

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

Managing Forest Ecosystems

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Editors

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in Central Hardwood Forests USA

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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 recurrently 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, bison, 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 Fetting, 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 1

Introduction to Natural Disturbances and Historic Range of Variation: Type, Frequency, Severity, and Post-disturbance Structure in Central Hardwood Forests

Cathryn H. Greenberg, Beverly S. Collins, W. Henry McNab,
Douglas K. Miller, and Gary R. Wein

Abstract Throughout the history of upland hardwood forests of the Central Hardwood Region, natural disturbances have been integral to shaping forest structure and composition, and essential in maintaining diverse biotic communities. In this chapter, we introduce the geographic scope and dynamic history of climate, natural disturbances, and human influence on central hardwood forests. We briefly introduce biotic and abiotic agents of disturbance to provide a foundation for the book and further discussion of whether and how historic disturbance regimes should guide forest management within national forests and other public lands.

Keywords Central Hardwood Region • Upland hardwood forests • Disturbance agents • Forest management • Historic disturbance regime

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1.1 Central Hardwood Forests: A Dynamic History of Climate, Natural Disturbances, and Human Influence

In upland hardwood forests of the Central Hardwood Region (CHR) (Fig. 1.1), natural disturbances, which we define here as non-anthropogenic disturbances, are integral to shaping forest structure and composition, and essential in maintaining diverse biotic communities. Wind, fire, ice, drought, insect pests, oak (*Quercus*) decline, floods, landslides, and beaver (*Castor canadensis*) damming are some recurring or episodic natural disturbances that can kill or damage trees at scales ranging from scattered to small, or large, groups of trees and across small to large areas (e.g., Fig. 1.2). The spatial extent, frequencies, and severities differ among these natural disturbance types and create mosaics and gradients of structural conditions and canopy openness within stands and across the landscape.

Land managers and planners have identified a need for additional information on natural disturbance types and the range of variation in their impacts on forest structure. A recent USDA Forest Service planning rule (USDA Forest Service 2012) requires that terrestrial and aquatic ecosystems and watersheds of national forests be managed to sustain or restore ‘ecological integrity’ and within the ‘historic range

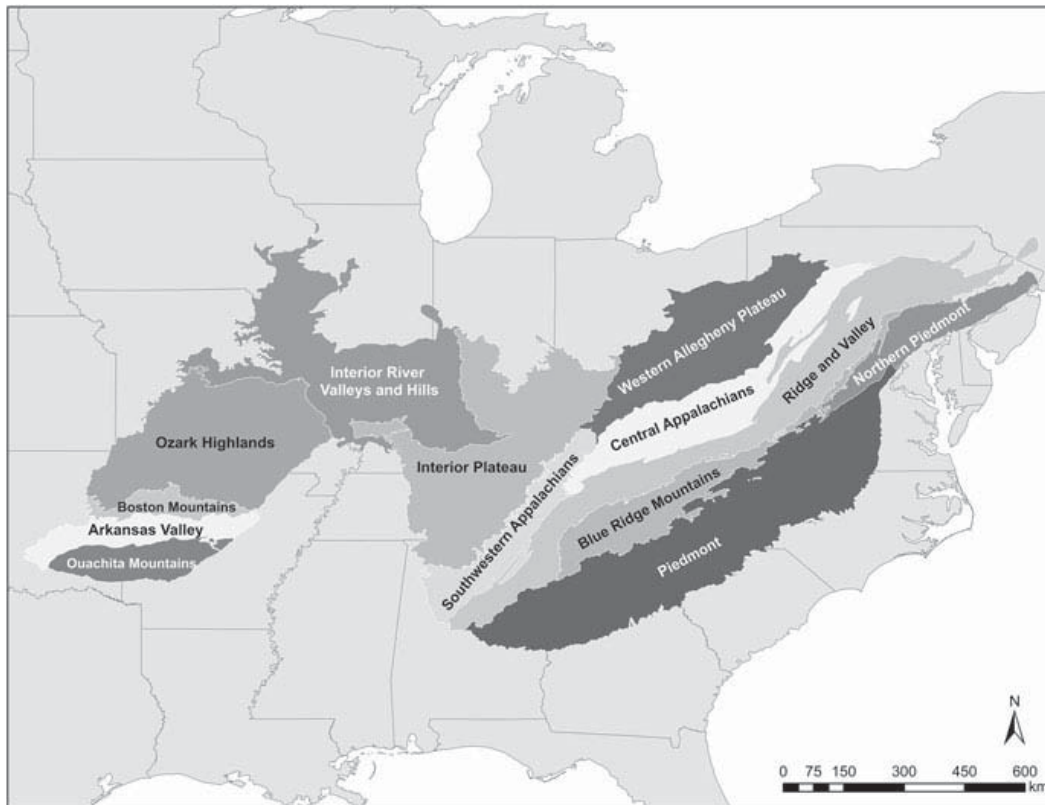


Fig. 1.1 The CHR encompasses 13 ecoregions, defined by similarity in climate, geology, physiography, soils, hydrology, land use, wildlife, and predominant types of disturbances (Omernik 1987)

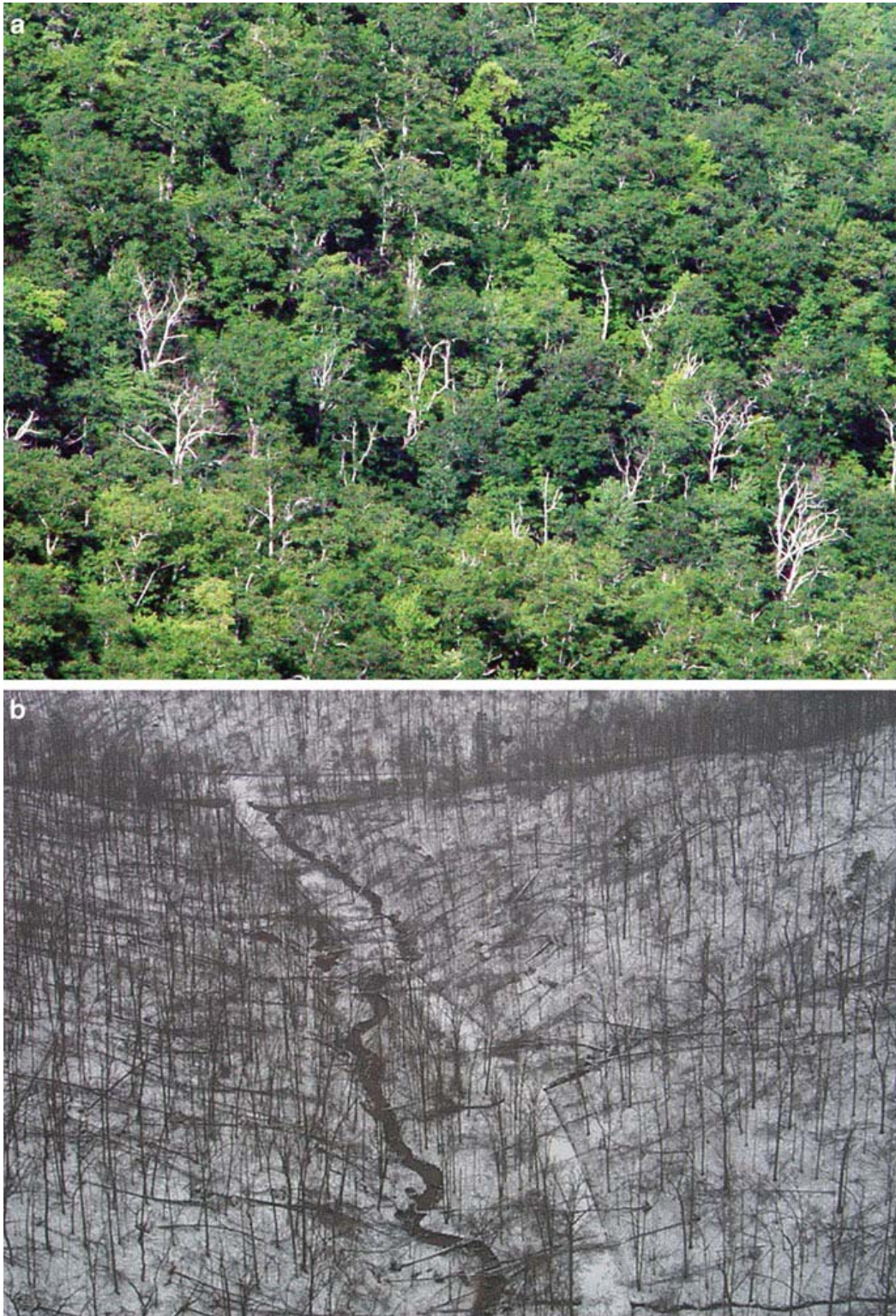


Fig. 1.2 Examples of different natural disturbance types in central hardwood forests: **(a)** oak decline in the southern Appalachians (Photo courtesy of Steve Oak); **(b)** ice storm damage on the Daniel Boone National Forest, 2003 (Photo courtesy of USDA Forest Service State and Private Forestry); **(c)** springtime mountain wave, Great Smoky Mountains National Park (GSMNP; Photo

