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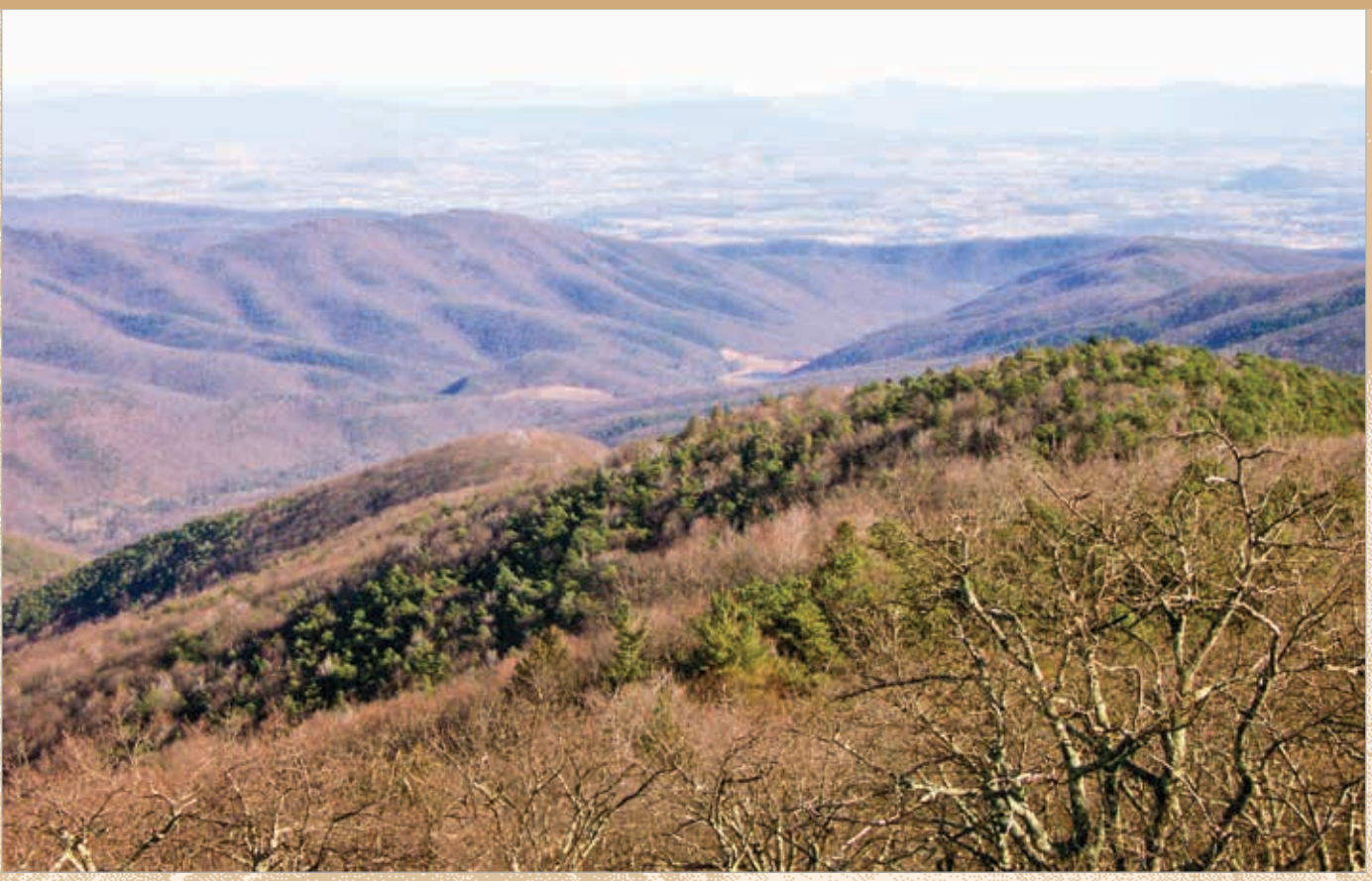
Fire History of the Appalachian Region:

A REVIEW AND SYNTHESIS

Charles W. Lafon, Adam T. Naito, Henri D. Grissino-Mayer,
Sally P. Horn, and Thomas A. Waldrop



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Cover photo

View to the east from the top of Reddish Knob on the Virginia-West Virginia border, George Washington National Forest. In this photo can be seen the oak-pine mosaic that is the typical vegetation cover on mountain slopes in the Ridge and Valley province. The pine stands are dominated by Table Mountain pine (*Pinus pungens*) and pitch pine *(Pinus rigida*), some of which have been scarred by fires in the past. These fire-scarred trees are a valuable source of information about fire history. The Reddish Knob fire history site discussed in this report is located on the slope to the south (right) of the pond in the middle ground. The Shenandoah Valley and the Blue Ridge Mountains lie in the background.

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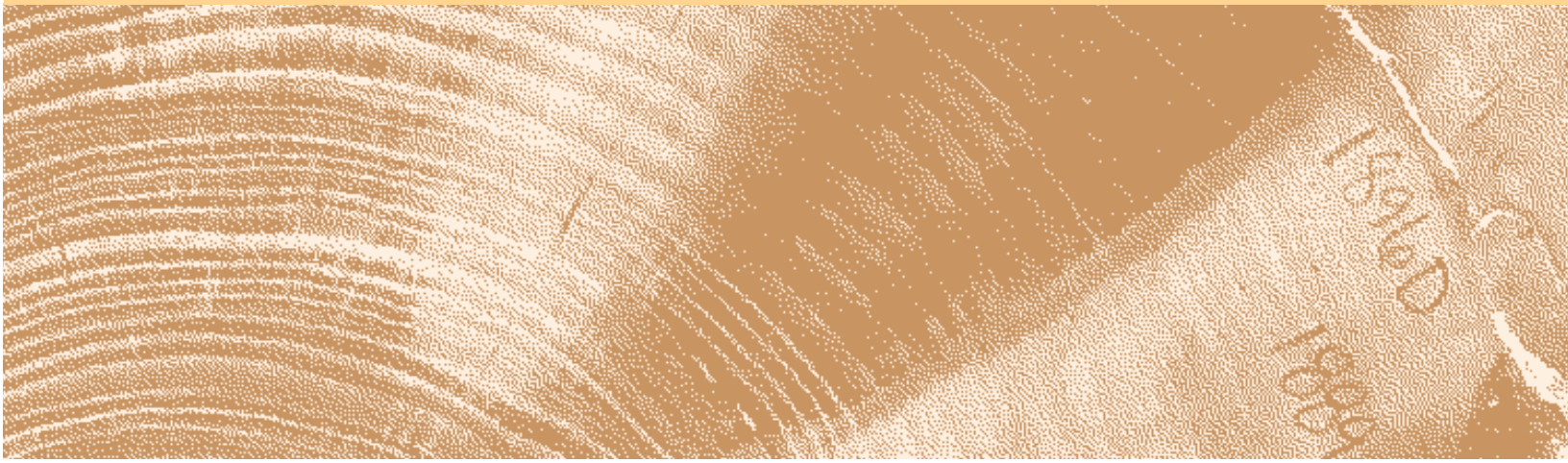

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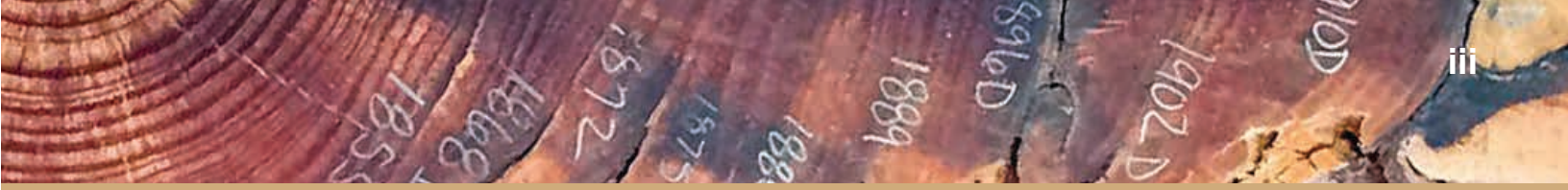
Abstract

