boston Mountains, Arkansas Valley, and Ridge and Valley ecoregions. The Ozark Highlands had, by far, the highest oak density of all ecoregions (63.5 %)

Table 3.1 Prevalent historic attributes of CHR forests

Attribute	Pre-twentieth century	Twentieth century to present
Social/cultural	Small agrarian population	Large urbanized population
	Resource utilization/exploitation perspective	Resource conservation/protection perspective
Disturbance	Frequent fire of mostly anthropogenic origin	Near-complete fire suppression
	Frequent logging/utilization	Limited logging
Forest composition	American chestnut regionally abundant	Mixed oak predominant
	Vigorously sprouting woody species favored (e.g. oaks)	More shade tolerant woody species favored (e.g. red maple)
Forest structure	Diverse herbaceous understory; woody understory persists as sprouts	Dense woody understory
	Widely spaced, large diameter overstory	Dense, smaller diameter overstory
	More complex age structure	Aging oak cohorts 80–100 years old

Table 3.2 Mean proportion of BA in oak species and number of FIA plots in each oak BA proportion category by CHR ecoregion

	Mean %	Percentage oak BA category				
Ecoregion	oak BA	0	1–25	26–50	51–75	>75
Arkansas Valley	44.0	53	103	102	110	102
Blue Ridge Mountains	31.8	305	351	418	345	182
Boston Mountains	48.3	24	59	111	130	136
Central Appalachians	28.6	475	716	477	375	253
Interior Plateau	25.3	597	755	551	415	346
Interior River Valleys and Hills	31.4	505	439	391	374	320
Northern Piedmont	33.4	113	102	75	62	72
Ouachita Mountains	31.6	192	230	243	134	78
Ozark Highlands	63.5	114	242	478	907	2,121
Piedmont	21.8	2,031	1,429	1,048	667	355
Ridge and Valley	37.1	463	630	617	604	618
Southwestern Appalachians	31.7	143	247	309	237	106
Western Allegheny Plateau	25.0	715	698	455	329	268
Entire Central Hardwood Region	33.2	5,730	6,001	5,275	4,689	4,957

and the highest proportion of plots in the densest category (55 % of all plots with >75 % oak BA). The ecoregion with the next highest oak density was the Boston Mountains – 48.3 % mean oak BA and 30 % of all plots with >75 % oak BA. The only ecoregion with mean percent oak density below 25 % was the Piedmont at 21.8 % (see Greenberg et al. Chap. 1, Fig. 1.1 for ecoregions map).

The geographic distribution of the proportion of oak BA on forested lands was mapped by interpolating plot values (Fig. 3.1). Plots in the >75 % oak BA category were particularly concentrated in the Ozark Highlands of Missouri. In addition, oak BA exceeded 50 % in parts of the Arkansas Valley, and Boston and Ouachita Mountains as well as the Western Highland Rim area of the Interior Plateau in Tennessee and the northern half of the Ridge and Valley in Virginia, West Virginia and western Maryland. Non-forest land was most noticeable in the Northern Piedmont and Interior River Valleys and Hills, though a few pockets of high oak BA forest were detected in the latter ecoregion. Details of the methodology employed to create the interpolated BA surface displayed in Fig. 3.1 are available in Morin et al. (2005).

There is no doubt that contemporary forest composition and structure are products of prevalent disturbances over at least the past two centuries. Choosing the reference condition upon which to base management practices compatible with the historic range of variation of natural disturbances presents a dilemma for land managers concerning the role of humans in forest ecosystems. The range of natural disturbance and the shape of forest composition and structure prior to human habitation of the CHR can only be generally inferred and ignores the reality of the past five to ten millennia (see Greenberg et al. Chap. 12). Alternatively, selecting a dis-

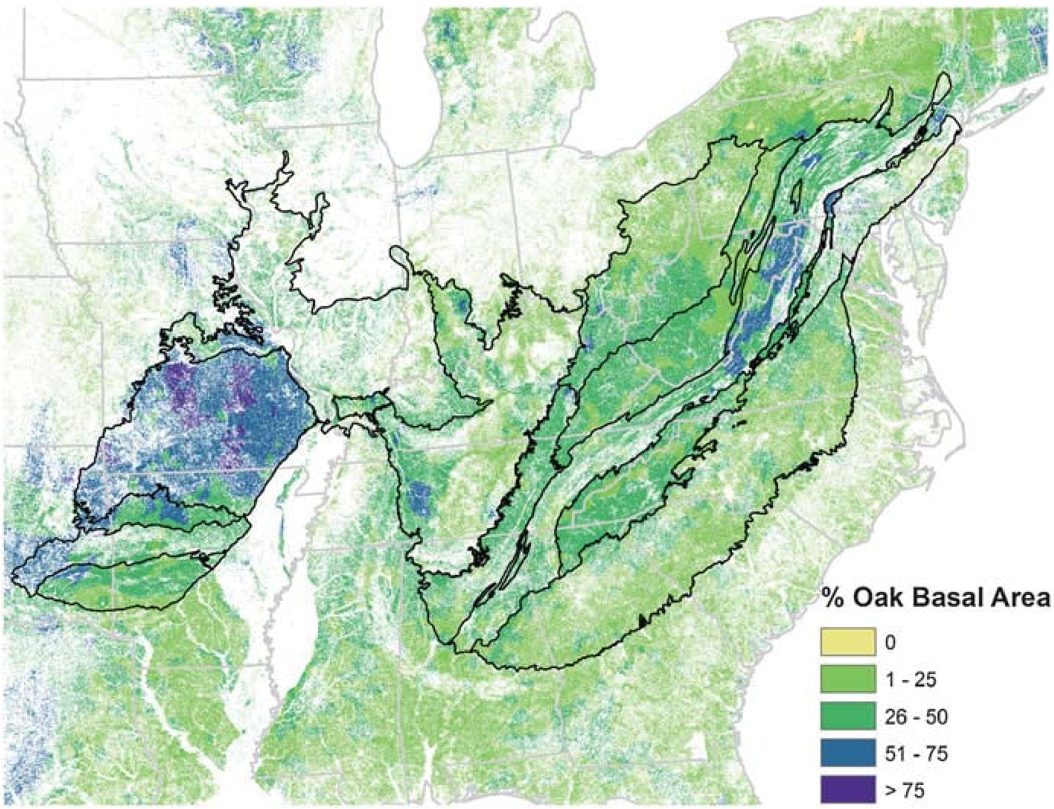

Fig. 3.1 The geographic distribution of the proportion (%) of oak basal area on forested lands in the eastern USA. The map was created by interpolating the values from 93,611 forest inventory plots in 37 states (Morin et al. 2005). The data were extracted from the USDA Forest Service Forest FIA Eastwide data base, which consists of data collected during the 1980s and 1990s (Hansen et al. 1992) (Map credit to Randall S. Morin)

turbance regime that includes human interventions along a spectrum from early aboriginal to contemporary times is a philosophical and arbitrary process. In any case, CHR forests cannot be termed ‘natural’ until the full suite of forest plants (including American chestnut) and animals present before the arrival of humans in the CHR are restored and functioning as part of ecosystems (see Zenner Chap. 14).