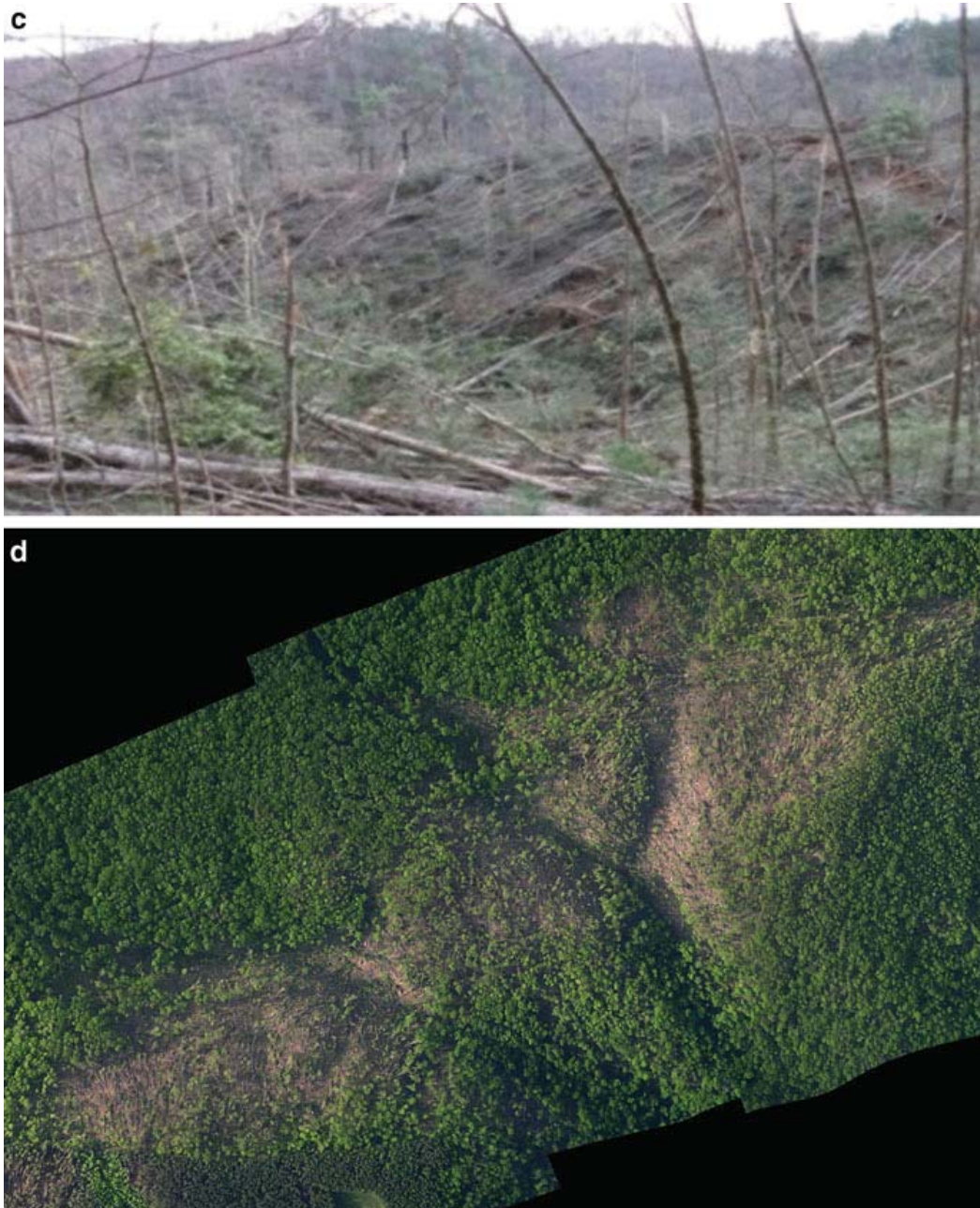


Fig. 1.2 (continued) courtesy of Jim Renfro); **(d)** tornado damage in Dade County, Georgia, 2011 (Photo by NOAA, National Ocean Service, April 2011 Tornado Response Imagery); **(e)** upper track of 2004 Peaks Creek debris flow, Macon County, North Carolina (Photo courtesy of Rick Wooten); **(f)** close up view of 2004 Peaks Creek debris flow, Macon County, North Carolina (Photo courtesy of Rick Wooten); **(g)** lightning-ignited Calderwood fire, ignited on private land, 17 August 2010, and spread into GSMNP (Photo courtesy of GSMNP staff); **(h)** flooding caused by beaver dam, Watauga County, North Carolina, July 2014 (Photo courtesy of Cathryn Greenberg)



Fig. 1.2 (continued)



Fig. 1.2 (continued)

of variation' of natural disturbances and vegetation composition and structure. This highlights the need to use the best available science to describe the historic types, frequencies, and severities of natural disturbances, and the scales and gradients of forest structural conditions they created.

Today's CHR forests are a legacy of natural and anthropogenic disturbances. Over the long-term, climate shifts through the Holocene have affected both forest types and (almost certainly) disturbance regimes. Pollen records indicate that just 18,000 years before present (BP), during the last glacial maximum, spruce (*Picea* spp.) and jack pine (*Pinus banksiana*) forests were widespread across much of this region, which is now occupied by hardwood forests (Delcourt and Delcourt 1981; Jackson et al. 2000). By around 14,000 years BP, a warming climate coincided with the arrival of humans (*Homo sapiens*) and the extinction of remaining megafauna (see Greenberg et al. Chap. 12), and thus began a slow transition to diverse deciduous forests; frequent burning by humans also facilitated the expansion of prairies, open woodlands, and savannas into eastern North America (Delcourt and Delcourt 1981, 2004). By 5,000–7,000 years ago, forest types familiar to us today were in place (Delcourt et al. 1993, 1998; Spetich et al. 2011). Climate fluctuations over the last several years include the warmer hypsithermal (7,500 to 5,000 years BP), followed by a cooling trend (5,000–120 years BP) excepting a warmer 'Medieval Climate Anomaly' (1,050–750 years BP) (Driese et al. 2008; Mann et al. 2009) and the 'Little Ice Age' (600 to 120 years BP) (Carroll et al. 2002). The confluence of changing climate and forest types with the increasing influence of humans over the last 3,000 years (Delcourt and Delcourt 2004) was certainly concurrent with shifting disturbance regimes and resulting forest composition and structure.

Although this book aims to characterize the range of variation in natural disturbances, the historic influence of humans on the landscape blurs separation of 'natural' and 'unnatural' disturbance effects. Current estimates of the human population in the eastern USA based on archaeological and historical information range between 0.5 and 2.6 million in 1500 AD (Milner and Chaplin 2010). Guyette et al. (2006a, b) found that human population density and culture were a major influence on historic fire frequencies; historically, human-caused fire was at least 200 times more frequent than lightning-caused fire in the eastern USA (see Spetich et al. 2011). Frequent burning and (or) abandonment of farmlands by Native Americans and later by European settlers likely created and maintained oak savannas, grassy balds, shortleaf- (*P. echinata*) and pitch pine (*P. rigida*)-dominated forests, and mixed pine-oak forests on sites that would otherwise, in many cases, be hardwood-dominated (Delcourt et al. 1998; Delcourt and Delcourt 2004). As a consequence of this conversion, effects of native southern pine beetle (*Dendroctus frontalis*) outbreaks on forest types that were heavily influenced by humans were historically greater than they might have been on landscapes where humans were absent. Similarly, the historic occurrence, distribution, and population sizes of some wildlife species, such as elk (*Cervus canadensis*), bobwhite quail (*Colinus virginianus*), or golden-winged warblers (*Vermivora chrysoptera*) that require different variants of open conditions, were likely predominantly a function of frequent burning by humans (see Greenberg et al. Chap. 12).



Fig. 1.3 Characteristics of disturbances over time and within a regional context

Anthropogenic disturbances have especially shaped CHR forests over the last 200 years. Key among these human impacts: (1) widespread, heavy logging in the early 1900s resulted in younger, relatively even-aged forests with smaller-diameter trees; (2) European settlement resulted in land being cleared for home sites and agriculture; (3) non-native invasive plants, pests, and pathogens affected forest composition, including a non-native ‘blight’ (*Cryphonectria parasitica*), introduced in 1904, which eliminated mature American chestnut (*Castanea dentata*) trees that historically composed up to 50 % of trees in eastern forests (Elliott and Swank 2008; Burke 2012); and (4) human population grew from an estimated fewer than 2.3 people per km² throughout most of the CHR in 1790 (US Census Bureau undated) to 29 – >77 people per km² today (worldatlas.com; 2012 census), leading to fragmented and more heavily used forests. Further, heavy use of fossil fuels by humans is accelerating climate change, which may already be affecting forests (McNab et al. 2014) and wildlife (Greenberg et al. 2014), or likely will in the near future (see Dale et al. Chap. 13). These anthropogenic impacts interact with natural disturbances and can enhance or diminish their effects throughout the CHR (see Dale et al. Chap. 13).

In addition to understanding the interactions with anthropogenic disturbances, assessing the range of variation of natural disturbances in forests requires moving beyond a single disturbance event at a specific site, to considering the entire disturbance regime; i.e., frequency, spatial extent, and multiple interacting types of disturbance, within the larger landscape, subregional, and regional context (Fig. 1.3). For example, severe wind events (see Peterson et al. Chap. 5) or ice storms (see Lafon et al. Chap. 7) may rarely reoccur in the same forest stand, but nonetheless occur with relatively higher frequency within a landscape or region (White et al. 2011). Similarly, forests often are subject to multiple, interacting biotic and abiotic disturbances. For example, drought may precipitate oak decline, particularly on dry, low-quality sites, and weakened oak trees may then be especially vulnerable to windthrow during a high wind event (Greenberg et al. 2011). Chapters in this volume assess the intensity, spatial extent, and return interval of both biotic (e.g., oak decline, Oak et al. Chap. 3; southern pine beetle, Nowak et al. Chap. 4; or keystone wildlife species and prehistoric humans, Greenberg et al. Chap. 12) and abiotic (e.g., wind, Peterson et al. Chap. 5; fire, Grissino-Mayer Chap. 6; ice storms, Lafon Chap. 7; flooding and erosion, Leigh Chap. 8, and landslides, Wooten et al. Chap. 9) natural disturbances at multiple scales to provide a broader picture of how the disturbance regime shapes forest structure or composition.

Reconstructing historic frequency, range of severity, and spatial extent of natural disturbances depends in part on availability of records and physical evidence. For example, comprehensive, systematic climate records are relatively recent (since 1895; National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center), and weather-severity rankings such as the Fujita scale of tornado severity are often based on the built environment (e.g., tornado damage to buildings), with less applicability to forests. Scientists in this book use a combination of intensive data such as stand or plot-level measurements of forest composition and structure, tree rings, soil charcoal, and sedimentology; extensive data such as southern pine beetle surveys; limited surveys such as disturbance damage for a salvage sale; anecdotal descriptions of specific disturbances (e.g., Abell 1934); and non-quantitative regional surveys (e.g., Ashe and Ayers 1901), or descriptions (Hursh and Haasis 1931) to capture the historic range of disturbances in central hardwood forests. In this chapter, we introduce the CHR and historic spatial and temporal range of variation of natural disturbances to provide a foundation for the book and further discussion of whether, and how, historic disturbance regimes should guide forest management within national forests and other public lands.