The importance of fire in shaping Appalachian vegetation has become increasingly apparent over the last 25 years. This period has seen declines in oak (*Quercus*) and pine (*Pinus*) forests and other fire-dependent ecosystems, which in the near-exclusion of fire are being replaced by fire-sensitive mesophytic vegetation. These vegetation changes imply that Appalachian vegetation had developed under a history of burning before the fire-exclusion era, a possibility that has motivated investigations of Appalachian fire history using proxy evidence. Here we synthesize those investigations to obtain an up-to-date portrayal of Appalachian fire history. We organize the report by data type, beginning with studies of high-resolution data on recent fires to provide a context for interpreting the lower-resolution proxy data. Each proxy is addressed in a subsequent chapter, beginning with witness trees and continuing to fire-scarred trees, stand age structure, and soil and sediment charcoal. Taken together, these proxies portray frequent burning in the past. Fires had occurred at short intervals (a few years) for centuries before the fire-exclusion era. Indeed, burning has played an important ecological role for millennia. Fires were especially common and spatially extensive on landscapes with large expanses of oak and pine forest, notably in the Ridge and Valley province and the Blue Ridge Mountains. Burning favored oak and pine at the expense of mesophytic competitors, but fire exclusion has enabled mesophytic plants to expand from fire-sheltered sites onto dry slopes that formerly supported pyrogenic vegetation. These changes underscore the need to restore fire-dependent ecosystems.

Keywords: Age structure, Appalachian Mountains, charcoal, fire history, fire regime, fire scars, witness trees.



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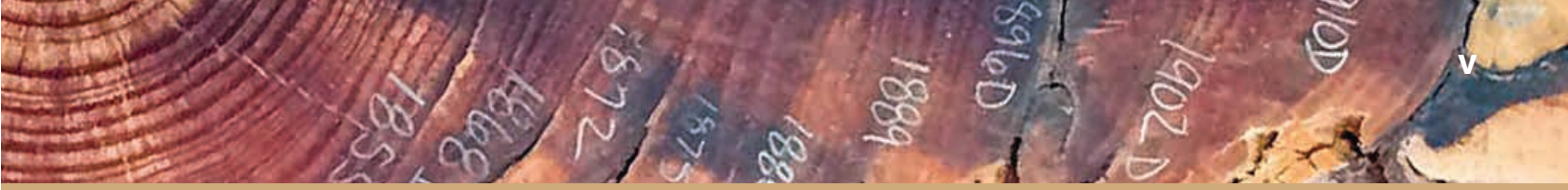

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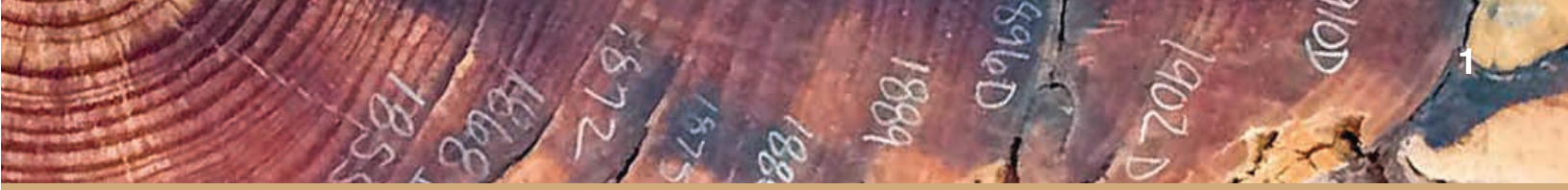


Chapter 1. Introduction

WHAT ROLE HAS FIRE PLAYED IN APPALACHIAN VEGETATION DEVELOPMENT?

The last 25 years have witnessed a surge of scientific interest in Appalachian fire history. Much of this attention can be traced to concerns over the declining abundance of important ecosystems, especially the widespread and ecologically important oak (*Quercus*)- and pine (*Pinus*)-dominated forests (e.g., Brose and others 2014, Nowacki and Abrams 2008, Williams 1998). These forests are dominated by trees with fire adaptations such as thick bark, extensive hypogeal roots, rot resistance, and serotinous cones: traits that enable the trees to withstand fire or recolonize soon after a burn. The abundance of overstory trees with these traits suggests that the forests developed under a history of burning.

Fires sometimes occur today but not at their former frequency or scale because prevention and active suppression have curtailed their ignition and spread. The absence of fire appears to be favoring a regional shift in vegetation toward maples (*Acer* spp.) and other mesophytic taxa that are not well adapted to recurrent fires, especially at short intervals (Nowacki and Abrams 2008). In light of this broad vegetation shift, it has been hypothesized that fires were a common disturbance before the advent of effective fire prevention and suppression (e.g., Abrams 1992, Brose and others 2001, Lorimer and others 1994, Williams 1998). To assess this hypothesis, researchers have collected evidence about past burning from several proxy sources, notably witness trees used in original land surveys, fire scars that formed on trees injured by fire, establishment dates of trees in the stands containing fire-scarred trees, and charcoal that has accumulated in soil and sediments.

Nearly all this research has been conducted within the last 25 years, and most of it within about the past decade. A literature review published in 1990 (Runkle 1990) suggested that at that time, fires and other broad-extent disturbances were understood to have largely been confined to the peripheries of eastern North America's temperate forest region: places such as the pine woods along the Gulf and Atlantic Coastal Plains and the forests' western margins along the prairie border. Nearly all studies of disturbance in the core of the region—including Appalachia—had been focused on small treefall gaps. Recently, however, a different picture has begun to emerge, one in which fire played a prominent role in vegetation development before the era of fire prevention and suppression.

In this report, we review and synthesize the research on fire history to characterize what is known today about fire in the central and southern Appalachian region and how burning has varied over time. We include fire history research from the Appalachian Plateau, the Ridge and Valley province, the Blue Ridge Mountains, and the Piedmont (fig. 1.01). The Appalachian Plateau makes up the western part of the Appalachian highlands. It is a region underlain by almost horizontal sedimentary rock layers of Paleozoic age, although in some areas the layers have been deformed (Shankman and James 2002). The bedrock has been dissected, producing rugged terrain of modest elevation in most places. The plateau is covered primarily with mixed mesophytic forest, which transitions into northern hardwood forest in northern Pennsylvania and New York. Northern hardwood and red spruce (*Picea rubens*) forests also extend southward into the high elevations along the eastern edge of the plateau in West Virginia, where elevations reach 4,800 feet.