3.2 Oak Decline Etiology and Symptoms

Oak decline is a stress-mediated disease that results from the interactions of three groups of factors first described by Sinclair (1965), and later elaborated by Manion (1991). The individual factors in each group that combine to result in a specific oak decline episode can vary widely. The first group includes long-term predisposing factors that act to reduce the resilience of healthy trees to stress or attack by pathogens and insects. Among these are edaphic conditions such as soil depth and texture; topographic factors such as slope and aspect; and physiological maturity (distinguished from chronological age). Hyink and Zedaker (1987) characterized the concept of physiological age as having greater biological significance than chronological age. They described advanced physiological age (senescence) as the progression toward critical levels of physiological relationships such as water transport and translocation efficiencies, hormone balances, and the balance between photosynthesis and respiration. When critical levels are exceeded, internal resources are unavailable for effective tree response to stressors thereby predisposing them to decline. Oak et al. (1991) created an index of physiological age using site index (SI) and chronological age that was useful in oak decline risk rating (Oak et al. 1996).

The second group is comprised of inciting factors associated with the initiation of decline and the earliest, non-specific symptoms: depletion of stored food reserves, reduced growth, and dieback. Factors in this group include prolonged drought or spring defoliation caused by some insect species or late frost. The third group is comprised of contributing factors. These are biotic agents and often are implicated as the cause of mortality but in fact, are opportunists normally incapable of killing vigorous trees. However, they are well adapted to exploit predisposed trees that have been further weakened by the inciting factors. The most commonly cited fungal parasites involved in oak decline mortality are *Armillaria mellea* (though complex interactions with other *Armillaria* species have been described by Bruhn et al. 2000) and *Biscogniauxia atropunctata* (cause of hypoxylon canker of oaks). Both are widely distributed facultative parasites in natural ecosystems. *Armillaria mellea* is common in soil, decaying roots, and dead wood; *Biscogniauxia atropunctata* resides as an endophyte in stems and branches decaying sapwood. They become more aggressive pathogens when conditions are appropriate for pathogenesis and cause root disease and stem cankers. The most commonly cited insect pest is the two-lined chestnut borer (*Agrilus bilineatus*) which creates meandering galleries in the inner bark of weakened trees (Wargo et al. 1983).

The earliest visible aboveground symptom of oak decline is dieback of the live crowns of trees in upper canopy positions beginning with the outer twigs and branches. This can sometimes occur during the growing season, leaving dead foliage attached. More commonly it occurs during the dormant period with affected limbs failing to refoliate the following spring. Relatively slow, progressive dieback downward and inward, involving larger limbs occurs over years or even decades and is a distinctive symptom of oak decline. The death of branches in the crown results in the production of sprouts along the larger limbs and main stem. Eventually, severely declined trees die. Species in the red oak group (e.g., black oak (*Q. velutina*), scarlet (*Q. coccinea*), northern red oak (*Q. rubra*), southern red oak (*Q. falcata*), and blackjack oak (*Q. marilandica*)) are more susceptible to decline-induced mortality than are species in the white oak group including white oak (*Q. alba*), chestnut oak (*Q. montana*), and post oak (*Q. stellata*).

Crown dieback reflects root disease progression belowground where armillaria root disease is an important contributing factor. Carbohydrate chemistry is altered in roots of trees stressed by drought and defoliation and is accompanied by decreased levels of starch and increased levels of simple sugars (Parker 1970; Wargo 1972, 1977). Growth of *A. mellea* is stimulated by these changes and becomes more aggressive, attacking more of the stressed tree's root system. The crown must die back to accommodate the impaired root system. Long-term monitoring of symptomatic trees has shown that dieback (and presumably root disease) may abate 10 years after the return of good growing conditions so long as it has not progressed beyond about one-third of the live crown volume (Oak, unpubl. data). Moisture stress also is important in stimulating *Biscogniauxia atropunctata* to transform from a sapwood endophyte to a more aggressive cankering pathogen and sapwood rotter (Bassett and Fenn 1984).

3.3 Distribution

Millers et al. (1989) reviewed the literature of forest tree declines and reported 57 episodes in the eastern USA between 1856 and 1986 where oak mortality was higher than expected in areas covering at least 400 ha. Details of survey methodology and data collection often were not included, and authors of cited reports usually attributed the mortality to one or two causes without naming oak decline specifically. This was true even after the first elucidation of decline etiology and symptoms was published (Sinclair 1965). Despite this lack of specificity, the summarized causes included multiple interactions consistent with the published disease etiology. The first systematic regional surveys of oak decline using consistent data collection protocols were conducted mostly in the South in the mid-1980s using ground and aerial photo methodologies (Starkey et al. 1989, 2000; Oak et al. 1990), and continuous forest inventory plot networks (Oak et al. 1991, 2004). Combining these sources reveals that every state in the CHR has experienced oak decline damage and mortality in at least one decade dating back to earliest reports in the mid-nineteenth century (Table 3.3). Notable concentrations of oak decline episodes were evident in Appalachian and Ozark Mountain states (Arkansas, Georgia, Missouri, North

Table 3.3 Oak decline and mortality reports for states within the CHR by decade

State[a]	Pre-1900	1900s										2000s	
		00	10	20	30	40	50	60	70	80	90	00	10–13
AL									■	■			
AR							■		■	■	■	■	
DE							■			■			
GA	■		■	■			■	■	■	■	■		
IA									■	■			
IN									■				
IL									■	■			
KY									■	■			
MD							■			■			
MO									■	■		■	
NC	■		■	■		■	■	■	■	■	■		
NJ							■	■	■				
NY							■	■	■	■			
OH									■				
OK									■				
PA					■	■	■	■	■	■			
SC										■			
TN			■	■		■				■	■		
VA	■		■	■		■	■	■	■	■	■		
WV	■						■		■	■			

Adapted from Millers et al. (1989), Starkey et al. (1989, 2000), Oak et al. (2004)
[a]Most states are only partially within the CHR

Carolina, Pennsylvania, Tennessee, Virginia, and West Virginia) from the 1950s through the 1990s. Intensified survey activities may have contributed to part of the increase in reported oak decline distribution, incidence, and severity over this period. The USDA Forest Service formed the Division of Forest Pest Control in 1956 (later variously named Forest Insect and Disease Control, Forest Insect and Disease Management, Forest Pest Management, and Forest Health Protection) to survey and interpret forest health conditions on federal lands. State forest health programs servicing state and private forest landowners began in the 1960s under cost sharing agreements with the USDA Forest Service State and Private Forestry and have flourished in the decades since.