1.2 The Central Hardwood Region: Geographic Scope, Climate, and Forests

The CHR is characterized by a humid, temperate climate with evenly distributed annual precipitation and occasional soil moisture deficits during the middle to late summer growing season (Bailey 1995). This region of deciduous hardwood forests is centrally located in the eastern USA and is dominated by species of oaks and hickories (*Carya*) (Fig. 1.4). The predominantly oak-hickory forests of the CHR have long been recognized and described (Mattoon 1936), but their extent has been variously mapped (Mattoon 1937; Schnur 1937; Braun 1950; Society of American Foresters 1964; Eyre 1980; Merritt 1980; Dyer 2006), particularly in transition areas with adjoining forest regions. The region we define as the CHR generally follows the area delineated by Fralish (2003), with two exceptions. We include the hardwood-conifer forests of the Piedmont and the Ouachita Mountains, which had a high component of oaks and hickories before settlement (Nelson 1957; Foti and Glenn 1990) but now are largely dominated by pines; Fralish (2003) considers these areas as transition zones with the Southern Pine Region. The extent of the CHR in this book agrees well with 13 aggregated ecoregions identified by Omernik (1987) (Fig. 1.1), which are large ecological subdivisions that are relatively uniform in climate, geology, physiography, soils, hydrology, land use, wildlife, and predominant types of natural disturbances. However, other ecologists have used other terms to define regions of ecological similarity, as do some of the authors in this volume. For example, Braun (1950) referenced the area similar to the Blue Ridge Mountains ecoregion (Fig. 1.1) as the ‘southern Appalachians,’ whereas Ashe and Ayers (1901) defined the ‘southern Appalachians’ as (approximately) the group of seven ecoregions east of the Interior Plateau.

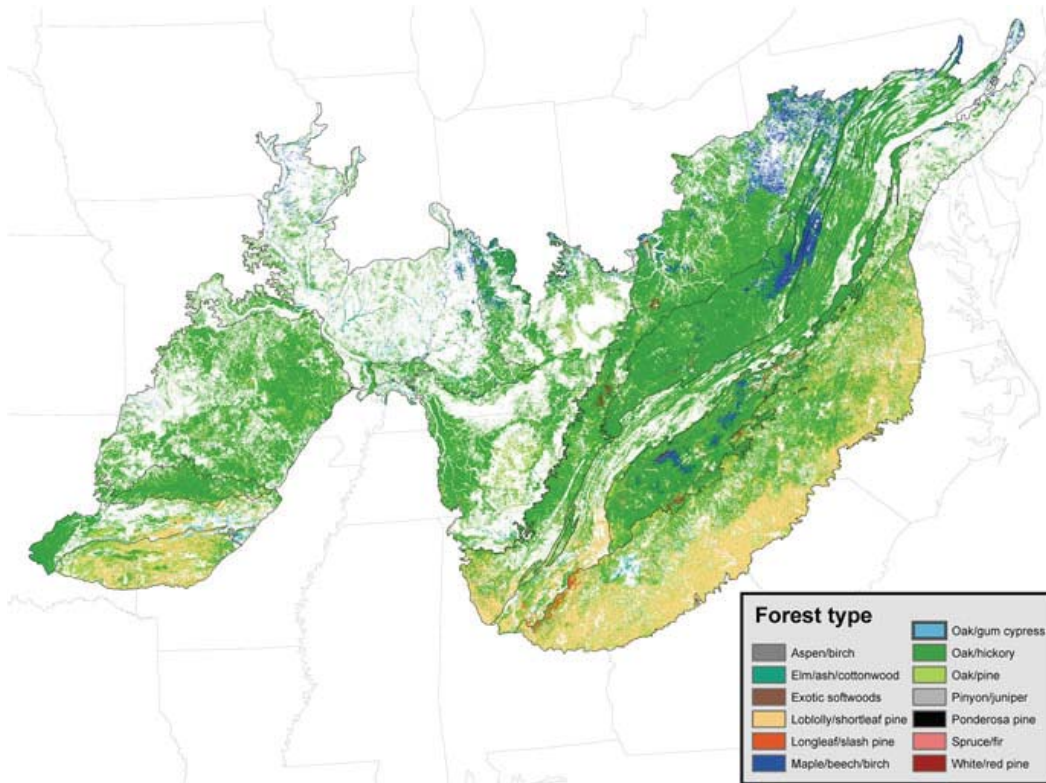


Fig. 1.4 Oak-hickory and pine-hardwood mixtures are the predominant cover types where forests have not been cleared for agriculture and other land uses in the CHF (Ruefenacht et al. 2008)

Except for the loss of American chestnut from the canopy in the eastern part of the CHF, species composition has changed little from pre- to post-European settlement (Fig. 1.5), but structure, and in some cases species dominance, has changed and fragmentation has increased (Riitters et al. 2002). Much of the CHF forested area has been selectively harvested several times, beginning with high-grading and fuelwood cutting associated with subsistence farming by pioneer European settlers during the late 1700s, and followed by several episodes of exploitation for commercial purposes (Schmidt and McWilliams 2003). The extent of this early human disturbance was described by Schnur (1937) who reported that most of the 100 mature, even-aged timber stands he sampled throughout the CHF in the early 1930s had originated from sprouts following harvest. At that time, more than half of the area of most states in the CHF was used for agriculture, farm size averaged about 30 ha, and only about 12 % of farmland was reported as non-pastured woodlands (US Census Bureau 1932).

Today, nearly 90 % of the CHF remains in private ownership with an average tract size of about 20 ha (Roberts et al. 1995). The largely private lands coupled with a climate favorable for agriculture has resulted in a mosaic of land uses and vegetative cover types throughout much of the region. Forested land ranges from 21 % in the Interior River Valleys and Hills ecoregion to 91 % in the Blue Ridge Mountains; overall, the vegetative cover on about 60 % of the CHF land area consists of trees (Fig. 1.6). Forests are less fragmented in the mountainous ecoregions, where steeper

Fig. 1.5 Oaks and hickories typically dominate the canopy of mature forests on middle and upper slopes in the CHR, such as this stand in the southwestern Appalachians ecoregion in Scott County, Tennessee (US Forest Service photo, F.E. Olmsted 1901; US Forest Service photograph collection #P9801. DH Ramsey Special Collections, UNC-Asheville)

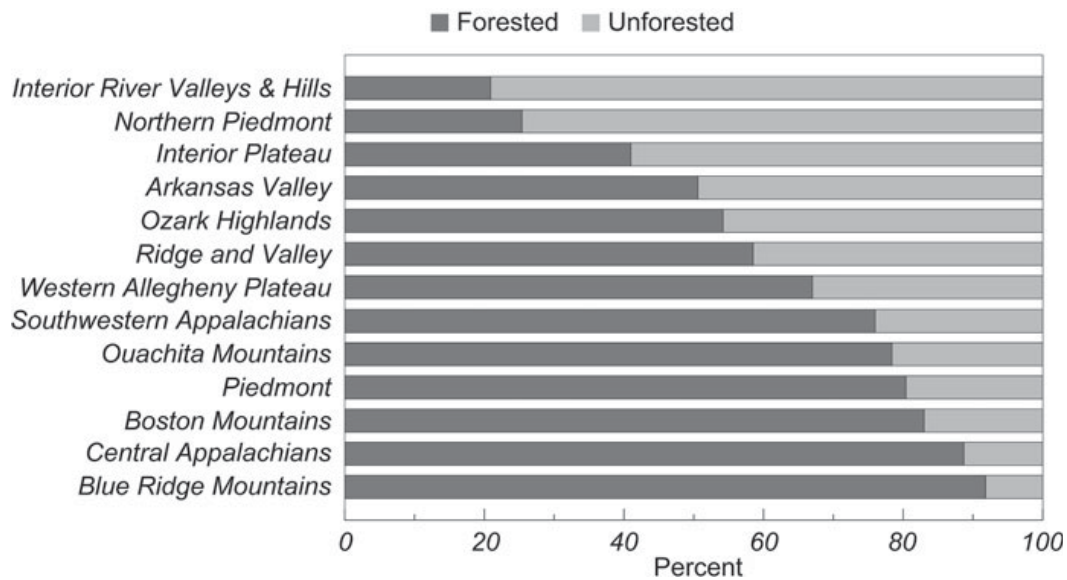
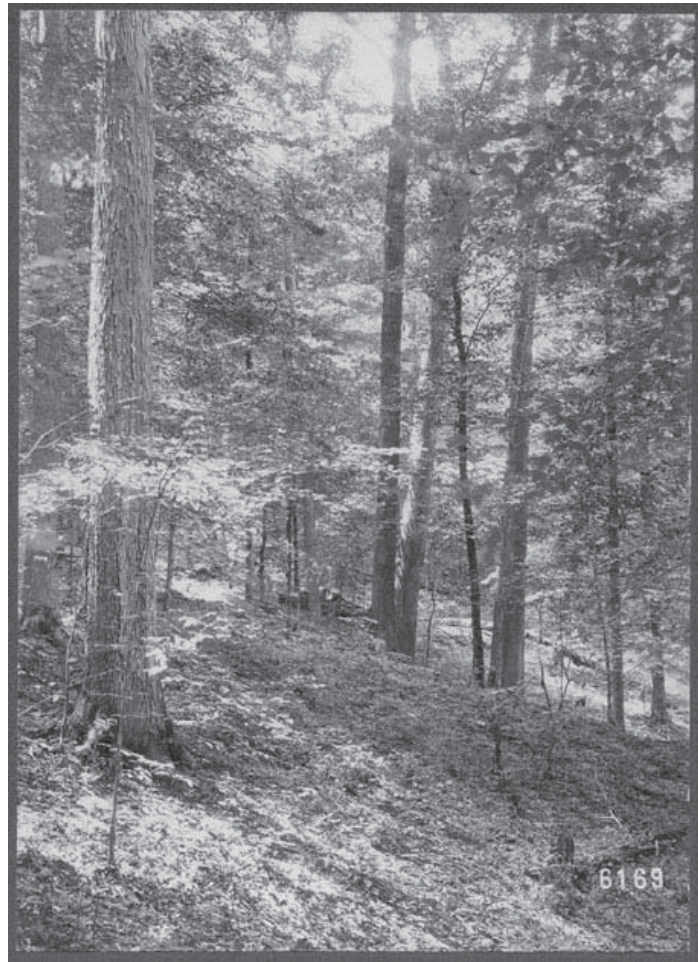