The Ridge and Valley province lies to the east of the Appalachian Plateau. It is a mountainous region where long, parallel valleys have been eroded into folded and faulted sedimentary bedrock of Paleozoic age (Shankman and James 2002). The valleys alternate with ridges that attain elevations as high as 4,700 feet in western Virginia. These ridges are covered primarily with oak-dominated forest, although composition varies with topography and elevation, resulting in a complex mosaic of oak-dominated

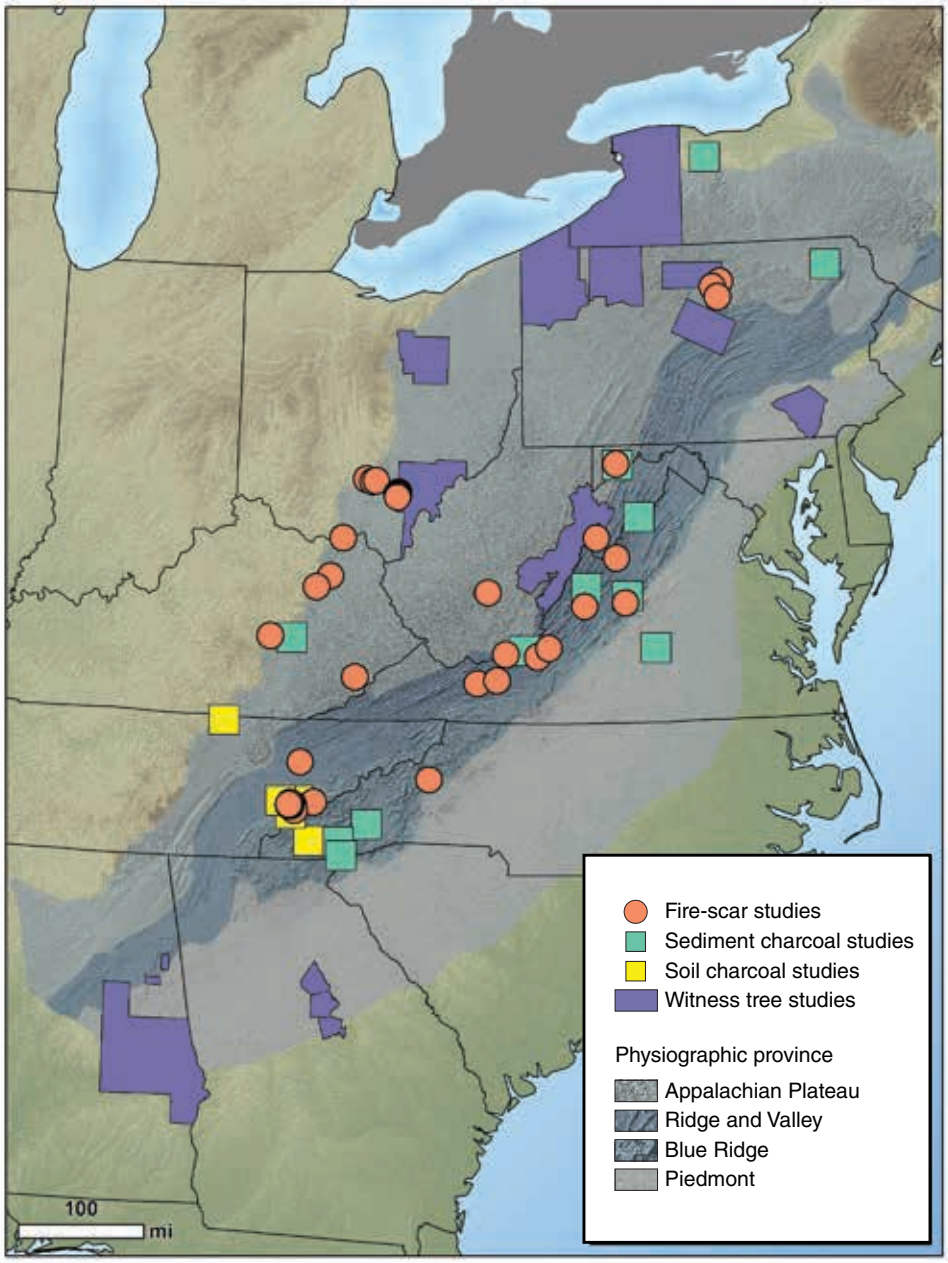


Figure 1.01—Location of study sites in published studies from which data were mined and/or synthesized for this report. Purple polygons denote study areas for witness tree records. Orange circles indicate the locations of fire-scar study sites. Teal and yellow squares show locations of sediment and soil charcoal samples, respectively. The four physiographic provinces of the Appalachian region are indicated in blue-gray.

stands alternating with pine-dominated stands on the driest sites and mesophytic stands in moist coves and high elevations. The eastern section of the Ridge and Valley province consists of the Great Valley, the widest valley in the province.

The Blue Ridge Mountains rise above the Great Valley and form the eastern ramparts of the Appalachian Mountains. The Blue Ridge bedrock is primarily metamorphic rock of Precambrian and Paleozoic age (Shankman and James 2002). North of Roanoke, VA, the Blue Ridge province is quite narrow (only 9–12 miles in width in places), but it broadens southward toward North Carolina and Tennessee, where it contains numerous high ranges that attain elevations of nearly 6,700 feet. The Blue Ridge Mountains are covered primarily with oak-dominated forest but with topographic and elevational variations resembling those of the Ridge and Valley province. In general, however, mesophytic forests have a greater extent in the Blue Ridge Mountains than in the Ridge and Valley province, and the high elevations permit the existence of extensive stands of northern hardwoods and spruce-fir (*Picea-Abies*).

The Piedmont province is a hilly region of fairly low elevation (mostly less than about 1,000–1,500 feet) situated between the Blue Ridge Mountains and the Atlantic Coastal Plain. The Piedmont is underlain by metamorphic and igneous bedrock of Precambrian age (Shankman and James 2002). The forests of this region are dominated by a mix of oaks and other hardwoods, as well as pines.

The mountainous core of the region—the Ridge and Valley province and the Blue Ridge Mountains—has been the primary focus for fire history researchers. These areas contain the highest relief and the largest concentration of public lands in the Eastern United States and therefore provide considerable opportunities for restoring fire-favored vegetation. As for the Piedmont, it is often not considered part of the Appalachian region, but it is linked to the Appalachian Mountains—geologically, ecologically, and culturally—and by including it here, we are able to report fire history information from a few additional studies.

ORGANIZATION OF THIS REPORT

To contextualize what has been learned from the various fire history datasets that we discuss in this report, we begin in this introductory chapter by sketching a general history of human fire use and how this burning appears to have affected Appalachian vegetation. Although lightning ignites some fires in the region (Lafon and others 2005, Lynch and Hessl 2010), anthropogenic ignitions are more common at present and are thought by most researchers to have played the dominant role in the past as well (e.g., Aldrich and others 2014, Hessl and others 2011). The human control over fire is also exemplified by the near absence of fire during the exclusion era. Therefore, conceptual models of Appalachian fire and vegetation history align strongly with human land use episodes. These conceptual models provide a framework for situating the fire history studies to be synthesized in subsequent chapters.

In chapter 2, we begin our deeper exploration with the best understood period of fire history, the most recent few decades within the fire-exclusion era. Fires cannot be entirely excluded, and a sufficient number of fires occurs today to permit us to detail the present fire regime—the typical patterns of fire frequency, extent, seasonality, and severity, and the relationships between fire and climate. This knowledge will help us interpret the proxy records of past fire regimes.

In chapter 3, we focus on the evidence provided by witness trees, which offer a glimpse of tree species distribution at the time of European settlement. These records can help determine whether fire-dependent trees, such as pine and oak, were widespread before European settlement. Although such vegetation patterns do not provide direct evidence of past fires, they afford an indirect assessment by showing the extent of fire-dependent tree species.

Chapter 4 addresses the direct evidence of fire history provided by tree-ring dating of fire scars on trees that were wounded by fires but subsequently healed. Dated fire scars offer the most detailed records available of fire history over the last few centuries. Researchers use the scars and tree rings in sections from fire-scarred trees to estimate fire interval, fire seasonality, and fire-climate relationships. Fire-scarred trees also provide some evidence about the spread of fire over Appalachian landscapes.