3.4 Oak Decline Patterns at Various Spatial Scales

Oak decline patterns have been described and analyzed across a range of spatial scales with varying methodologies tailored to survey objectives. Reports commonly included estimates of areal extent (patch size), incidence and severity of symptoms, and (less frequently) description of effects on growth, species composition, and forest structure. Patch size, incidence and severity, and effects will be detailed within this section.

Initial surveys were at a local scale and limited to the characterization of decline-affected stands (Millers et al. 1989; Starkey et al. 1989; Law and Gott 1987). Random surveys representing all health classes were conducted later and broadened the scope to establish disease incidence and impacts in a landscape context. These surveys used large format aerial photography (Oak et al. 1990) or aerial sketch mapping (Starkey et al. 2000) and were supported by ground sampling for validation. Description of stand and site features from the ground validation was used later for risk rating and effects modeling (Oak et al. 1996). Regional scale analyses were conducted using data collected from risk-based polygon sampling (Guldin et al. 2006) and by continuous forest inventory plot networks (Oak et al. 1991, 2004; Fan et al. 2012).

3.4.1 Patch Size

The pattern of oak decline on the landscape varies widely with tree species composition, age structure, and mortality incidence. Small patches consisting of scattered individuals or small groups of oaks occur in landscapes where age structure, tree species composition, and correlated site conditions are relatively diverse. In contrast, patches encompassing several thousand ha can occur where species composition and site conditions are relatively less diverse. Such large areas have developed on landscapes in the Blue Ridge Mountains and Ridge and Valley ecoregions of western Virginia, and more recently in the Ozark Highlands, Boston Mountains, and Ouachita Mountains ecoregions of Missouri, Arkansas, and Oklahoma. Landscapes in these provinces are dominated by cohorts of physiologically mature trees in species of the red oak subgenus growing on sites of average to lower productivity and are subject to periodic drought (Greenberg et al. Chap. 1, Fig. 1.8). Since the mid-1980s in the east, recurrent defoliation by the non-indigenous gypsy moth has also been an important inciting factor. During the 1990s in the west, unprecedented outbreaks of the indigenous red oak borer (*Enaphalodes rufulus*) contributed.

Aerial survey methods supplemented with ground truth assessments provide the perspective for estimating patch size that is lacking in ground-based surveys alone. Oak decline and mortality were evaluated on two national forests in the Ridge and Valley and Blue Ridge Mountains ecoregions of Virginia by Rauschenberger and Ciesla (1966) using aerial sketch mapping of about 70 % of the forest land inside the forest boundaries, supplemented with ground survey. Areas delineated with at least 5 % mortality totaled approximately 42,016 ha on the George Washington National Forest in northwestern Virginia. Patch size ranged from 61 to 2,424 ha. Mortality was less prevalent and patches were smaller overall on the Jefferson National Forest in southwestern Virginia (range 113–485 ha; mean = 297). This survey predated by 20 years the widespread infestation of Virginia forests by the gypsy moth (*Lymantria dispar*). Outbreaks of this insect usually are of longer duration, the intensity of defoliation greater and return interval shorter than for native defoliators. These dynamics often incite very severe decline episodes with catastrophic levels of mortality. While patch size estimates are lacking for post-gypsy moth decline episodes in Virginia, they are likely substantially larger.

Law and Gott (1987) interpreted large-scale color infrared aerial photos acquired over the Mark Twain National Forest, Missouri within the Ozark Highlands ecoregion and found mortality areas ranged from <0.5 to 28 ha (mean = 4 ha). The decline episode that prompted this assessment followed prolonged drought and several other predisposing and inciting conditions. However, about a decade later a much more severe and widespread episode occurred, accompanied by an unprecedented outbreak of the red oak borer. As was the case for gypsy moth-associated decline events in Virginia, the size of mortality patches were not measured, but probably increased significantly over earlier estimates.

3.4.2 Incidence and Severity

Starkey et al. (1989) surveyed 38 decline-affected stands from Virginia to Georgia and west to Arkansas and Missouri. All were on public lands with most located in National Forests. Oaks dominated the composition, with 50 % in red oak group species, 31 % in white oak group species, and 7 % hickory (*Carya*) species. Diagnosis of decline and decline mortality was confined to dominant and codominant trees with progressive dieback symptoms. Dieback and mortality among trees of all species in intermediate and suppressed crown positions was attributed to suppression and not to decline. Decline was observed in 80 % of dominant and codominant trees of all species. Hickories were the only non-oak species exhibiting appreciable symptom incidence. Advanced decline (>33 % live crown loss) was present in 20 % of all trees, and 17 % were dead with decline symptoms. Red oak group species were more prone to decline-associated mortality compared with white oak group species (24 % vs. 8 %, respectively). Among red oak group species, black oak was most vulnerable to oak decline mortality (34 %) followed by scarlet oak (23 %). The mortality incidence among hickory species was comparable to that recorded among white oak trees (12 %).

In addition to mortality impacts, Starkey et al. (1989) also analyzed the impact of oak decline on tree growth. Radial growth for 77 pairs of declined and healthy red oak trees was compared by in stands located in North Carolina, Tennessee, and Arkansas. Overall, declined trees grew 17 % more slowly than healthy trees for the last 45 years of the growth history, and 27 % more slowly for the last 20 years.

Tainter et al. (1990) further elaborated the predisposing effects of drought that were evident for several decades after the cessation of stress on oak populations of different physiological ages. They suggested that severe drought over several years in the early 1950s altered oak populations resulting in two health classes. One class had diminished resilience to subsequent droughts and eventually died while the other survived and recovered at least some of its former growth rate. Dwyer et al. (1995) observed similar drought dynamics in different age classes of black and scarlet oaks in Missouri dating back to stress events up to 45 years earlier.