Fig. 1.6 Relative proportion (%) of land forested or unforested (e.g. water bodies, agricultural fields, built-up urban areas) by ecoregion in the CHR (Ruefenacht et al. 2008)

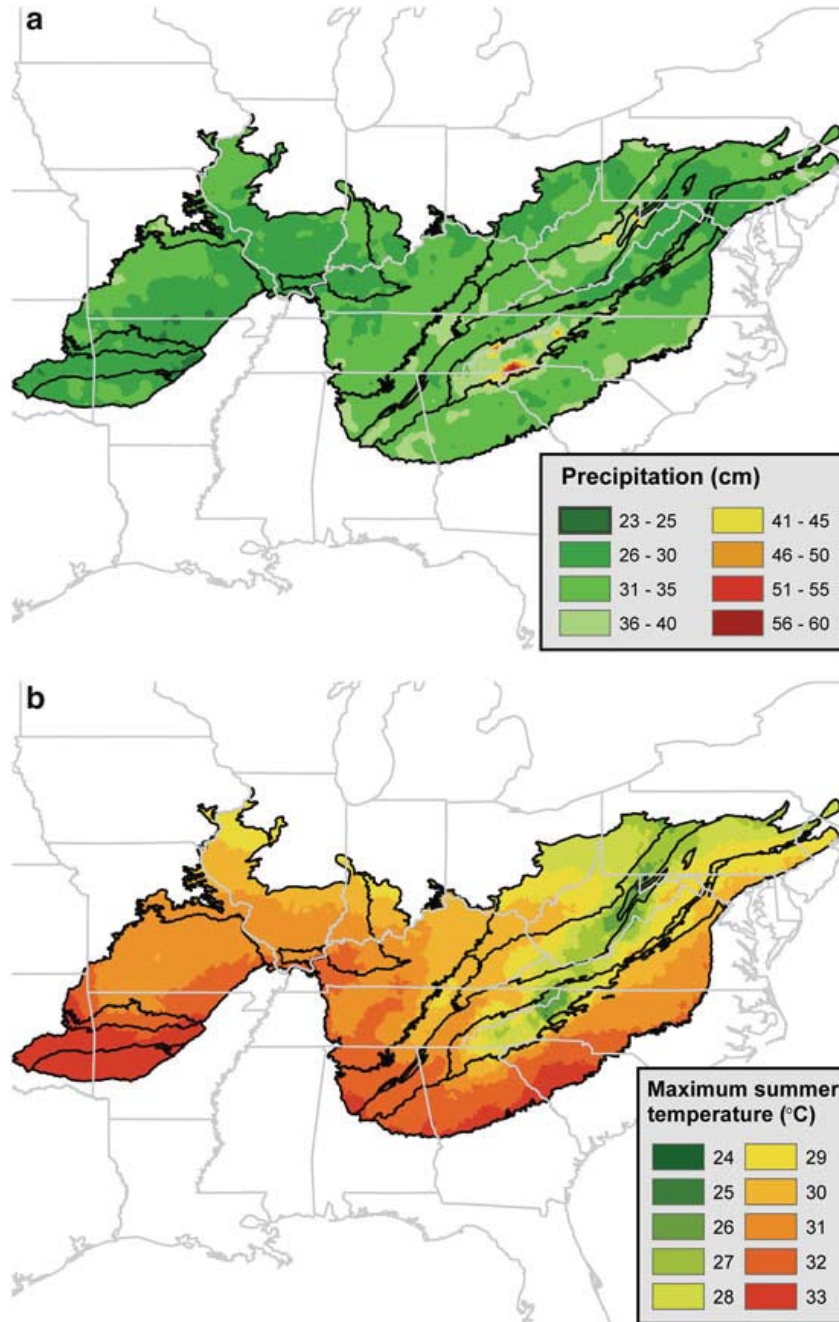


Fig. 1.7 Mean summer (June – August) (a) precipitation and; (b) maximum temperatures, in the CHR

topography is less suitable for cultivation and public ownership of land as state and national forests and parks is higher than elsewhere. An analysis by Gallant et al. (2000), for example, indicates forest patch size is more than five times larger in the mountainous Blue Ridge Mountains compared to the hilly topography of the adjacent Piedmont ecoregion. Forested areas are lowest in the Interior River Valleys and

Hills ecoregion, where the climate, and soils are well-suited for grain crops and in the Northern Piedmont ecoregion, where high population densities result in relatively greater land uses for urban purposes than elsewhere in the CHR.

Mean annual precipitation is variable throughout the CHR, ranging from 95–140 cm among ecoregions; higher amounts are associated with mountainous ecoregions. However, mean summer (June – August) precipitation, which influences forest species composition and productivity more than annual rainfall, is relatively uniform among ecoregions, ranging from 24–28 cm (Fig. 1.7a). Mean maximum summer temperature is relatively uniform throughout the CHR, except in the cooler eastern mountainous ecoregions (Fig. 1.7b). Except for small areas in the Interior Plateau and Interior River Valleys and Hills ecoregions, in southern Indiana and Illinois, the last period of Pleistocene glaciation did not extend into the CHR. Bedrock geology varies greatly in age and lithology throughout the CHR. Flat-lying to gently inclined sedimentary strata of sandstone, shale, limestone and dolomite underlie much of the CHR. Folded and faulted sedimentary strata are subordinate to the gently inclined sedimentary strata in the Southwestern and Central Appalachian ecoregions, but dominate the Ouachita Mountains and the Ridge and Valley ecoregions. Folded, faulted, and metamorphosed sedimentary and metamorphosed igneous bedrock underlies the greater part of Blue Ridge Mountains and Piedmont ecoregions, and consists mainly of varieties of slate, phyllite, schist, and gneiss. The Blue Ridge Mountains and Piedmont also include large, unmetamorphosed and weakly metamorphosed igneous intrusions. Soils in the CHR are mostly moderately productive Alfisols, formed from limestones. Ultisols are prevalent throughout but are typically lower in fertility and are more common in ecoregions underlain with highly weathered rocks of the Blue Ridge Mountains and Piedmont. Inceptisols also occur throughout, typically in concave areas of steep, hilly terrain. Table 1.1 summarizes environmental characteristics and common disturbances in each of the 13 ecoregions of the CHR.

Composition of the hardwood dominated forests of the CHR, consisting of more than 100 arborescent species, has long been described simply as oak-hickory or oak-chestnut (Pinchot and Ashe 1897; Holmes 1911). The more descriptive forest cover types identify 18 major communities, named for the one to three tree species that comprise the majority of canopy stocking (Table 1.2) (Eyre 1980). The upland group of cover types are dominated by one or more of nine species of oaks and generally occupy drier slopes and ridges; the other cover types, which form a group commonly occurring on bottomlands or moist slopes, usually include species of oak as minor stand components. One or more of six species of hickory (*Carya* spp.) are typical canopy associates with oaks in both upland and bottomland cover types. White oak (*Q. alba*) is the most extensive cover type, extending throughout the eastern USA and into Canada (Greeley and Ashe 1907); bear oak (*Q. ilicifolia*), is most restrictive, occurring in a patchy distribution primarily on xeric ridge tops in the Ridge and Valley, and barrens of other ecoregions in the northeastern area of the CHR (Little 1977). With only several exceptions (e.g., bur oak (*Q. macrocarpa*), chestnut oak (*Q. montana*)), the upland oak cover types occur throughout the CHR, but can vary in dominance in response to moisture gradients at both regional and

Table 1.1 Environmental characteristics within ecoregion subdivisions^a of the CHR

Ecoregion area (km ²) ^b	Physiography & elevation range (m)	Geologic formations & soils	Mean annual Temp (°C) ^c	Mean annual Ppt (mm) ^c	Land cover & uses	Primary natural disturbances
Ouachita Mountains (26,896)	High hills, low mountains (88–820)	Sedimentary; Ultisols, Inceptisols	15–17	1,090–1,675	Mostly pine-oak forests; pasture and croplands	Ice storms, fire, tornados, landslides
Arkansas Valley (28,421)	Plains with hills (75–839)	Sandstone, shale; Ultisols, Inceptisols	15–17	1,040–1,575	Patchwork of agriculture, wood lands, built-up residential,	Fire, tornados, landslides
Boston Mountains (14,178)	Deeply dissected plateau (65–853)	Sandstone, shale; Ultisols, Inceptisols	13–14	1,118–1,372	Oak-hickory forests	Fire, tornados, landslides
Ozark Highlands (106,391)	Moderately dissected plateau; (80–560)	Limestone, sandstone, shale; Ultisols, Alfisols	12–15	965–1,244	About equal areas of forests and agriculture	Tornados, fire
Piedmont (166,117)	Moderately dissected plains (40–880)	Metamorphic schist, gneiss; Ultisols, Entisols	13–17	1,080–1,650	Mosaic of pine-oak forests, agriculture, pasture, large built-up urban areas	Ice storms, hurricane, occasional tornados, southern. pine beetle, fire
Northern Piedmont (30,459)	Low hills, plains (50–350)	Metamorphic gneiss-schist; Alfisols, Inceptisols	11–13	930–1,250	About 25 % urban and developed, forest and cropland about equal.	Ice storms, occasional remnants of hurricanes
Blue Ridge Mountains (46,595)	Hilly plateaus, mountains (250–2,040)	Metamorphic gneiss-schist; Inceptisols, Ultisols	7–14	1,100–2,500	Forests, urban in broad valleys	Ice and rain storms, occasional hurricane, landslides, fire
Ridge and Valley (115,483)	Low, parallel ridges and valleys (90–1,300)	Sedimentary, limestone, sandstone; Ultisols, Inceptisols	8–16	900–1,350	Woodland, cropland and pasture mosaic; about 60 % forested	Ice and rain storms, landslides,