Additionally, tree-ring dating is used to estimate forest age structure, the topic of chapter 5. By characterizing age structure, researchers gain insights into past fire severity and learn how vegetation responded when the fire regime was altered, for example, during the era of fire exclusion.

Obtaining a longer record of past fires requires the analysis of charcoal in soils or sediments, the topic of chapter 6. Charcoal fragments can be quantified and directly or indirectly dated by using radiocarbon analyses to estimate the level of fire activity over several centuries to millennia, albeit at a coarser temporal and spatial resolution than data from fire-scarred trees. Further, pollen grains recovered from sediment cores reveal the broad vegetation changes that coincided with variations in fire activity.

Chapter 7 offers conclusions based on these records. Taken together, the various lines of evidence, although differing in resolution and extent, demonstrate that fire played a crucial role on Appalachian landscapes for several centuries to millennia until the abrupt decline in fire activity during the exclusion era.

CONTEXT: A SKETCH OF APPALACHIAN FIRE HISTORY

The Past Century

A hundred years ago, forests were being logged in every corner of Appalachia (Ayres and Ashe 1905, Clarkson 1964), and fires burned widely through the cutover lands, threatening forest recovery. Logging technologies had developed rapidly with industrialization, beginning in the Northeast, where the timber was largely exhausted by about 1860 (Williams 1989). Industrial logging then spread to the Great Lakes region, accelerating as new technologies emerged, and by 1900 the Great Lakes timber was depleted. From there logging moved to the South, including the southern Appalachian Mountains, where it peaked in 1909 and was virtually complete by 1930 (Williams 1989).

The logging operations left slash strewn over the landscape, providing fuel for catastrophic wildfires (Clarkson 1964, Lafon 2010). Ignition sources were abundant. Lightning undoubtedly ignited some fires, but most were apparently set by humans. Log trains threw out sparks, and local residents fired the cutover

lands to promote pasture grasses and blueberry production, or to reduce populations of snakes, ticks, and chiggers. Concerned that forests would fail to regenerate under the incessant burning, the Forest Service, U.S. Department of Agriculture, and State foresters sought to deter fire through a campaign of prevention and suppression (Pyne 1982, Sarvis 1993). These efforts often provoked local resistance, including incendiarism, but wildfire detection and suppression were largely succeeding by the early to middle 20th century. Through labor- and capital-intensive campaigns against wildfire, the incidence of fire plummeted. Forest vegetation rebounded in Appalachia and throughout eastern North America, and today the region contains the largest area of temperate forest remaining on Earth.

The foregoing synopsis of fire history is well understood qualitatively. Quantitative characterizations of the fire regime during the industrial logging period are not widely available, but old silvicultural reports provide some indications. For example, in assessing the potential for a system of Appalachian forest reserves (later, national forests) in the southern Blue Ridge Mountains, Ayres and Ashe (1905) traveled the roads and trails across an area of 10,000 square miles taking notes, measuring timber, and mapping forest extent and timber condition in every stream basin. Fire was an important focus of their attention. Frequent surface fires had killed tree seedlings and saplings on about 80 percent of the land area. Springtime burning was practiced so regularly in some watersheds that fires occurred at intervals of only 1 or 2 years.

The heavy and widespread burning that occurred around the turn of the 20th century undoubtedly favored plant species that are well adapted to resist fire or to reproduce in the aftermath of fire. Among trees, the Appalachian endemic Table Mountain pine (*Pinus pungens*) and the commonly associated pitch pine (*P. rigida*) are the best suited to such a fire regime. Both species have thick bark and resinous wood that resists rot when injured by fire (Williams 1998). Table Mountain pine typically bears serotinous cones. At present, forest stands dominated by one or both species are common as small patches—generally only a few acres in extent—within a hardwood forest matrix. The pine stands usually occupy dry south- or west-facing mountain slopes and ridges, where fire and poor soils likely created an environment that thwarted the establishment of most hardwood tree species.

The existence of these pines and other fire-adapted species implies a long history of burning in the Appalachian region, but the extent of such vegetation before the industrial logging phase is not well known. According to a conceptual model of Table Mountain pine–pitch pine stands developed by Williams (1998), the stands were largely restricted to rock outcrops and other xeric sites before European settlement and under the sparse human populations of early settlement. As settlements then crept into marginal farm lands in more remote valleys, burning increased on the adjacent mountainsides, and the pine stands gradually expanded. Yet according to Williams' model, it was the logging episode that enabled pine forests to expand widely across deforested mountain slopes. Today, the pine stands are shrinking. Most have been heavily encroached by hardwood shrubs, primarily mountain laurel (*Kalmia latifolia*); by oaks, especially chestnut oak (*Quercus montana*); and by red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), white pine (*Pinus strobus*), and a few other tree species.

Williams' (1998) model of the dynamics of Table Mountain pine and pitch pine stands can be viewed as a hypothesis about fire history, i.e., that fire activity increased over the course of settlement, peaked during industrial logging, and plummeted as fire prevention and suppression gained success. Indeed, a similar conceptual model was published by Brose and others (2001) with specific reference to the Appalachian oak forests (fig. 1.02). Because the dominant Appalachian oaks thrive under periodic surface fires, Brose and others estimated that fires occurred regularly, typically at intervals of perhaps a decade, under aboriginal habitation and throughout White settlement until the latter half of the 19th century. This long period of regular burning was followed by a spike in fire frequency and severity during the logging episode. Fire activity subsequently declined under fire exclusion.

Was Fire Common Before the Logging Episode?

At the time the foregoing models were developed, only the last two fire history episodes in each were understood with any certainty—fires were known to have been common during industrial logging and to have become much less common under the fire exclusion that followed. The fire regimes before the

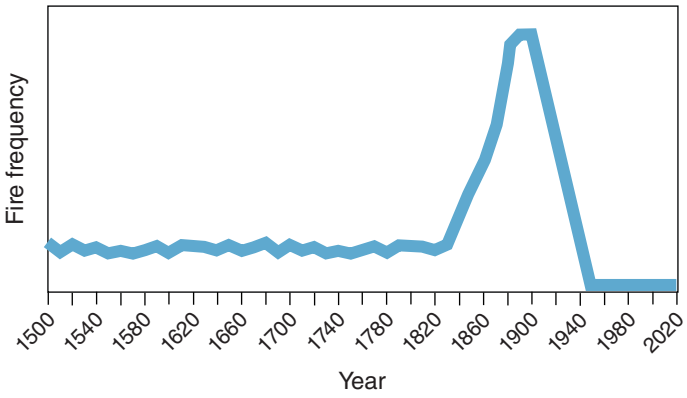


Figure 1.02—Conceptual model of Appalachian fire history, after Brose and others (2001). According to this model, fires occurred regularly during aboriginal habitation and European settlement before spiking in frequency during the industrial logging episode of the late 1800s. The spike was followed by a rapid decline in fire frequency during the fire exclusion era that began in the early to mid 1900s.

logging episode differ in the two models. The Brose and others (2001) model proposes frequent and fairly steady burning for at least the last few centuries. The Williams (1998) model, in contrast, suggests that fire activity was limited before European settlement and did not increase until White populations had risen and expanded their influence in the middle to late 19th century. Which, if either, model is correct?

Aboriginal Burning Before European Settlement

Resource managers and scientists alike have focused considerable attention on the "presettlement" fire regime of the Eastern United States (e.g., Brown 2000, Day 1953, Frost 1998, Russell 1983). What was the role of fire before European settlement? Did Native Americans burn frequently across much of the region, or was their influence limited to the vicinity of their villages? How broadly did they affect plant distributions? This presettlement emphasis reflects a management goal of restoring the landscape states that existed before European settlers had altered them. It also links to the concept of climax (Clements 1936), the natural vegetation that would develop under a particular climate in the absence of disturbance. The climax concept dominated ecological thought and management practice over much of the 20th century, but once fires and other disturbances had been recognized as common events on presettlement landscapes, a strict climax interpretation was precluded. Nonetheless, presettlement burning and its influence on the vegetation have continued to attract much interest.