Reports of increased oak mortality in the Ozark Highlands ecoregion on the Mark Twain National Forest, Missouri prompted surveys of declined areas on the Fristoe Unit in 1982 (Law and Gott 1987). Mortality areas were detected by interpretation of large-scale aerial photographs on 15.6 % of the 2,384 ha surveyed. Ground validation surveys confirmed that 53 % of the volume in scarlet oak was dead or dying, along with 35 % of black oak and 26 % of northern red oak. The 71–80 year age class was the most severely affected with 42 % of stand volume dead or dying.

Aerial sketch mapping followed by ground validation surveys were initiated in 1999 after concentrations of oak decline damage were reported on the Pleasant Hill Ranger District, Ozark National Forest, Arkansas in the Boston Mountains ecoregion. Moderate-to-severe damage was detected on approximately 17,372 ha (16 %) of the Ranger District. In the severe damage stratum, 24 % of the BA was declined or dead (Starkey et al. 2000).

Oak decline in a larger, landscape, context was evaluated in surveys of three national forest ranger districts: the Lee Ranger District on the George Washington National Forest in the Ridge and Valley ecoregion in Virginia; the Wayah Ranger District on the Nantahala National Forest in the Blue Ridge Mountains ecoregion in North Carolina; and the Buffalo Ranger District on the Ozark National Forest in the Boston Mountains ecoregion in Arkansas (Oak et al. 1990). These areas represented much of the diversity in climate, physiography, soils, and hardwood tree species composition where oak decline had been a recurring problem (Millers et al. 1989). A two-stage sampling design was used. Large-scale aerial photo samples were interpreted and stratified by tree size and damage class, with the results validated by ground plot sub-sampling. The survey yielded decline damage area and damage severity estimates. The Lee Ranger District had the highest incidence of decline (56 % of hardwood forest type). The Wayah Ranger District had intermediate incidence (35 % of hardwood forest type), whereas 28 % was affected on the Buffalo Ranger District. Within damaged strata, incidence of mortality plus advanced decline ranged from 10 % to 16 % of dominant and codominant trees compared with 1–3 % in undamaged strata.

Guldin et al. (2006) evaluated oak decline on 181 plots systematically distributed across the Interior Highlands of Arkansas, Oklahoma, and Missouri, and found about 12 % of the area in the most heavily damaged class (>6.67 m^2/ha of BA unhealthy, a category which included dead trees and those displaying at least 34 % crown dieback). Mean stem density over the entire surveyed area was 95.3 trees/ha, of which 12.9 trees/ha were unhealthy (13.4 %). The percentage of mean total BA in an unhealthy condition was slightly higher (14.5 %). This damage was concentrated in the red oak group. Thirty percent of the BA in species of this group was unhealthy compared with about 9 % of species in the white oak group.

Other regional oak decline assessments were possible using large-scale continuous forest inventory plot networks. A 1986 inventory in Virginia afforded the opportunity to evaluate oak decline in the northern Piedmont and western mountains survey units (Oak et al. 1991) that lie within the Northern Piedmont, Blue Ridge Mountains, and Ridge and Valley ecoregions. Virginia had experienced chronic and severe oak decline since the earliest reports of the disease (Millers et al. 1989) and was in the midst of a widely reported severe decline episode during the inventory year. Decline occurred on an estimated 444,400 ha of oak forest (16.4 %) with the northern mountain unit (Blue Ridge Mountains and Ridge and Valley ecoregions) sustaining the highest incidence (29.7 %). Estimated annual mortality was greatest for counties with concentrations of decline. Shenandoah County in the Ridge and Valley ecoregion sustained average losses of 1.74 m^3 per ha per year from 1977 to 1986 which represented the highest rate in the assessment area. Average annual mortality in decline-affected plots overall was 1.84 m^3 per ha compared with 1.03 m^3 per ha in unaffected plots.

Stand and site factors associated with oak decline incidence (vulnerability) and severity (risk, as measured by volume losses when decline did occur) were examined for potential use in predicting oak decline. Factors showing promise included tree species composition, site quality, stand age, SI to age ratio, physiography, and stand density. The relationships between individual factors and oak decline vulnerability and risk were complex. For example, less productive sites were more vulnerable to oak decline but 33 % of the total affected area and 36 % of the oak mortality still occurred on sites with higher productivity (SI$\geq$21 m). Chestnut oak forest types were the most vulnerable to oak decline, but risk was highest in oak-hickory forest types.

Oak et al. (2004) used FIA inventory data collected by the USDA Forest Service Southern and Southeastern Forest Experiment Stations to conduct an analysis of geographic and temporal decline trends in 12 southern states over two survey periods, 1984–89 and 1990–97. Data were originally interpreted by state, but were partitioned by CHR ecoregions within the inventoried area for this discussion. The Northeastern Forest Experiment Station FIA unit used different damage coding methods during these periods which precluded analysis in the northern part of the CHR (Fig. 3.2).

Just under half of the total CHR area, 47 million ha, was included in the oak decline analyses (Table 3.4). Ecoregions poorly or not represented were the Interior River Valleys and Hills (0 % inventoried), Western Allegheny Plateau (0 %), Central Appalachians (11 %), Ozark Highlands (24 %), northern Piedmont (25 %) and Interior Plateau (40 %). Among these, the Central Appalachians and Western Allegheny Plateau have high relative oak density (Table 3.2; Fig. 3.1) and have experienced recurrent, and sometimes severe, oak decline episodes in historical accounts (Millers et al. 1989).

Inventories conducted during the 1980s detected forests vulnerable to oak decline on about 9.8 million ha in CHR ecoregions, of which about 10.3 % were affected