Southwestern Appalachians (37,994)	Moderately dissected plateau (90–730)	Sedimentary, sandstone; Ultisols, Inceptisols	12–16	1,200–1,700	Forest and woodland; little agriculture	Rain storms, fire, landslides
Central Appalachians (62,050)	High, dissected plateau; (170–1,400)	Sedimentary, Sandstone, shale; Ultisols, Inceptisols	7–13	980–1,500	Mostly forests, pasture, surface coal mining	Ice storms, summer rain storms
Western Allegheny Plateau (81,440)	Dissected plateau, steep hills; (150–580)	Sedimentary formations; Alfisols, Inceptisols, Ultisols	8–13	900–1,150	Forest and woodlands; extensive coal mining	Ice and rain storms, landslides, fire
Interior Plateau (123,523)	Plains, dissected plateaus, hills and ridges; (105–460)	Sedimentary formations, shale, limestone, siltstone; Ultisols, Alfisols	12–16	1,015–1,470	Forest, wood-lots, pasture, cropland, urban	Ice storms, fire, occasional tornados, severe drought
Interior River Valleys and Hills (120,405)	Wide, flat valleys, dissected glacial till plains (90–305)	Sedimentary, sandstone, limestone; Alfisols, Mollisols	10–14	860–1,320	Mostly cropland, pasture, scattered woodlands	Flooding in river bottoms, occasional tornados, severe drought

^aSee Fig. 1.1 for location of ecoregions

^bLevel III ecoregions (Omernik 1987)

^cRange of mean annual temperature (Temp) or precipitation (Ppt) occurring within each ecoregion

Table 1.2 Distribution and ecological relationships of major forest cover types occurring in the CHR (Eyre 1980)

Forest cover type ^a	Geographical distribution ^b	Ecological relationships
Post oak – blackjack oak (<i>Q. stellata</i> , <i>Q. marilandica</i>)	Throughout all ecoregions of the CHR	Xeric sites – shallow clayey and deep sandy soils
Bur oak – (<i>Q. macrocarpa</i>)	Scattered occurrences; prairie-forest transitions of western ecoregions	Xeric to dry sites; prairie moist bottomlands
Chestnut oak (<i>Q. montana</i>)	Moderate to steep slopes of eastern ecoregions	Dry sites; ridge-tops and southerly slopes
White oak (<i>Q. alba</i>)	Throughout CHR, most common in Ozark Highlands, Interior Plateau, and Interior River Valleys and Hills ecoregions	Most common on dry-to moderately wet sites
Black oak (<i>Q. velutina</i>)	Common in Ozark Highlands, Interior Plateau, and Interior River Valleys and Hills ecoregions; scattered elsewhere	Generalist on many sites; occurrence largely result of disturbance
Northern red oak (<i>Q. rubra</i>)	Throughout; pure stands rare	Moderately moist to mesic sites
Yellow-poplar (<i>Liriodendron tulipifera</i>)	Large stands occur in ecoregions Northern Piedmont, Blue Ridge Mountains, Ridge and Valley ecoregions; patches elsewhere	Mesic coves and slopes, flood plains.
River birch – sycamore (<i>Betula nigra</i> , <i>Platanus americana</i>)	Throughout	Flood plains of large rivers, river bottoms,
Silver maple – American elm (<i>Acer saccharinum</i> , <i>Ulmus americana</i>)	Throughout	Mesic floodplains, old fields in bottomlands
Pin oak – sweetgum (<i>Q. palustris</i> – <i>Liquidambar styraciflua</i>)	Throughout, but particularly prevalent in Interior Plateau, Interior River Valleys and Hills ecoregions	Mesic sites of broad stream bottoms
Eastern red cedar (<i>Juniperus virginiana</i>)	Throughout; large stands uncommon except along prairie transition	Dry, shallow soils; rock outcrops

^aMinor forest cover types include bear oak (*Q. ilicifolia*), black locust (*Robinia pseudoacacia*), yellow-poplar (*L. tulipifera*)/eastern hemlock (*Tsuga canadensis*), yellow-poplar (*L. tulipifera*)/white oak (*Q. alba*)/northern red oak (*Q. rubra*), sassafras (*Sassafras albidum*) – persimmon (*Diospyros virginiana*), pitch pine (*P. rigida*)

^bSee Fig. 1.1 for location of ecoregions

landscape scales. The widely occurring and xerophytic post oak (*Q. stellata*), for example, increases as a stand component in the drier western ecoregions and also responds to soil moisture variation in relation to topography at the landscape scale (Stahle and Hehr 1984; see Wilfahrt et al. Chap. 11). The association of vegetation with environmental gradients is most apparent at landscape scales within

mountainous ecoregions where moisture and temperature gradients are formed from interactions of topography with elevation.

Elevation is a strong environmental factor in the eastern portion of the CHR that affects cover types in the mountainous Blue Ridge Mountains and Central Appalachians ecoregions, and somewhat in the Southwestern Appalachians ecoregion. In the high mountains of the Blue Ridge Mountains ecoregion, elevation and topography form temperature and moisture environments manifested by distinctive forest communities (Pinchot and Ashe 1897). Historically, a canopy mixture of pines and oaks was typical of the hotter and drier hilly topography of the low elevation intermountain valleys, referred to as plateau forests because of their similarity in soils and species with the adjacent Piedmont ecoregion. Forests of middle elevations, from 900 to 1,500 m, consisted primarily of oaks, hickories and patches of conifers on dry slopes and ridges (and American chestnut before 1920); yellow-poplar (*Liriodendron tulipifera*), northern red oak (*Q. rubra*) and other mesophytic species were common on moist slopes and in coves. The colder and wetter environments above 1,500 m in North Carolina results in a transition from oak-hickory forests to northern hardwoods and red spruce (*Picea rubens*). A similar transition from oak-hickory forests to northern hardwoods and spruce occurs above about 1,200 m elevation on the Dolly Sods plateau and near the summit of Spruce Mountain in the Central Appalachians ecoregion of West Virginia. The current distribution of red spruce stands in the Blue Ridge Mountains ecoregion is better related to disturbances associated with timber harvest during the early 1900s than with environmental factors (Korstian 1937; Pielke 1981). In the dissected plateau and low mountains of the Southwestern Appalachians ecoregion, where elevations reach only 730 m, moisture gradients associated with relief are the primary factor affecting distribution of the oak-hickory and mixed mesophytic upland forest vegetation.

In the western mountainous ecoregions of the CHR (i.e., Ouachita Mountains, Arkansas Valley, and Boston Mountains), the highest elevation occurs at Mt. Magazine (840 m), one of several flat-topped, mesa-like ridges in the Arkansas Valley ecoregion. This ecoregion, an 80-km wide synclinal trough with diverse landforms including plains, hills, ridges, mountains and narrow floodplains along the Arkansas River, is situated between the Ouachita Mountains and the Boston Mountains ecoregions. In the Ouachita Mountains to the south the highest peak is Rich Mountain (817 m). There, temperature-moisture gradients associated with aspect results in a greater proportion of conifers (e.g., shortleaf pine) on the warmer and drier southern slopes compared to the slightly more mesic northern slopes dominated by oaks and hickories (Pell 1983). The Boston Mountains ecoregion is a deeply dissected former tableland, with highest elevations of about 650 m. Forests there are dominated by white, northern red, and black oaks (*Q. velutina*) on well drained slopes, although pines are prominent on southern slopes and mesophytic hardwoods are common on moist slopes and in ravines. In comparison with vegetation, however, the distribution of aquatic insect fauna has a stronger alliance with elevation in the mountainous landscapes of the Arkansas ecoregions (Bowles and Mathis 1989).

The landscape-scale distribution of forest cover types in the seven non-mountainous ecoregions is primarily associated with topographic moisture gradients, although disturbance is an important factor for many of these, including the upland oak types. The pitch pine cover type can regenerate on some very dry sites, but usually follows fire elsewhere. The sassafras (*Sassafras albidum*) – persimmon (*Diospyros virginiana*) type is typically found only on dry abandoned fields with red cedar (*Juniperus virginiana*) and pines. Likewise, the widely distributed and successional black locust (*Robinia pseudoacacia*) type has been described as primarily ‘man-made.’ Except for the relatively long-lived nature of a few cover types, primarily those with species in the white oak group (e.g., white oak, chestnut oak, post oak) and perhaps yellow-poplar, most are transitory and dependent on periodic disturbances to maintain their presence on the forested landscape (Eyre 1980).

Species composition of upland oak-hickory stands in the CHR before the current policy of wildfire suppression (beginning in the 1930s) may be inferred from stand inventory data presented by Schnur (1937) (Table 1.3). He found a relationship of species with site quality; either white oak or black oak occurred in more than 90 % of all stands, and one of several species of hickory was present in 70 % of stands. Red maple (*Acer rubrum*) occurred in 52 % of stands across all site qualities, and yellow-poplar occurred in 20 % of stands, mostly on high-quality sites. Shortleaf, Virginia (*P. virginiana*), or pitch pine was present in over half of stands sampled. Altogether, Schnur found 15 species of oak, five species of hickory, and approximately 50 other associated tree species, including American chestnut, which by that time had been removed as a dominant canopy species in forests of eastern ecoregions by mortality from the introduced blight (Frothingham and Stuart 1931).

Oak-dominated forests are the most common upland type throughout the CHR (Table 1.4). Conifers are present in relatively high proportions in forests of the Ouachita Mountains and Piedmont ecoregions and elsewhere on low quality sites and topographic positions that are more vulnerable to summer drought, and where lightning-ignited fires may have historically been most common. Historically, some central hardwood forests now dominated by oak and hickory had a heavy overstory component of shortleaf pine and pitch pine, especially on dry sites where frequent burning by Native American and (later) European settlers provided seedbed and light conditions suitable for their regeneration. Additionally, nearly pure second-growth yellow pine forests occurred in abandoned clearings, covering large areas (Ashe and Ayers 1901; Mattoon 1915; Ashe 1922; Balch 1928; Delcourt and Delcourt 2004).