The vegetation, fire regimes, and human cultures that were encountered by the first European visitors to North America had developed over the Holocene, the geological epoch and interglacial period in which we live, which began 11,700 years ago. During the previous Pleistocene Epoch, large ice sheets had repeatedly covered much of the continent, and the major biomes of eastern North America had shifted generally southward and downslope under cool glacial climates, with migration reversing during warmer interglacial periods (Graham 1999). The last continental ice sheet to cover North America reached its maximum extent during the last glacial maximum between 26,500 and 19,000 years ago (Clark and others 2009). At this time, ice covered the northern Appalachian region as far south as northern Pennsylvania and Ohio, and boreal forest dominated by spruce (*Picea*), fir (*Abies*), and jack pine (*Pinus banksiana*) prevailed over much of the Appalachian region (Graham 1999). The Holocene saw a dramatic rise in temperature. The ice sheet melted and vegetation shifted northward and upslope. Boreal relicts became confined to the high peaks of the Appalachian Mountains, and temperate broadleaf forests came to dominate most of the region.

Human impacts on the land intensified through the Holocene. During the late Pleistocene and early Holocene, hunter-gatherers lived in small, nomadic family groups (Delcourt and Delcourt 2004, Kehoe 1981). These people may have exerted strong influences on their environment, despite sparse populations and primitive technology, possibly driving mammoths and other large mammals to extinction. By roughly 9,500 years ago, people with more sophisticated social organization and localized cultures had emerged, marking the beginning of the Archaic archaeological period (Delcourt and others 1986). Human influences on vegetation likely increased during the late Archaic, with the domestication of plants such as sunflower (*Helianthus annuus*), goosefoot (*Chenopodium berlandeieri*), squash (*Cucurbita pepo*), and marshelder (*Iva annua* var. *macrocarpa*), and as Native Americans transitioned from foragers to farmers (Delcourt and Delcourt 2004, Smith 1989). Fire was used for cooking, warmth, and driving game (Delcourt and Delcourt 1997), and forest fires set purposefully or by accident likely promoted oak, chestnut (*Castanea dentata*), and pine.

During the Woodland Period (2,800–1,000 years ago), Native Americans in North America developed agriculture, pottery, textiles, and trade networks (Delcourt and others 1986). Their populations were likely concentrated, and burning and agricultural activities occurred in close proximity to dwellings (Anderson 2001, Chapman and others 1982, Cridlebaugh 1984, Delcourt and others 1998, Kneller and Peteet 1993). Maize (*Zea mays*) arrived from Mesoamerica (Smith and Yarnell 2009) and became a critical crop by the middle and late Woodland Period (Munoz and others 2010).

More sedentary lifestyles and permanent settlements emerged in the Appalachian region during the Mississippian Period (1,000–300 years ago), when temple mounds and large, protected villages were constructed (Blitz 1999, Delcourt and others 1986, Schroeder 1999). Agricultural activities were intensive and widespread through the region (Cridlebaugh 1984, Delcourt and others 1986, Fritz 1990), with maize constituting a significant portion of the diet and holding ritual significance (Schroeder 1999). Farming necessitated the use of fire for clearing the land, particularly near settlements, and promoted the development of open landscapes (Cridlebaugh 1984, Delcourt and Delcourt 1998, Delcourt and others 1986) and forest dominance by oak, chestnut, and pine (Delcourt and Delcourt 1998). Compilations of eyewitness accounts made by early European travelers suggest that landscapes of eastern North America had many small prairie openings and some extensive grasslands (Bartram 1794, Rostlund 1957), which were maintained in part by fire. The high diversity of endemic grassland species in the Southeastern United States suggests that they are natural features that were originally maintained by lightning-ignited fires (Noss 2012); however, they likely expanded under aboriginal burning.

The role of Native Americans in structuring their environments through fire and other technologies has been widely debated. Many writers and scholars have argued that Native Americans minimally altered their environment and that forests of eastern North America existed in largely primeval condition before

Europeans appeared (e.g., Bakeless 1950, Clements 1936). Others (e.g., Denevan 1992, Rostlund 1957) have proposed that Native Americans had thoroughly humanized the continent before European arrival, with fire as the means through which their impact was extended beyond the immediate environs of their settlements. But how often or how widely these fires might have burned is largely a matter of conjecture. Heavy impacts may have been concentrated around the most densely populated sites, leaving large areas of uninhabited mountainous terrain virtually untouched (e.g., Matlack 2013, Williams 1998; cf. Allen 2002).

What is clear is that the aboriginal impact declined after European contact, which ushered in the Historic Period (300 years ago until present) and brought disease, war, and social disruption that led to the collapse of native populations (Denevan 1992, Egloff and Woodward 2006, McEwan and others 2011). Depopulation was not necessarily followed immediately by European settlement. Some areas of Appalachia and the Eastern United States probably remained unoccupied for many decades or even a century or more in advance of White settlement. Consequently, some researchers have proposed that these early settlers encountered landscapes where fire was less frequent and vegetation more "pristine" than it had been a century earlier (e.g., Denevan 1992).

Fire History During and After European Settlement

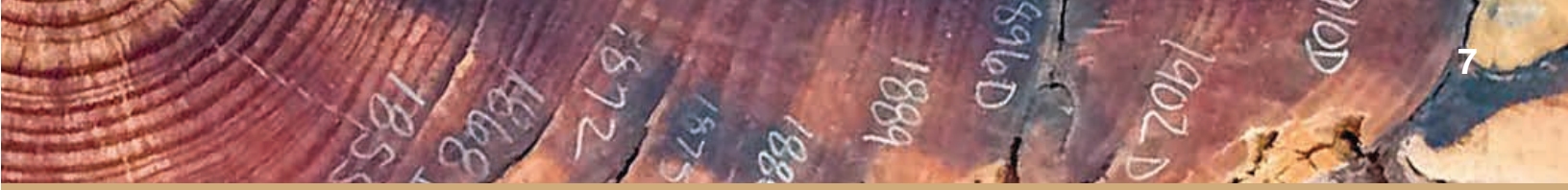
White settlement began at different times in different areas of Appalachia. The lower (northern) Shenandoah Valley, for example, saw settlement in the early 18th century (Meinig 1986, Mitchell 1972), but for much of the region beyond the major valleys, settlement did not begin until around 1800, and marginal lands on mountainous terrain were never populated to any large extent. Even fairly remote areas were probably touched by anthropogenic fires, however, at least on occasion. Many Appalachian settlers were of rural English or Scotch-Irish descent, a background that included a heritage of burning to facilitate hunting and open-range livestock herding (Johnson and Hale 2002). These burning traditions were perpetuated in the New World, with the result that a culture of extensive burning emerged in Appalachia and the South.

This woods-burning tradition remained intact as populations rose and as the wave of industrial logging and mining spilled across the region in the late 19th century (Pyne 1982). Logging would have facilitated traditional land uses, especially livestock herding, by opening the forest and promoting the growth of forage and berries. Therefore, many of the fires that coincided with the industrial logging epoch were probably ignited by local herdsmen, not necessarily by the loggers or log trains. This burning continued after the wave of logging had passed. By inhibiting forest regeneration, the wildfires became a powerful motivator for fire prevention and suppression during the early 20th century.