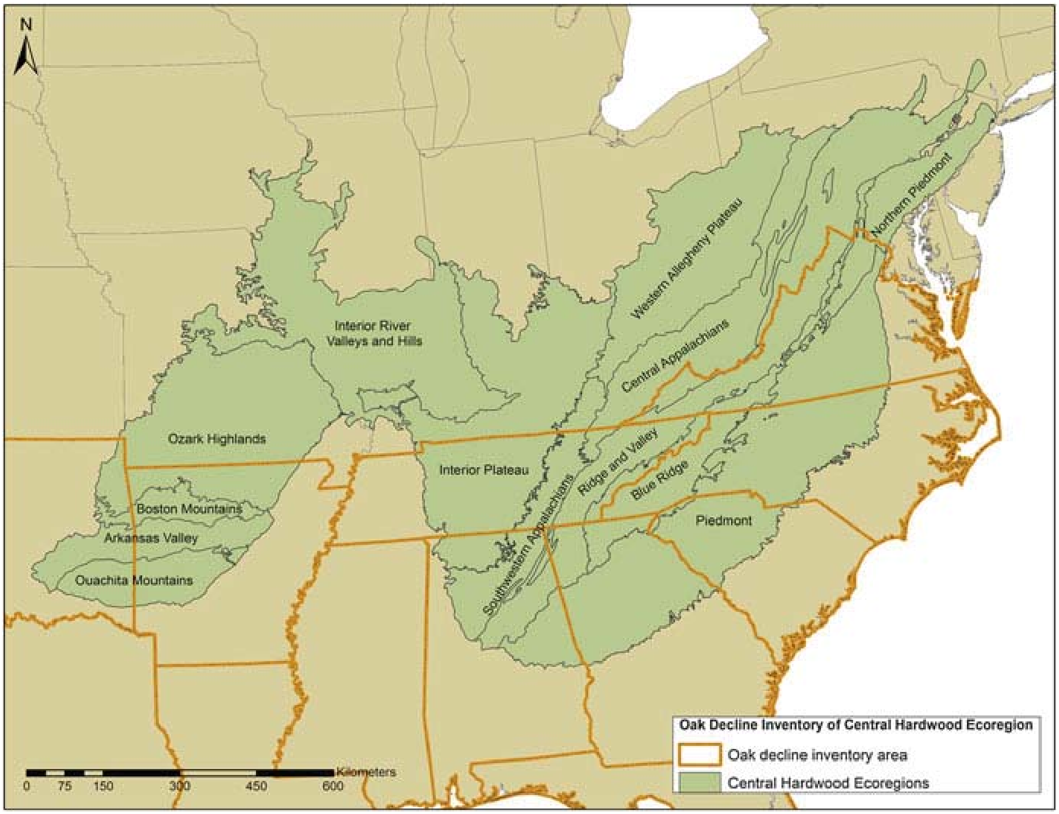

Fig. 3.2 CHR ecoregions and area included in USDA Forest Service FIA oak decline assessments conducted between 1984 and 1997 (Oak et al. 2004) (Map credit to Ida Evretjarn)

Table 3.4 Area of CHR ecoregions inventoried for oak decline by USDA Forest Service Southeastern and Southern Research Station FIA work units, 1984–1997

Ecoregion	Area (1000 ha) Total	Inventoried	Percent
Arkansas Valley	2,842.1	2,842.1	100
Blue Ridge Mountains	4,659.5	4,506.5	96.7
Boston Mountains	1,417.8	1,417.8	100
Central Appalachians	6,205.0	674.6	10.9
Interior Plateau	12,352.3	4,951.8	40.1
Interior River Valleys and Hills	12,040.5	0	0.0
Northern Piedmont	3,045.9	748.0	24.6
Ouachita Mountains	2,689.6	2,689.6	100
Ozark Highlands	10,639.1	2,597.2	24.4
Piedmont	16,611.7	16,611.7	100
Ridge and Valley	11,548.3	6,511.3	56.4
Southwestern Appalachians	3,799.4	3,272.4	86.1
Western Allegheny Plateau	8,144.0	0	0.0
Total	95,995.2	46,823.1	48.8

Table 3.5 Oak decline vulnerable area, affected area, and affected incidence in CHR ecoregions in successive FIA inventory cycles 1984–1989 and 1990–1997

	1984–1989			1990–1997		
	Area (1000 ha)		Incidence	Area (1000 ha)		Incidence
Ecoregion	Vulnerable	Affected	(%)	Vulnerable	Affected	(%)
Arkansas Valley	474.1	14.7	3.1	438.0	46.7	10.7
Blue Ridge Mountains	1,497.9	191.9	12.8	1,454.1	309.7	21.3
Boston Mountains	512.8	36.8	7.2	693.6	79.1	11.4
Central Appalachians	227.0	50.2	22.1	232.5	18.1	7.8
Interior Plateau	818.0	126.5	15.5	875.7	59.6	6.8
Northern Piedmont	135.0	32.6	24.1	131.1	33.0	25.2
Ouachita Mountains	621.3	17.6	2.8	670.0	44.2	6.6
Ozark Highlands	695.3	49.0	7.0	811.2	107.8	13.3
Piedmont	2,437.6	139.3	5.7	2,233.9	224.8	10.1
Ridge and Valley	1,588.9	319.1	20.1	1,629.1	299.3	18.4
Southwestern Appalachians	788.9	36.0	4.6	997.4	69.6	7.0
Total	9,797.0	1,013.6	10.3	10,166.6	1,291.9	12.7

Adapted from Oak et al. (2004)

(1.0 million ha; Table 3.5). Ecoregions with incidence greater than the overall mean included the Blue Ridge Mountains, Central Appalachians, Northern Piedmont, and Ridge and Valley. However, relatively small portions of the Central Appalachians and Northern Piedmont were inventoried, yielding small sample sizes (around 100 vulnerable plots each). Therefore, confidence in the oak decline incidence estimates for these ecoregions overall is low compared to incidence estimates for ecoregions receiving more intensive inventory. The Ridge and Valley ecoregion had over 20.1 % oak decline incidence based on about 1.6 million acres of vulnerable forest (806 plots). Western ecoregions of the CHR (Arkansas Valley, Boston Mountains, Ouachita Mountains, and Ozark Highlands) had among the lowest oak decline incidences (2.8–7.2 % individually; 5.1 % combined).

The geographic distribution of plots vulnerable to oak decline during the 1980s inventories (Fig. 3.3a) generally reflected oak density displayed in Fig. 3.1, with high oak concentrations throughout the Blue Ridge Mountains, Ridge and Valley, Ozark Highlands, Boston Mountains and Ouachita Mountains, and in portions of the Southwestern Appalachians and Interior Plateau. High density of plots vulnerable to oak decline did not, however, translate directly to high density of affected plots. Instead, these were concentrated in the northern Ridge and Valley in Virginia; the southern Blue Ridge Mountains in North Carolina; and on the Western Highland Rim area of the Interior Plateau in Tennessee (Fig. 3.3b).