Across the CHR, both broadly and locally, an elevation gradient from pine, through dry site oaks and mesic oaks, to mesic hardwoods, including northern hardwoods, is associated with a decrease in ‘ground based’ natural and anthropogenic disturbances such as fire and grazing, and an increase in ‘canopy’ disturbances such as wind and ice (White et al. 2011). White et al. (2011) compared the relative frequency of disturbances among ecoregions of the CHR. Their analysis revealed that fire frequency, including both natural and anthropogenic sources, is higher in the Ouachita Mountains, Arkansas Valley, Boston Mountains, Ozark Highlands, and Interior Plateau ecoregions while remnant hurricanes and landslides are more common disturbances in the Blue Ridge Mountains, Ridge and Valley, Southwestern

Table 1.3 Percent occurrence and basal area of arborescent species ≥ 2.5 cm dbh on sample plots at nearly 100 locations in the CHR soon after initiation of a national policy of wildland fire control (Schnur 1937)

Species	Basal area (%)	Occurrence (%)
White oak (<i>Querus alba</i>)	28.23	95.3
Black oak (<i>Q. velutina</i>)	19.11	91.6
Scarlet oak (<i>Q. coccinea</i>)	17.08	79.7
Hickory (<i>Carya</i> spp) ^c	2.69	76.0
Chestnut oak (<i>Q. montana</i>)	13.73	63.4
Red maple (<i>Acer rubrum</i>)	1.31	52.2
Northern red oak (<i>Q. rubra</i>)	4.65	52.0
Black gum (<i>Nyssa sylvatica</i>)	0.48	37.6
Understory group ^d	0.57	30.2
American chestnut (<i>Castanea dentata</i>)	1.84	24.5
Yellow-poplar (<i>Liriodendron tulipifera</i>)	0.84	20.3
Black and red ash (<i>Fraxinus nigra</i> , <i>F. pennsylvanica</i>)	0.62	21.0
Black locust (<i>Robinia pseudoacacia</i>)	0.44	15.1
Virginia pine (<i>Pinus virginiana</i>)	1.86	14.1
Post oak (<i>Q. stellata</i>)	0.90	13.4
Sweetgum (<i>Liquidambar styraciflua</i>)	0.54	5.2
Pitch pine (<i>P. rigida</i>)	0.43	5.0
Shortleaf pine (<i>P. echinata</i>)	0.47	4.2
Southern red oak (<i>Q. falcata</i>)	0.60	4.2
Bottomland oaks ^b	0.05	3.0
Miscellaneous oaks ^a	0.14	2.0
Pin oak (<i>Q. palustris</i>)	0.40	1.7
Blackjack oak (<i>Q. marilandica</i>)	0.14	1.2

^aHills (*Q. ellipsoidalis*), bear (*Q. ilicifolia*), dwarf chinquapin (*Q. prinoides*)

^bSwamp white (*Q. bicolor*), willow (*Q. phellos*), shingle (*Q. imbricaria*)

^cBitternut (*C. cordiformis*), shagbark (*C. ovata*)

^dHophornbeam (*Ostrya virginiana*) blue beech (*Carpinus caroliniana*), persimmon (*Diospyros virginiana*), sourwood (*Oxydendrum arboreum*), American holly (*Ilex americana*), sassafras (*Sassafras albidum*)

and Central Appalachians, and Western Allegheny Plateau ecoregions, and ice storms are common in the northernmost ecoregions. Below, we discuss the primary natural disturbances and how they affect the structure and composition of forests within the within the CHR.

1.3 Agents of Natural Disturbance: Biological Process and Living Organisms

The ongoing, continuous process of decline, death, or breakage of forest trees is a ‘background’ disturbance that creates canopy openings and promotes fine-scale structural heterogeneity and diversity in central hardwood forests. Current gap

Table 1.4 Forest composition by species type^a and ecoregion in the CHR

Ecoregion	Misc. conifer forests (%) ^b	Oak-conifer forests (%) ^c	Upland oak-hickory forests (%) ^d	Misc. hardwood forests (%) ^e
Ouachita Mountains	51.3	20.0	26.3	2.4
Arkansas Valley	19.7	9.0	63.9	7.4
Boston Mountains	6.7	2.8	90.5	0.0
Ozark Highlands	2.0	2.9	94.1	1.0
Piedmont	52.3	10.1	36.2	1.4
Northern Piedmont	6.6	3.6	83.3	6.5
Blue Ridge Mountains	4.4	7.9	82.2	5.5
Ridge and Valley	12.0	3.1	76.7	8.2
Southwestern Appalachians	23.0	4.9	71.3	0.8
Central Appalachians	1.1	0.3	83.8	14.8
Western Allegheny Plateau	1.2	1.4	80.9	16.5
Interior Plateau	2.6	8.2	82.3	6.9
Interior River Valleys and Hills	0.2	0.8	78.6	20.4

^aSpecies types are combinations of USDA Forest Service, Forest Inventory and Analysis (FIA) forest groups shown on Fig. 1.4

^bMiscellaneous conifer forests may consist of species groups including White/red/jack pine; Spruce/fir; Longleaf/slash pine; Loblolly/shortleaf pine; Pinyon/juniper; Ponderosa pine; and Exotic softwoods

^cOak-conifer forests consist of species in the oak/pine group

^dUpland oak-hickory forests consist of species in the oak/hickory group and includes mesophytic species in a forest type commonly referred to as ‘cove hardwoods’

^eMiscellaneous hardwood forests may consist of species groups including Oak/gum/cypress; Elm/ash/cottonwood; Maple/beech/birch; and Aspen/birch

formation rates are about 1–2 % per year, which may be lower than historical rates and linked to changes in forest regeneration patterns. Gaps vary in size, shape, and rate of closure, all of which combine to produce a fine-scale patchwork of different tree species, ages, diameters, heights, crown spreads, and growth rates. In this volume, Hart (Chap. 2) discusses how fine-scale gap dynamics have historically affected structural and compositional heterogeneity in central hardwood forests.

Tree mortality is periodically accelerated by drought, native insects, or pathogens, resulting in pulses of more, variably-sized ‘gaps’ and potentially affecting forest composition. For example, oak decline, which can be induced by drought in combination with other factors such as low site quality, shoe string fungus (*Armillaria mellea*), or insects such as red oak borer (*Enaphalodes rufulus*), causes progressive crown dieback and eventual death of physiologically mature oaks in the red oak group (*Erythrobalanus* species) (Starkey et al. 2004). Oak decline has been documented across all surveyed central hardwood forest ecoregions (Oak et al. Chap. 3; Table 3.5) (Starkey and Oak 1989), and can impact a few trees in forests with diverse species composition and age structure, to several thousand hectares in landscapes dominated by *Erythrobalanus* species, especially in the

western ecoregions. Southern pine beetle outbreaks in the CHR, also induced by drought, occur at 7 – 25 year intervals and accelerate gap dynamics by killing pines (Nowak et al. Chap. 4; Table 4.1). Historically, these cyclical outbreaks likely created a continuum of perforated forest structure, where pines were killed in mixed pine-oak stands, to large patches of dead trees where pines were dominant, such as on ridge tops dominated by Table Mountain (*P. pungens*) and pitch pine forests. Over the past 80 years, southern pine beetle outbreaks, in combination with decades of suppressing fire (most anthropogenically-ignited), have promoted a gradual shift in the composition of pine or mixed pine-oak-hickory forests (historically influenced by human activities such as burning, grazing, and field abandonment) to predominantly oak-hickory forests. In this volume, Oak et al. (Chap. 3) discuss historic spatial and temporal variability in the occurrence of oak decline, and the probability and severity of oak decline events using models based on regional long-term monitoring surveys, as part of the Forest Vegetation Simulator. Nowak et al. (Chap. 4) discuss the southern pine beetle as an agent of natural disturbance that periodically killed pines in small- to large patches, creating incremental, long-lasting structural heterogeneity across central hardwood forest landscapes.

Historically, some wildlife species also functioned as agents of disturbance. Grazing by elk and bison that once commonly occurred within the CHR likely helped to maintain grass-dominated open woodlands or prairies that probably originated from, and were also maintained by, frequent anthropogenic burning in many cases. Beavers, historically abundant within the CHR, also functioned as ‘ecosystem engineers’ by damming streams and creating large wetlands and ‘beaver meadows,’ providing habitat for amphibians, aquatic reptiles, and birds and mammals associated with wetlands, edge, and moist, grassy habitats (Askins 2000; Greenberg et al. Chap. 12). In this volume, Greenberg et al. (Chap. 12) discuss how some animal species were themselves important agents of natural disturbance that helped to create and maintain heterogeneous habitats within the CHR.

1.4 Agents of Natural Disturbance: Abiotic Process and Severe Weather

Across the CHR, many natural disturbances are directly or indirectly due to severe weather. Individual weather events, such as wind, rain, and ice storms, are influenced primarily by season, latitude, altitude, and proximity to large water bodies. In the eastern USA, most transitory weather events, which last only one or two days, are strongly influenced by the Gulf of Mexico, Atlantic Ocean, and Appalachian Mountains, in addition to the global weather patterns that support their development and decay. Extreme or repeated events can lead to landslides or local flooding. Persistent weather events, such as drought, can last months to years and owe their existence primarily to a stagnant regional weather pattern. The frequency of both persistent (drought) (Table 1.5, Fig. 1.8) and transitory (precipitation and wind) severe weather events (e.g., Peterson et al. Chap. 5) vary over the CHR.

Table 1.5 Total number of years (1895–2013) with moderate ($\text{PDSI}^1 \leq 2$) or severe ($\text{PDSI} \leq 4$) growing season droughts^{a,b} and number of multi-year droughts in the 13 ecoregions^c of the CHR

Ecoregion	Ecoregion area (km ²)	Moderate drought (years)	Severe drought (years)	Total drought (years)	Total multi-year (>2 years) droughts
Ouachita Mountains	26,896	15	2	17	2 (2-years)
Arkansas Valley	28,421	14	0	14	0
Boston Mountains	14,178	14	2	14	1 (2-year)
Ozark Highlands	106,391	14	3	17	1 (5-year)
Piedmont	166,177	17	2	19	2 (3-year) + 1 (2-year)
Northern Piedmont	30,459	12	2	14	1 (2-year) + 1 (4-year)
Blue Ridge Mountains	46,595	9	2	11	2 (2-year)
Ridge and Valley	115,483	10	2	12	1 (2-year)
Southwestern Appalachians	37,994	15	3	18	3 (3-year) + 1 (4-year)
Central Appalachians	62,050	19	2	21	2 (2-year) + 1 (3-year)
Western Allegheny Plateau	81,440	15	1	16	3 (2-year) + 1 (3-year)
Interior Plateau	123,523	20	4	24	4 (2-year) + 1 (3-year)
Interior River Valleys & Hills	120,405	15	7	22	5 (2-year) + 1 (3 year)

^aBased on Palmer's Drought Severity Index (PDSI). Source of PDSI data: <http://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers.php>; Website maintained by Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service, National Climatic Data Center, 151 Patton Avenue, Asheville, NC 28801. Accessed on March 21, 2014, 12:18 PM; data range 1895–2013