Fast forward to the present, and we find that fire exclusion has been more successful than early foresters might have expected a century ago. But this success has its drawbacks, as recognized by many researchers and resource managers. Forest density and canopy closure have increased to the point that fire-favored trees, especially oaks and pines, are failing to reproduce and are being replaced (Lorimer and others 1994, Nowacki and Abrams 2008, Williams 1998). These genera are important for wildlife habitat, timber, and aesthetics, and as the canopy dominants die, they are being replaced by mesophytic species such as red maple that have colonized the shaded forest understory in the absence of fire. Other desirable plants, such as blueberries (*Vaccinium* spp.), have also waned while thickets of mountain laurel and rhododendron (*Rhododendron* spp.) have expanded. Such changes have prompted a considerable amount of recent research on fire ecology and fire history, and have motivated resource managers to implement prescribed burns to attempt to restore fire-dependent ecosystems.

Purpose of This Report

The present situation calls for a synthesis of the various strands of Appalachian fire history research to consolidate recent gains in knowledge and to ensure that resource managers have ready access to this knowledge. These needs provide the underlying motivation for our synthesis report. Most fundamentally, the report addresses the history and geography of fire in the Appalachian region to elucidate the role that fire has played in shaping Appalachian ecosystems. The report is particularly concerned with understanding the importance of fire before the exclusion era. Were fires common in the past? If so, were they primarily limited to the industrial logging episode, or did they occur frequently for a longer time? These overarching questions link to additional topics, such as the relationship of fire to climate, the role of anthropogenic versus lightning ignitions, and the vegetation shifts that have accompanied changes in the fire regime. By tackling these questions, we intend to provide insights that will benefit researchers, managers, and anyone else with an interest in the role of fire on Appalachian landscapes.



Chapter 2. The Current Appalachian Fire Regime

INTRODUCTION

We begin our examination of Appalachian fire history by characterizing the current fire regime. This is the regime of fire exclusion. Although this report focuses on evidence about the history of fires before the exclusion era, we begin with the current fire regime because of the availability of certain data that cannot be obtained from fire scars or other proxy records of fires that occurred before the exclusion era. The exclusion-era data provide a number of details—e.g., size of burn, date of fire, cause of ignition—that improve our ability to interpret the proxy records of earlier fires.

Fire incidence data are routinely collected for the lands managed by the Forest Service, National Park Service, and other land management agencies. Even though fires occur less commonly today than in the past, this exclusion-era record of fire permits answers to questions that are difficult or impossible to address using proxy data. For example, are fires associated with particular climatic or weather conditions? Do fires burn preferentially in certain types of terrain? Do spatial patterns of human- or lightning-ignited fires emerge across the Appalachian region? If so, are they related to any specific physical or cultural features?

Exploring such questions will establish a context for interpreting the proxy records of earlier fire regimes. For example, the fire-scar data to be discussed in chapter 4 indicate that past fires occurred mostly during the "dormant season" when trees were not growing new wood. This dormant period would include part or all of fall, winter, and spring. The probable timing of scar formation within the broader dormant season can be narrowed down through comparisons with the current fire regime, which shows predictable relationships with the seasonal cycles of weather and plant phenology. These cycles were probably similar in the past, and therefore the knowledge gained from the current fire regime helps us account for the seasonality of fire scars formed in previous centuries.

CONTROLS OF THE FIRE REGIME

For fire to ignite requires the interaction of three elements—fuel, oxygen, and heat—that are represented in the fire triangle (Parisien and Moritz 2009) (fig. 2.01). Fire occurs when the three elements are present at the proper levels to initiate combustion. Once begun, combustion can proceed until one or more of the three elements is removed. A fire regime reflects the degree to which the elements of the fire triangle are present on a landscape and whether those elements vary over space and time. Thus, for example, the conceptual models of Appalachian fire history (Brose and others 2001, Williams 1998) shown in the previous chapter imply that one or more of the elements has been changed by people over time. In fact, people have affected both the fuel and heat components of the fire triangle. They have altered the vegetation—fuel—in numerous ways that have at times promoted fire and at other times discouraged it. They have also ignited fires at some places and times and have sought to prevent ignitions at others. Additionally, they have applied water or other retardants to reduce the temperature of fires and bring them under control. The various combinations of these activities have contributed to the fire-regime changes proposed in the conceptual models.

Figure 2.01—The fire triangle. All three components (i.e., oxygen, heat, and fuel) of the triangle must be present for fire to occur.

Humans are not the only control over the elements of the fire triangle, however. The natural features of a landscape—its climate, terrain, and vegetation—also determine the levels at which the elements are present and how they vary spatially and temporally (Parisien and Moritz 2009). Consequently, fire regimes are related in consistent ways to the natural features of the Earth's surface. Three generalizations seem particularly important. First, places with moderately wet climates have greater fire activity than places that are extremely wet or dry (Meyn and others 2007, Parisien and Moritz 2009, Sauer 1950). Moderately wet environments—e.g., temperate and tropical grasslands and Mediterranean shrublands—receive enough precipitation to support continuous vegetation cover and fairly heavy fuel production. Dry climates, in contrast, typically support too little vegetation to fuel a fire, whereas in wet climates the vegetation usually remains too wet to burn.

Second, in any given environment, fire activity fluctuates over time with variations in weather and climate (Lafon and Quiring 2012, Meyn and others 2007). Even fire-prone ecosystems in the middle range of the precipitation gradient are not constantly flammable, although the nature of the fire-climate relationship differs over the broad range of intermediate climates. Humid ecosystems, including many temperate forests, become most flammable under drought conditions (e.g., Lafon and others 2005). On the other hand, moderately dry ecosystems, such as low- and mid-elevation forests and woodlands of the Southwestern United States, witness more burning after years with anomalous wetness; flammability is increased due to the production of fine fuels (during wet periods) that subsequently dry and become receptive to the ignition and spread of fire (e.g., Ireland and others 2012).

Third, burning occurs most frequently on landscapes with large fire compartments. A fire compartment is an area with continuous fuel through which a fire can spread unimpeded by streams, cliffs, or other firebreaks (Frost 1998). Large fire compartments often characterize flat terrain, where fires can sweep unimpeded across extensive uplands. Fire compartments are commonly smaller in hills and mountains because topographic complexities create fire breaks that limit the size of fires. All else equal, a landscape with smaller fires would burn less often than a landscape with larger fires. That is, small fires yield a long fire cycle.

Fire cycle is the number of years that would be required for fires to burn an area equivalent to the entire landscape (i.e., calculated as the reciprocal of the mean annual proportion of total land area burned) (Heinselman 1973). It is also known as fire rotation. If fires are small, they simply need a long time for their acreages to add up to an area the size of the landscape, unless the small fires are ignited at a very high density across the landscape.

Fire cycle is related to fire interval because it reflects the average fire interval for all points on the landscape (Kou and Baker 2006, Ward and others 2001). For example, a fire cycle of 10 years would indicate that each point on the landscape burns once every 10 years, on average, although this cycle might actually result in some parts of the landscape burning once every 5 years and other parts at longer intervals. Fire cycle and fire interval are essential measures of a fire regime because they influence how much fuel accumulates between successive fires and which plant species can colonize between one fire and the next.