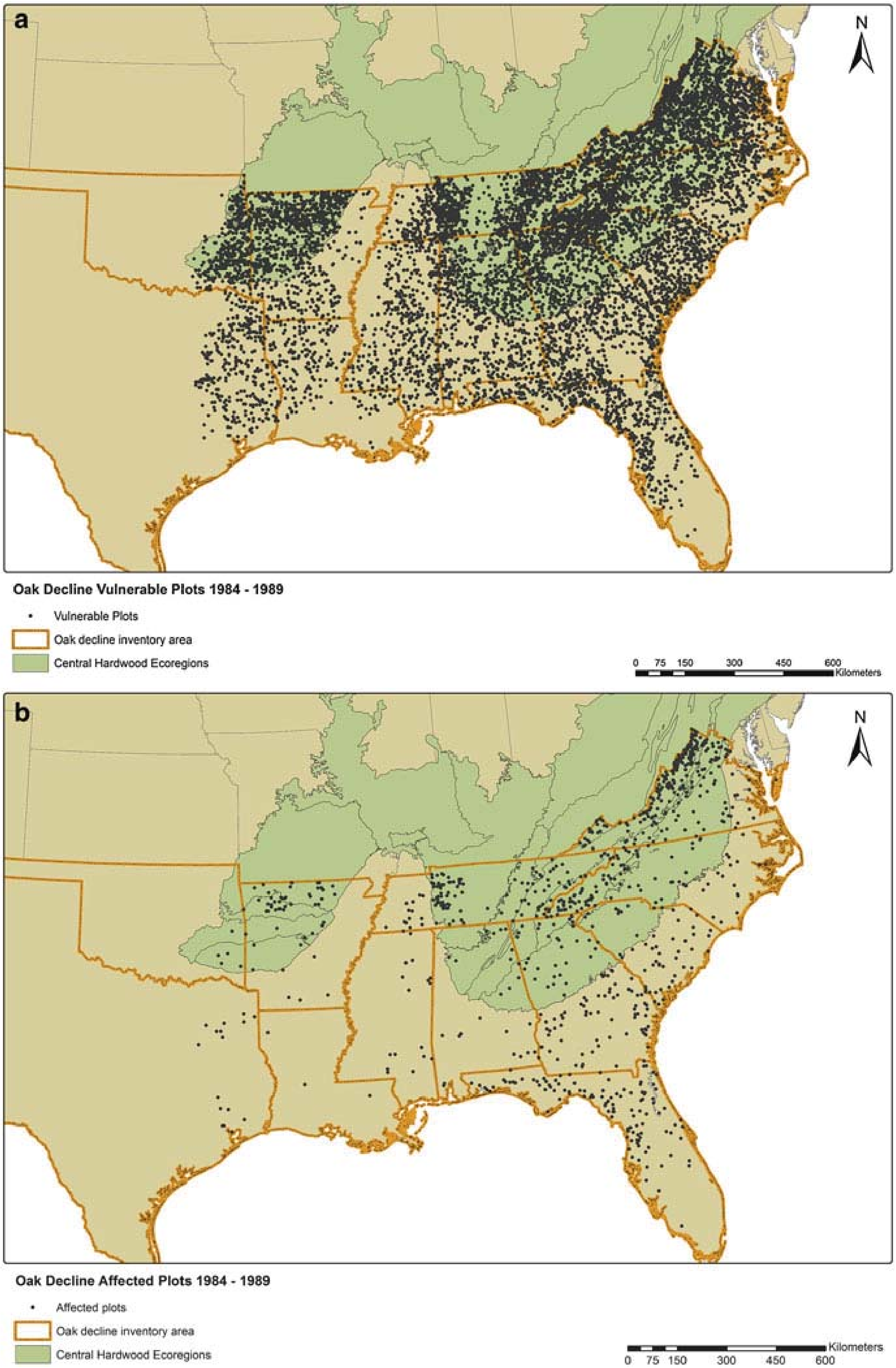

Fig. 3.3 Geographic distribution of USDA Forest Service FIA plots inventoried between 1984 and 1989 (**a**) vulnerable to and; (**b**) affected by oak decline within CHR ecoregions (Adapted from Oak et al. (2004); map credit to Ida Evretjarn)

The area vulnerable to oak decline increased in the 1990s over 1980s inventories by nearly 370,000 ha while affected area increased by 278,000 ha. A large increase in vulnerable area in the Southwestern Appalachians of more than 200,000 ha was offset by an equally large decrease in the Piedmont, with most of the net increase accounted for in the Boston Mountains and Ozark Highlands. Overall, incidence in inventoried CHR ecoregions increased to 12.7 % (Table 3.5). Incidence in the Ridge and Valley remained high while it increased markedly in the Blue Ridge Mountains (from 12.8 % incidence in the 1980s inventories to 21.3 % in the 1990s). Incidence nearly doubled in the westernmost ecoregions of the CHR (Ozark Highlands, Boston Mountains, Arkansas Valley, and Ouachita Mountains) from 5.1 % to 10.6 %, though the combined mean for these ecoregions was still slightly below the 1990s mean for the entire CHR. These inventories detected only the early stages of a very severe oak decline episode that would continue and intensify over the next decade (Starkey et al. 2000; Guldin et al. 2006; Fan et al. 2008, 2012). FIA inventories in Arkansas and Oklahoma which encompass the western ecoregions were conducted in 1995 and 1999, respectively (Hansen et al. 1992).

The increase in vulnerable area noted in Table 3.5 was barely detectable in the geographic distribution of vulnerable plots (Fig. 3.4a). However, increased density of affected plots was observed in the Blue Ridge Mountains ecoregion in western North Carolina and in the Ozark Highlands, Boston Mountains, Arkansas Valley, and Ouachita Mountains ecoregions of Arkansas and Oklahoma (Fig. 3.4b).

Fan et al. (2012) used 1999–2010 data from 6,997 FIA plots to examine spatial and temporal trends of oak decline across the Ozark Highlands of Arkansas and Missouri. This period marked the culmination of the oak decline episode first detected in the preceding inventory evaluated Oak et al. (2004). They found that mortality of red oak group species increased by 11 % of relative density and 15 % of relative BA while mortality among white oak group species remained comparable to non-oak species. Drought events were key inciting factors with unprecedented outbreaks of the red oak borer serving as contributing factors. The oak mortality response lasted up to 10 years after the cessation of inciting drought.