^bPDSI (1895–2013) defined based on average summer (June, July, August) PDSI from one climate division per ecoregion. Moderate is $\text{PDSI} -2.0$ to -3.99 , and severe is $\text{PDSI} \leq -4.0$. Data columns here include total number of years (whether single- or multiple successive years) with drought, and number of multiple, successive-year droughts

^cFrequencies in this table are not adjusted for per unit area of each respective ecoregion (Fig. 1.1). Comparisons of frequencies among ecoregions should first adjust for different ecoregion sizes

Persistent severe weather events, such as drought, occur with stagnant regional weather patterns, which are almost always associated with a stalled high pressure system at low- and mid-levels in the atmosphere. When stagnant high pressure occurs during the warm season, it often is accompanied by anomalously warm temperatures, which accelerate drying at the ground. Drought is also self-perpetuating, in that evaporation and evapotranspiration slow or cease as the soil and vegetation become increasingly dry, causing the atmosphere to become drier. Relief from drought only comes when the regional weather pattern shifts to bring humid air and precipitation sufficient to saturate the ground. Often, an active tropical cyclone season will provide enough humid air and accompanying precipitation to 'break' a drought, allowing water tables to begin to return to normal levels. Although the CHR usually receives enough precipitation to balance evapotranspiration, drought occurs sporadically throughout the region (Fig. 1.8) and transient summer drought is common on sites with sandy or thin soil. Severe growing season drought func-

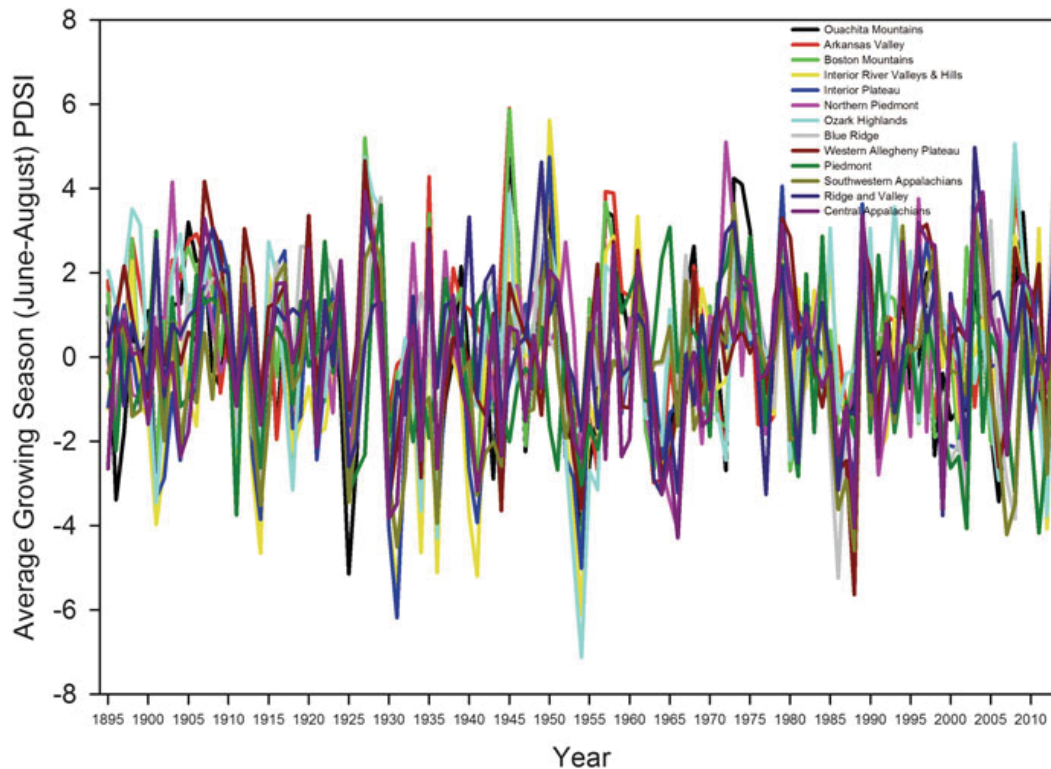


Fig. 1.8 Annual growing season (June-August) Palmer's Drought Severity Index (PDSI) in ecoregions of the CHR. PDSI ≤ 2 is considered moderate, and PDSI ≤ 4 is considered severe

tions as a natural disturbance both directly, by killing trees, and indirectly, by increasing vulnerability of weakened trees to pathogens and pests (such as oak decline or attack by southern pine beetles), windthrow, or breakage from subsequent severe weather events. Rare climatic events such as intense drought can initiate a pulse of recruitment following heavy tree mortality at the CHR scale, with effects on forest composition, age class, and structure lasting for centuries (Pederson et al. 2014). Droughts also increase the threat of wildfire.

Transitory severe weather events range in scale from convective storms (e.g., thunderstorms and squall lines) that last up to six hours, to tropical storms (e.g., dying hurricanes) that last a day or two, to large-scale mid-latitude storms that last three to five days. On the small end of the spatial spectrum, convective storms affect tens of km, while large-scale mid-latitude storms cover thousands of km. The speed of motion of these storms also varies, from stalled (zero km per hour) to 121 km per hour. At all scales, transitory storms are capable of producing damaging precipitation and wind.

Wind is produced in transitory convective weather events such as thunderstorms and squall lines when a cold downdraft of air encounters the ground and is forced to move horizontally. The winds at the edge of the downdraft air, called the 'gust front,' sometimes produce sufficient damage to be mistaken for a tornado. Destructive downdrafts are more common outside of the Appalachian Mountains, as storms are often disrupted as they cross the mountain chain. Air circulations

within the parent convective storm can produce tornadoes, which, like downdrafts, are more common away from the mountains (Peterson et al. Chap. 5; Figs. 5.3, 5.4). Damaging wind is also produced during transitory large-scale mid-latitude and tropical severe weather events when there are large gradients in atmospheric pressure; that is, when centers of strong high pressure and deep low pressure are close to each other. Large-scale mid-latitude storms are capable of producing strong winds in any region of the eastern USA. When there is a stable layer at mid-levels of the atmosphere, an intense pressure gradient can drive strong winds across the spine of the Appalachian Mountains after passage of a large-scale mid-latitude storm toward the northeast. These winds drive downslope windstorms, usually in the cool season, along the eastward-facing slopes of the Appalachian Mountains. Tropical storms primarily affect ecoregions closest to the Gulf of Mexico or Atlantic Ocean, as dying hurricanes rapidly lose their intensity after landfall, thus reducing the strength of the pressure gradient and the winds (Peterson et al. Chap. 5, Table 5.1, Fig. 5.2). High winds can create single- or multiple-tree windthrows that form small- to large gaps, or widespread, nearly complete destruction across large areas. For example, in the southern Appalachians, reports of timberland damage from remnants of Hurricane Hugo (1989) indicate that up to 25 % of trees were damaged (windthrown or blown tops) on 31,255 ha of timberland, and 25–50 % of trees were similarly damaged on an additional 1,769 ha in Ashe, Avery, and Watauga Counties, North Carolina (Dogett 1993). Further, heavy precipitation often accompanies high wind, saturating the soil and increasing the vulnerability of shallow-rooted trees to windthrow (Coutts et al. 1999). In this volume, Peterson et al. (Chap. 5) examine patterns and consequences of wind disturbance in central hardwood forests.

Damaging precipitation involves either (1) flooding, where runoff associated with precipitation exceeds the transport capacity of channels (see Leigh et al. Chap. 8); (2) mudslides and/or debris flows caused by high pore water pressures in steep, shallow soils (see Wooten et al. Chap. 9) or; (3) receiving precipitation in a form (e.g., ice, snow, or hail) that excessive accumulation can cause the loss of limbs or entire sections of trees (see Lafon Chap. 7). Excessive rainfall can occur in the eastern USA at any time of year due to stalled or slow moving convective storms, weather fronts, tropical storms, or large-scale mid-latitude storms. Excessive precipitation can also occur in the central hardwood ecoregions located on the windward side of the Appalachian Mountains when humid air masses are forced upward, either triggering a convective storm or enhancing pre-existing large-scale upward motion to produce a localized region of heavy precipitation. Excessive rainfall can result in floods, and, in hilly or mountainous regions (e.g., Blue Ridge Mountains, Ridge and Valley, and Southwestern Appalachians ecoregions), landslides and debris flows (Tao and Barros 2014). For example, heavy rainfall from tropical and extra-tropical cyclones triggered hundreds to thousands of debris flows on steep slopes in 1916 (North Carolina), 1940 (North Carolina), 1969 (Virginia, West Virginia), 1977 (North Carolina), 1985 (Virginia, West Virginia) and 2004 (North Carolina); rainfall from other more localized storms in these and other years triggered tens to hundreds of debris flows. Debris flows can carry whole trees, rocks, and soil (Band et al. 2012; Tao and Barros 2014), altering forest structure and hydrology by creating large canopy gaps and disrupting aquatic ecosystems. Forest

cover is an important stabilizing factor through precipitation interception, evapotranspiration, and root reinforcement. Landslides can increase recruitment of early successional tree species, leading to persisting patches of early successional vegetation in older forests (Seiwa et al. 2013). In this volume, Wooten et al. (Chap. 9) examine the historical frequency and spatial patterning of landslide events, and their influence on forest structure, and Leigh (Chap. 8) examines paleoenvironmental floods and fires in the Blue Ridge Mountains.