CURRENT APPALACHIAN FIRE CYCLE

Agency fire statistics can be used to estimate the current fire cycle by tallying the total acreage burned during the years for which the data were collected. Such calculations demonstrate that Appalachian fire cycles are long under fire exclusion. Fire statistics for the southern Blue Ridge Mountains of Tennessee and North Carolina (Barden and Woods 1974) show that human-ignited wildfires burned 14,176 acres within Cherokee National Forest and Great Smoky Mountains National Park between 1960 and 1969. The size of these two federally managed lands is 1,120,000 acres, or 79 times the acreage burned over the decade. To burn an area equivalent to the entire area, therefore, would require 79 decades, or 790 years. A 790-year fire cycle far exceeds the fire cycle/fire interval thought to have existed before fire exclusion (cf. Brose and others 2001). The fire cycle for lightning-ignited wildfires was even longer: 28,500 years for Great Smoky Mountains National Park, based on data for 1960–1971, and 10,427 years for Cherokee National Forest, based on data for 1960–1969. A recent study (Flatley and others 2011) obtained comparable results using a longer (77-year) record of wildfires that burned Great Smoky Mountains National Park between 1930 and 2003: a cycle of 1,257 years for anthropogenic fires, 25,397 years for lightning-ignited fires, and 1,197 years for both ignition sources combined.

Further north in eastern West Virginia and western Virginia, a 34-year record of wildfires (Lafon and others 2005) yielded a similarly long fire cycle for an area spanning parts of the Appalachian Plateau, Ridge and Valley province, and Blue Ridge Mountains within Monongahela and George Washington National Forests, part of Jefferson National Forest, and Shenandoah National Park. The fire cycle was 1,001 years based on the combined record of human- and lightning-ignited wildfires between 1970 and 2003. Considering anthropogenic ignitions alone yielded a fire cycle of 1,196 years, and lightning ignitions gave a cycle of 6,138 years.

Shorter fire cycles have been calculated for some areas. A 70-year record of fires that occurred across the entire State of West Virginia from 1939 to 2008 yielded a statewide fire cycle of

192 years (Lynch and Hessl 2010). This record was compiled by the West Virginia Division of Forestry and includes fires that burned on private and State-owned lands, but not Federal lands. Therefore, it excludes the National Forest data analyzed by Lafon and others (2005). Similarly, a fire cycle of 204 years was obtained for Shenandoah National Park in the Blue Ridge Mountains of Virginia for the years 1930–2003 (Flatley and others 2011). But even these fire cycles are quite long compared to the shorter cycles of about a decade that are proposed for the pre-exclusion fire regime (e.g., Brose and others 2001).

If we ignore the precise fire cycle calculations and their variations between studies, the broad-brush picture that emerges is that the Appalachian region has witnessed little burning over the last few decades. Fire apparently is rare today because of the fire prevention and suppression campaigns waged since the early 20th century and because of the change in vegetation from flammable forests, woodlands, and grasslands to farm land and to less flammable forests containing mesophytic species (e.g., Harrod and others 2000, Nowacki and Abrams 2008). Fire prevention has undoubtedly reduced the density of ignitions, while suppression and landscape fragmentation (by farms, roads, etc.) have kept most fires small. If fires are kept small, most of the landscape will remain unburned for a long time (Ward and others 2001). The exclusion of large fires is the primary reason that fire cycles are so long today.

Examining the statistical distribution of fire size underscores the importance of large fires for the fire regime. In any fire regime, a handful of the largest fires are responsible for most of the area that is burned (Pyne 1982). The fire size distribution typically shows strong positive skew, where numerous small fires burn an acre or two apiece but contribute little to the overall fire regime while a handful of larger fires achieve most of the burning. For National Forest and National Park lands noted above in eastern West Virginia and western Virginia, a total of 1,557 anthropogenic wildfires occurred between 1970 and 2003 (Lafon and others 2005). These fires burned 75,248 acres, giving a mean fire size of 48 acres. However, the median fire size was only 1 acre. Fires of 1 acre or less burned a total of only 276 acres, or less than 1 percent of the entire acreage burned during the 34-year period. In contrast, the single largest fire of 16,015 acres accounted for 21 percent of the total area burned during the period. Lightning ignitions showed a similar pattern, although fewer of them occurred (344 fires) and the maximum size was only 2,934 acres; the relatively limited extent of the fires explains why lightning-ignited fires had a longer cycle than anthropogenic fires.

GEOGRAPHIC VARIATIONS IN BURNING ACROSS THE APPALACHIAN REGION

The fire cycles documented here do not apply uniformly across the Appalachian region. Pronounced geographic differences are evident. These differences have been investigated for the previously mentioned area of eastern West Virginia and western Virginia by separating the fire statistics according to physiographic province (Lafon and Grissino-Mayer 2007). On the western side, Monongahela National Forest, which is located primarily on the high eastern edge of the Appalachian Plateau, witnessed exceptionally long fire cycles—10,845 years for all fires combined and 12,216 years and 96,637 years for anthropogenic and lightning-ignited fires, respectively. The fire cycles for the Ridge and Valley province to the east were shorter: 1,274 years for all fires combined, 1,472 years for anthropogenic fires, and 9,461 years for lightning-ignited fires. Fire cycles declined still farther to the east, where the Blue Ridge Mountains had fire cycles of 284 years for all fires, 347 years for anthropogenic fires, and 1,560 years for lightning-ignited fires.

This spatial gradient in fire cycle corresponded to a gradient in fire size (Lafon and Grissino-Mayer 2007). The fire size-class distribution became increasingly skewed from west to east for both ignition sources, with the Blue Ridge Mountains experiencing especially large fires. The maximum size of anthropogenic fires increased from 237 acres on the Appalachian Plateau to 4,357 acres in the Ridge and Valley province and 16,015 acres in the Blue Ridge Mountains, whereas the corresponding maximum sizes for lightning-ignited fires were 141 acres, 551 acres, and 2,934 acres.

These spatial variations in fire cycle and fire size reflect differences of terrain, vegetation, climate, or human activities (Lafon and Grissino-Mayer 2007). The climate is cool and moist on the high eastern edge of the Appalachian Plateau, standing as it does in the path of eastward-moving storms. Orographic enhancement of the precipitation makes this one of the wettest and snowiest areas in the Eastern United States. The rain and late-lying snow probably keep the litter moist during much of the spring and thwart the ignition and spread of fire, and the mesophytic forests that cover most of the landscape yield relatively incombustible leaf litter.

The Ridge and Valley province is a drier environment. It stands in the rain shadow of the Appalachian Plateau, which intercepts moisture from the west, and of the Blue Ridge Mountains, which impede Atlantic moisture from the east (Lafon and Grissino-Mayer 2007). Therefore, the Ridge and Valley province has

the driest climate within the region, and its mountain slopes generally have well-drained, nutrient-poor soils derived from weathered sandstone and shale bedrock.[1] These environmental conditions have favored the extensive cover of oak- and pine-dominated forests that produce flammable litter. The broad, dry slopes, covered with xerophytic forest, would seem to present large fire compartments that make the Ridge and Valley province conducive to fire.

The Blue Ridge province receives an amount of precipitation similar to the Appalachian Plateau (Lafon and Grissino-Mayer 2007), and it has nutrient-rich soils with good water retention that are derived from weathered metamorphic rocks (see footnote 1). Therefore, its flammability must reflect factors other than the moisture conditions in this environment (Lafon and Grissino-Mayer 2007). Fuel and terrain are probable contributors because the Blue Ridge Mountains also have broad slopes covered with oak- and pine-dominated vegetation. Precipitation variability is another potential factor. According to one hypothesis (Lafon and Grissino-Mayer 2007), differing regimes of precipitation delivery are more important than the mean annual precipitation in governing the geographic differences in fire across the Appalachian region. Subsequent work (Lafon and Quiring 2012) supports this hypothesis. In particular, the Appalachian Plateau has relatively frequent, but light, precipitation events, which probably rewet the litter regularly enough that it is difficult for fires to ignite or spread. To the east, precipitation delivery becomes increasingly irregular so that in the Blue Ridge Mountains, and to some extent in the Ridge and Valley province, heavy precipitation events are separated by many consecutive rain-free days that permit fuels to dry and fires to ignite and spread. Thus, even though annual precipitation totals are similar between the Appalachian Plateau and the Blue Ridge Mountains, the differences in precipitation frequency seem to contribute to the vastly different fire regimes. In fact, the study of Lafon and Quiring (2012) shows that the link between burning and precipitation variability applies beyond the Appalachian Mountains to the entire temperate-forest region of the Eastern United States.