3.4.3 Oak Decline Effects on Forest Structure

An obvious and immediate change in oak abundance in overstory crown positions was noted following oak decline episodes due to mortality. Oak diversity was also reduced as a consequence of greater susceptibility of red oak group species relative to white oak group species. Long term changes in species composition are dependent upon canopy replacement of oak species by reproduction in competitive positions in the canopy gaps. Competitive advance oak reproduction (i.e., large seedlings and saplings) is lacking throughout CHR forests (Loftis 1983; Beck and Hooper 1986), as are disturbance regimes necessary for development and subsequent recruitment into the forest overstory (McEwan et al. 2011). As a result, oaks are

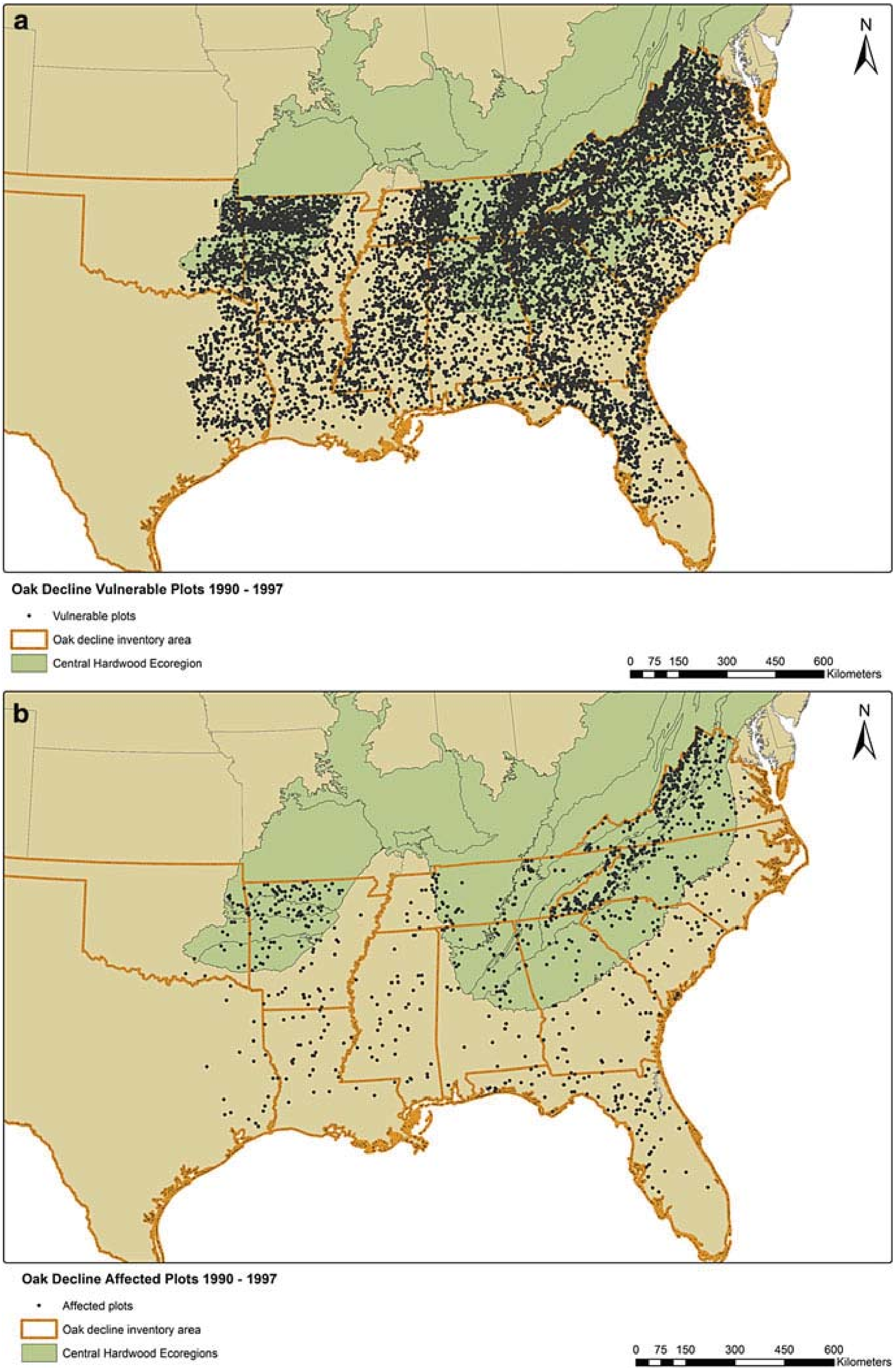

Fig. 3.4 Geographic distribution of USDA Forest Service FIA plots inventoried between 1990 and 1997 (**a**) vulnerable to and; (**b**) affected by oak decline within CHR ecoregions (Adapted from Oak et al. (2004); map credit to Ida Evretjarn)

already decreasing relative to other hardwood species (Abrams 1992; Aldrich et al. 2005; McGee and Hooper 1970; Loftis 1983; Beck and Hooper 1986). Oak recruitment into canopy positions after silvicultural disturbances is widely acknowledged to be problematic on more productive sites (McGee and Hooper 1970; Loftis 1983; Beck and Hooper 1986) but not on less productive sites (Roach and Gingrich 1968; Sander and Clark 1971). However, oak regeneration performance has been studied only in the context of silvicultural disturbances (e.g., clearcutting and shelterwood cutting, with or without treatment of competing vegetation). Whether these site productivity relationships and oak reproduction performance will hold following oak decline mortality, with or without silvicultural interventions, is unresolved. However, the relationship between the current importance values of oaks and maples and a regeneration index presented by McEwan et al. (2011) strongly suggests the oak composition will continue to decrease over a wide range of sites throughout the CHR under prevailing disturbance regimes.

3.5 Modeling and Managing Oak Decline Using the Forest Vegetation Simulator

The probability and severity of oak decline events in the CHR and effects on forest dynamics can be simulated using the Oak Decline Event Monitor (http://www.fs.fed.us/foresthealth/technology/od_rating.shtml), which was developed using data from extensive regional surveys of affected and healthy areas (Starkey et al. 1989; Oak et al. 1990; Oak and Croll 1995; Starkey et al. 2000). The Event Monitor runs within the structure of the Forest Vegetation Simulator (FVS), an individual-tree, distance-independent, growth and yield model (Dixon 2002). The probability of an oak decline event is computed from stand and site data (Oak et al. 1996), and mortality is scheduled according to the stand risk rating, with greater mortality scheduled for stands with elevated risk. Variants of FVS and the Event Monitor are available for the southern and central states sub-regions within the CHR. Table 3.6 displays output from simulation of a mixed oak stand in the Blue Ridge Mountains ecoregion of North Carolina using the Southern Variant of FVS. In this example, oak decline risk was high in the first simulation cycle and remained so through 7 cycles (35 years) Based on probability computed from stand and site factors, oak decline events were scheduled at the end of the second and seventh cycles (+10 and +35 years). Total stand BA was reduced by 8.3 m^2 per ha after the first event and by 6.4 m^2 per ha after the second. The effect on species composition was a depletion of the oak component from 84 % of stocking at the beginning of the simulation to 23 % after 10 cycles (50 years). The simulated changes in overall stand density and oak composition after the eighth cycle resulted in a reduction of decline risk to the low category.