Excessive accumulation of frozen precipitation can occur during the warm (hail) and cool (ice and snow) seasons. Excessive hail accumulation is most likely in central hardwood ecoregions located away from the coastlines of the Gulf of Mexico and Atlantic Ocean, and west of the Appalachian Mountains (Ouachita and Boston Mountains, Arkansas Valley, Ozark Highland, Western Allegheny and Interior Plateau, Interior River Valleys and Hills ecoregions), where mid-level dry layers that promote hail production are more likely. Ice storms can occur in any region of the eastern USA when the cold or warm front of a transiting large-scale mid-latitude storm moves in the vicinity during the cool season. Another scenario that commonly contributes to excessive ice accumulation occurs along the eastward-facing slopes of the Appalachian Mountains (Piedmont, Northern Piedmont, Blue Ridge Mountains, and Ridge and Valley ecoregions). Surface high pressure located over the northeastern USA in the winter and early springtime often forces a dome of cold air against the slopes of the eastward-facing Appalachian Mountains, sometimes called ‘cold air damming’ or a ‘wedge,’ and in the presence of a precipitating mid-latitude storm, can result in excessive ice accumulation. Ice storms also can be restricted to a ‘belt’ within an altitudinal range that extends for several km (e.g., Ashe 1918), and forests on exposed slopes are most often affected. Ice storms can affect large areas. For example, a 1987 ice storm damaged trees across an estimated 12,140 ha, and 60 % of the 482 km of trails were blocked by fallen trees in the Pisgah District of the Pisgah National Forest in the southern Appalachians (Osborne 1987); heavy ice storm damage covered an area approximately 270 km long and up to 170 km wide in eastern Arkansas through northern Mississippi, and in 2000 two ice storms damaged approximately 40 % of the 7.4 million ha of forest in Arkansas (see Bragg et al. 2003). In general, ice storms can create fine-scale to intermediate structural heterogeneity in forests, depending on the severity of damage to trees, the number of trees, and the area affected. In this volume, Lafon (Chap. 7) examines the historical frequency and range of damage by ice storms in the CHR.

Lightning-ignited fires are relatively uncommon in central hardwood forests (Table 1.6) (Mitchener and Parker 2005; Guyette et al. 2006a; Cohen et al. 2007). When they do occur, they are most frequent along ridgetops, or dry south-facing slopes where microclimates are more conducive to burning (Delcourt and Delcourt 1997; Harmon 1982). Not coincidentally, fire-adapted plant species such as Table Mountain pine, pitch pine, and others are also found primarily in these dry, low quality, more fire-prone sites (see Chaps. 6, 10, 11). Fire frequency is strongly associated with human populations, giving further indication that human ignitions were likely the source of most fires in central hardwood forests (Guyette et al. 2006a, b; Greenberg et al. Chap. 12). Fire reconstruction studies using soil charcoal or tree ring analyses indicate that fire frequencies vary among ecoregions, landscapes, and

Table 1.6 Mean $\pm$ SE annual number of reported^a human-caused and lightning-ignited wildfires (1970–2013; n = 44 years)^b per 2,000 km² in National Forests of the CHR

National forest	Area ^c (km ²)	Ecoregion(s) ^d	Mean $\pm$ SE (range) annual number of human-caused wildfires per 2,000 km ²	Mean $\pm$ SE (range) annual number of lightning-ignited wildfires per 2,000 km ²
Bankhead NF	733.4	Southwestern Appalachians	52.1 $\pm$ 6.2 (8.2–199.1)	1.1 $\pm$ 0.4 (0.0–13.6)
Chatahoochee NF	3,036.2	Blue Ridge Mountains & Ridge and Valley	51.7 $\pm$ 5.6 (14.5–171.3)	2.5 $\pm$ 0.4 (0.0–13.2)
Cherokee NF	2,658.4	Blue Ridge Mountains	73.2 $\pm$ 7.8 (13.5–227.2)	3.8 $\pm$ 0.8 (0.0–27.8)
Daniel Boone NF	2,269.6	Central Appalachians	93.7 $\pm$ 8.0 (26.4–268.8)	1.8 $\pm$ 0.4 (0.0–13.2)
George Washington NF	4,311.4	Ridge and Valley & Northern Piedmont	12.9 $\pm$ 1.3 (2.3–38.0)	2.9 $\pm$ 0.5 (0.0–11.1)
Hoosier NF ²	820.8	Interior Plateau	60.4 $\pm$ 11.4 (7.3–180.3)	1.0 $\pm$ 0.5 (0.0–9.7)
Jefferson NF	2,928.0	Blue Ridge Mountains	16.1 $\pm$ 1.5 (3.4–44.4)	2.0 $\pm$ 0.3 (0.0–8.9)
Mark Twain NF	6,040.4	Ozark Highlands	65.8 $\pm$ 5.3 (14.6–207.3)	1.1 $\pm$ 0.2 (0.0–6.6)
Monongahela NF	3,728.6	Central Appalachians	4.8 $\pm$ 0.5 (0.0–17.2)	0.4 $\pm$ 0.1 (0.0–2.1)
Nantahala NF	2,150.2	Blue Ridge Mountains	46.0 $\pm$ 3.4 (10.2–103.2)	2.7 $\pm$ 0.5 (0.0–14.9)
Oconee NF	472.5	Piedmont	34.1 $\pm$ 5.0 (0.0–152.4)	4.2 $\pm$ 1.2 (0.0–42.3)
Ouachita NF	7,236.8	Ouachita Mountains & Arkansas Valley	25.4 $\pm$ 1.8 (6.6–60.8)	5.9 $\pm$ 0.7 (0.8–18.5)
Ozark NF	4,609.7	Boston Mountains	28.9 $\pm$ 2.1 (7.8–66.8)	2.5 $\pm$ 0.4 (0.0–15.6)
Pisgah NF	2,076.4	Blue Ridge Mountains	52.7 $\pm$ 10.3 (9.6–392.0)	4.2 $\pm$ 0.7 (0.0–17.3)
Shawnee NF	1,076.7	Interior River Valleys and Hills	58.0 $\pm$ 6.6 (3.7–219.2)	0.5 $\pm$ 0.2 (0.0–5.6)
Sumter NF	1,501.0	Piedmont & Blue Ridge Mountains	27.6 $\pm$ 2.7 (6.7–98.6)	3.1 $\pm$ 0.6 (0.0–17.3)
Talladega NF	1,597.4	Piedmont	69.7 $\pm$ 5.6 (20.0–180.3)	7.8 $\pm$ 1.1 (0.0–30.0)
Uwharrie NF	205.0	Piedmont	77.6 $\pm$ 6.7 (0.0–195.2)	1.3 $\pm$ 0.6 (0.0–19.5)
Wayne NF ²	971.9	Western Allegheny Plateau	90 $\pm$ 15.2 (12.3–240.8)	0.3 $\pm$ 0.2 (0.0–4.1)

^aSource: Fire Family Plus (database): (Main et al. 1990)^bData for Hoosier NF and Wayne NF reported 1994–2013 (n = 20 years)^cSource: USDA Forest Service (2013) Land areas of the National Forest system. USDA For Serv FS-383, Washington DC^dSee Fig. 1.1; the majority of National Forest area is within the ecoregion listed first in table

even specific sites (Hart and Buchanan 2012). In this book, Leigh (Chap. 8) uses river valley sediments and soil charcoal to examine the paleoenvironmental range of variation in floods and fires, and Grissino-Mayer (Chap. 6) uses fire reconstruction data to examine historical fire frequencies in yellow pine and mixed pine-hardwood forests of the southern Appalachians, and how fire (whether lightning- or human-caused) helped to shape the composition and distribution of these forest types across the landscape.

1.5 Disturbance and Diversity: Adaptation and Distribution Across a Dynamic Landscape

Historically, background (gap dynamics) and pulses of natural disturbances through time have been integral in shaping structurally diverse forests and maintaining a diversity of flora and fauna. Anthropogenic disturbances, such as clearing and frequent burning by Native Americans, and later by European settlers, were also essential in maintaining diverse biotic communities. The occurrence and persistence of disturbance-adapted species of flora and fauna provides clues that disturbances historically created structural conditions with sufficient spatial and temporal frequency to sustain them, although their distributions and populations likely ebbed and flowed over time, and across landscapes. In plants, traits such as shade intolerance (e.g., yellow-poplar and yellow birch (*Betula alleghaniensis*)) or serotiny (e.g., Table Mountain pine), are clues that open forest conditions were continuously available historically, in quantities adequate to sustain them. Similarly, the association between fire-adapted plant species and fire-prone topographic positions suggest that fire was sufficiently common on those landscapes to sustain fire-adapted traits. Narrow habitat requirements by some animal species, such grassy sites with absent canopy (e.g., Eastern meadowlark (*Sturnella magna*) at lower elevations, or golden-winged warblers at higher elevations), or forests with open-canopy conditions and snag availability (e.g., Eastern bluebirds (*Sialia sialis*)), are clues that such sites were available historically. In this volume, Wilfahrt et al. (Chap. 11) explore the relationship between disturbance-adapted traits in tree species, productivity, and disturbance. Tuttle et al. (Chap. 10) use 1930s vegetation surveys and recent data to compare historic and current variation in forest structure and composition caused by natural and anthropogenic disturbances in the Great Smoky Mountains National Park. Greenberg et al. (Chap. 12) discuss how natural disturbances might have influenced the historic distribution patterns and relative abundance of disturbance-adapted wildlife species in the CHR, and suggest that humans functioned as a keystone species by creating suitable habitats in sufficient quantities and varieties to enable the persistence of a wide range of disturbance-adapted species.

1.6 Managing Central Hardwood Forests of Today and Tomorrow Within the Historic Range of Variation in Natural Disturbances

Today's central hardwood forests are different from those of yesterday. In general, forests are younger, reduced in area, more fragmented, isolated by surrounding urban development, and, in many cases, different in species dominance from the forests of 200 years ago. The historic structure and function of forests is further threatened by the introduction of non-native pests and pathogens, some of which have decimated entire tree species such as the American chestnut and, currently, eastern hemlock (*Tsuga canadensis*). Additionally, climate change could alter the severity and frequency of natural disturbances, such as severe storms, fires, droughts, floods, and insect outbreaks. Managing today's forests within the historic range of variation in natural disturbances may not be possible given their altered current condition and possible future condition in a changing environment. Further, managing solely for HRV in natural (non-anthropogenic) disturbances may not be adequate for attaining important objectives, such as sufficient habitat with specific and differing structural conditions (e.g., oak woodland or prairie) required by many disturbance-adapted plant and animal species. An important step in forest planning will be clear and careful definition of management objectives and desired reference conditions, which may or may not be entirely 'natural,' particularly if human activities that historically created different types of disturbed habitats used by disturbance-adapted species are not considered natural. In this volume, Dale et al. (Chap. 13) discuss climate change and the future of natural disturbance regimes, and Zenner (Chap. 14) concludes with a discussion of whether today's forests can, or should, be managed within the historic range of variation in natural disturbance, and silvicultural tools for attaining specific management objectives.

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