FVS and the Oak Decline Event Monitor can be used to evaluate the potential of management actions for reducing oak decline risk and for mitigating changes

Table 3.6 Output selected from a 50-year simulation of a mixed oak stand in the Blue Ridge Mountains ecoregion, North Carolina. The probability of an oak decline event in a subject stand is calculated using a logistic regression (Oak et al. 1996) from stand and site factors collected during standard inventories. An oak decline event is scheduled (value of 1 in this table) when the calculated probability exceeds a generated random number between 0.00 and 1.00. The severity of the event is determined by oak decline risk classification (Oak and Croll 1995) and mortality is imposed based on expectations synthesized from numerous published local and regional oak decline assessments. Different mortality rates are imposed on red oak group species (highest mortality rate), white oak group species (intermediate mortality rate), and hickory species (lowest mortality rate). After imposition of mortality, stand growth is simulated using the appropriate regional FVS variant for the selected time interval (the Southern Variant at 5 year intervals for this case), and a new oak decline probability computed from the new stand attributes. Results were converted to metric units. In this simulation, oak decline events were scheduled at 10 and 35 years. The consequence of these events resulted in a reduction of oak BA from 18.86 m^2/ha (84 % of total stand BA) to 5.06 m^2/ha (23 % of total stand BA) after 10 simulation intervals (50 years). Oak decline risk was reduced to the low category after the +35 year oak decline event due a reduction of oak density resulting from cumulative mortality

			BA (m^2/ha)		
Time (years)	Risk	Decline event	Total	Oak	% Oak
+5	High	0	22.54	18.86	84
+10	High	1	23.91	19.78	83
+15	High	0	15.64	11.04	71
+20	High	0	17.02	11.50	68
+25	High	0	18.17	12.19	67
+30	High	0	20.01	12.88	64
+35	High	1	22.08	13.34	60
+40	Low	0	15.64	4.60	29
+45	Low	0	20.01	4.83	24
+50	Low	0	22.08	5.06	23

deemed detrimental for various desired future stand compositions and structures. Managers may choose to change outcomes by altering susceptibility (risk or probability of an oak decline event) or vulnerability (severity of damage should a decline event occur). Susceptibility is influenced by changing species composition while vulnerability is reduced by improving overall stand vigor through removal of trees likely to die in such a decline event. Fan et al. (2008) examined more than 4,000 randomly selected trees in the Ozark Highlands during an oak decline event from 2002 to 2006. They found that oak mortality was mainly related to crown width and amount of crown dieback and produced models useful for marking trees for thinning or harvest. Though intended for stands threatened by defoliation caused by gypsy moth, many prescriptions described by Gottschalk (1993) are useful for managing stands susceptible or vulnerable to oak decline. Spring defoliation is a major inciting factor in oak decline etiology, and the outbreak dynamics of this non-indigenous insect compared with native defoliators (outbreaks of longer duration, shorter return interval, and with more complete defoliation) have often resulted in catastrophic mortality from oak decline.

3.6 Summary

Oak decline has been recorded throughout the CHR since the 1800s. Affected contiguous areas may range from a few to thousands of hectares and severity also can be highly variable. Severe and recurrent damage has been reported in the Northern Piedmont, Blue Ridge Mountains, and Ridge and Valley ecoregions in the eastern CHR, and in the Ozark Highlands, Boston Mountains, and Ouachita Mountains ecoregions in the western CHR. Advanced physiologic age and drought are common interacting factors throughout, with catastrophic mortality occurring where gypsy moth defoliation has occurred in the eastern CHR, and more recently in concert with outbreaks of a contributing factor, red oak borer, in the western CHR.

Visible symptomology includes slow, progressive crown dieback from the top down and from the outside inward of trees in upper canopy positions followed by tree mortality and typically occurs over many years or decades. This crown dieback is an indicator of the progression of root disease belowground. These symptoms are the result of a complex of many interacting factors. Etiology includes issues that stress healthy trees and are classified into three general groups: predisposing, long-term factors that reduce tree resilience, inciting factors that add further stresses to trees invoking the decline event, and contributing factors that take advantage of stressed trees but by themselves do not invoke oak decline. There can be considerable variation in the combination of these factors from one decline event or area to another.

Composition and structure of CHR forests have been altered through the influence of human activity, forest management policies and introduced pathogens. Two influences are particularly notable. The loss of American chestnut by way of an introduced pathogen, and the reduced incidence of fire used as a cultural practice for millennia by people inhabiting the CHR have had far-reaching impacts on these forests. Changes include less complex age structure, more shade tolerant fire sensitive woody species, and a dense, relatively small-diameter overstory. Thus, what was once an ecosystem dominated by American chestnut and mediated by fire of mostly anthropogenic origin has been radically transformed. Land managers are presented with a dilemma concerning the role of humans in forest ecosystems when choosing the reference condition upon which to base management practices compatible with the 'historic range of variability' in natural disturbances, particularly concerning fire, non-indigenous plants, pathogens, and insects, and extirpation of native flora and fauna. The range of natural disturbance effects on the shape of forest composition and structure prior to human habitation of the CHR can only be generally inferred and ignores the reality of the past five to ten millennia (see Greenberg et al. Chap. 12). Alternatively, selecting a disturbance regime that includes human interventions along a spectrum from early aboriginal to contemporary times is a philosophical and arbitrary process. In any case, CHR forests cannot be termed 'natural' until the full suite of forest plants (including American chestnut) and animals (see Greenberg et al. Chap. 12) present before the arrival of humans in the CHR are restored and functioning as part of ecosystems.

Systematic surveys of oak decline began in the mid-1980s and were invaluable in elucidating its spatial and temporal context. In the southern half of the CHR, the oak decline-affected area was shown to encompass over a million hectares from 1984–1987 and 1.3 million hectares from 1990–1997. Survey methodologies were refined and standardized during this time, resulting in a more comprehensive understanding of decline events, revealing factors that may help in the prediction of future decline.

The most significant impact of oak decline is due to tree mortality resulting in major changes in forest structure and composition with red oak group species typically having much higher mortality rates than species of the white oak group. Drought has been a major inciting factor in oak decline across the CHR and the impact of the cumulative influence of drought on oak decline related mortality may last for decades.

Acknowledgments We recognize with gratitude the career contributions of Dale A. Starkey in helping to increase understanding of oak decline in the southeastern USA. The assistance of Anthony Elledge and Edwin Yockey in recovery of FIA oak decline assessment data is gratefully acknowledged. We thank Ida Evretjarn for GIS analysis of these data and production of map products.

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