Climatic differences contribute to additional variations in fire activity across the Appalachian region. A comparison between Great Smoky Mountains and Shenandoah National Parks (Flatley and others 2011) shows that more burning occurs in the latter, with a fire cycle of 204 years, compared to 1,197 years in the former. These differences probably stem in part from the moister climate of the southern Blue Ridge Mountains. They could also reflect differences in human access. The narrow shape of Shenandoah National Park would seem to place more park perimeter near human activities and possibly expose the park to more human ignitions compared to Great Smoky Mountains National Park. However, the location of fires relative to the park boundaries suggests just the opposite—a greater percentage of fires was concentrated near the border of Great Smoky Mountains National Park compared to the percentage near Shenandoah National Park borders. Thus, human influences along the border are stronger for the Great Smoky Mountains. The differences in fire activity between the two parks appear, therefore, to reflect climatic differences.

A more probable influence of human ignitions on spatial patterns can be seen within the Appalachian Plateau. The analysis of West Virginia fires noted above (Lynch and Hessl 2010) depicted a gradient in which far more burning occurred in the southwestern part of the State than elsewhere between 1939 and 2008. Large fires (> 125 acres) were numerous in the southwest but virtually absent from the rest of the State. The southwest alone yielded a fire cycle of only 97 years, an unusually short fire cycle for a suppressed fire regime. Because the southwest is not the driest part of West Virginia, Lynch and Hessl (2010) proposed that non-climatic factors contributed to the widespread burning in that region: first, activities associated with widespread coal mining operations may have ignited many of the fires. Second, traditional cultural uses of fire may have persisted longer in southwestern West Virginia than elsewhere. Third, the rugged terrain may have hindered fire suppression. This last explanation seems to contradict the general understanding that fires grow larger on flat terrain than steep terrain, but that generalization probably applies best to unsuppressed fires. In the case of suppression, fires might spread farther on inaccessible terrain than on flatter, more accessible lands.

The cluster of large fires in southwestern West Virginia is part of a broader cluster extending southward along the Appalachian Plateau through Kentucky and Tennessee (fig. 2.02). This is one of the most extensive zones of burning in the entire Eastern United States, but whether it reflects the human influences and topographic constraints proposed by Lynch and Hessl (2010) is not known.

FIRE WEATHER AND CLIMATE

Implicit in considering wildfire in a humid region is that bouts of dry weather must occur periodically so that fuels can dry enough for fires to ignite and spread. Research conducted in temperate forests of the Northeastern United States (Pennsylvania, Wisconsin, and Michigan) (Haines and others 1983) demonstrates that the probability and number of fires can be predicted from basic weather variables (relative humidity or number of consecutive days since precipitation) or from fire-weather indices that incorporate multiple weather variables (precipitation, relative humidity, temperature, and wind speed).

[1] Personal communication. April 21, 2016. Steven Q. Croy, Ecologist/Fire Planner, George Washington and Jefferson National Forests, U.S. Department of Agriculture Forest Service. 5162 Valleypointe Parkway, Roanoke, VA 24019.

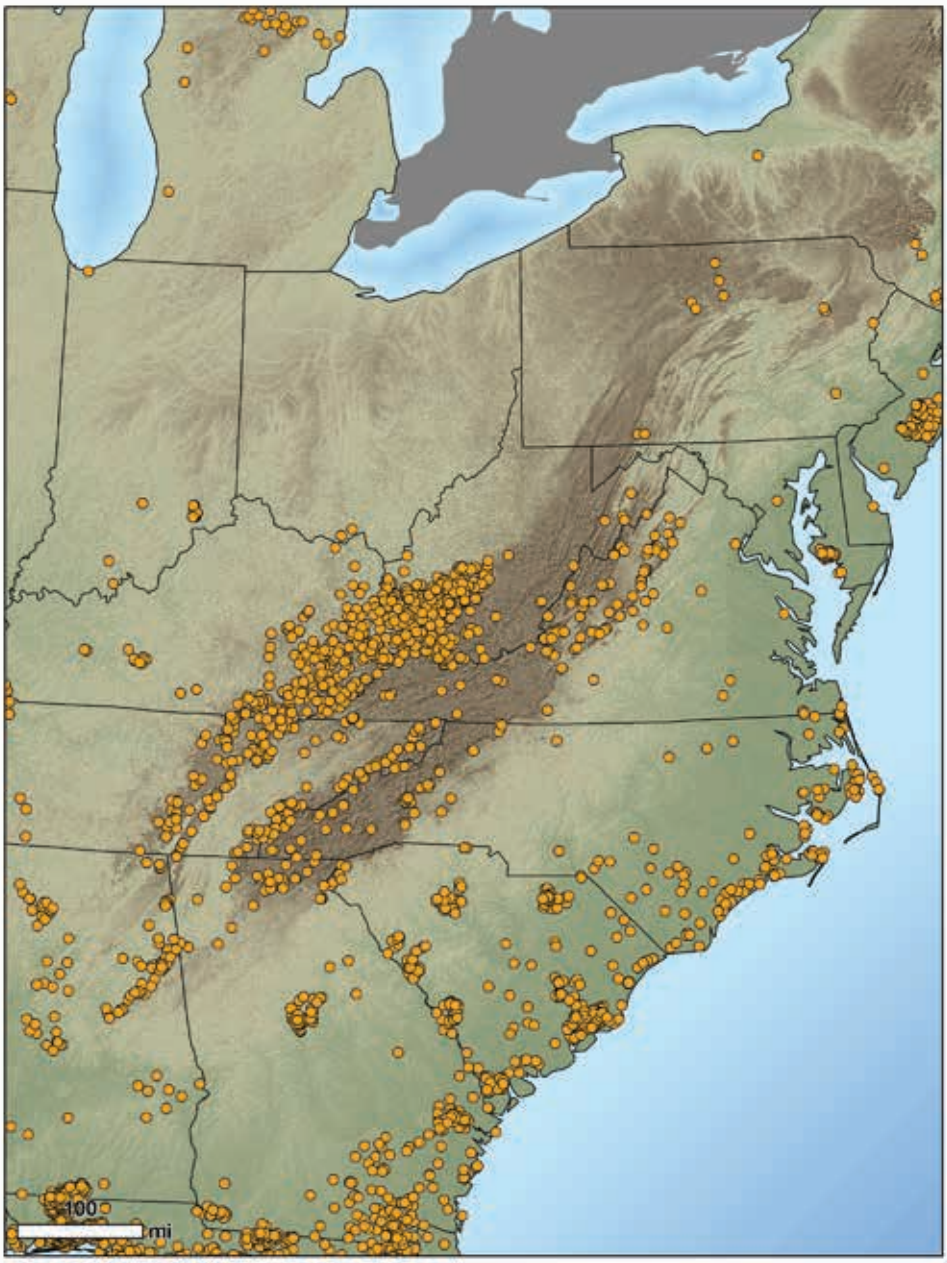


Figure 2.02—Locations (yellow dots) of large fires (> 500 acres in extent) in the Eastern United States for 1984–2014 (from USDA USFS RSAC and USGS EROS 2016; see Eidenshink and others 2007).

We have performed a preliminary analysis of similar nature for the Ridge and Valley province of West Virginia and Virginia, near the center of the study region considered in this report, to explore how the probability of fire is related to dry spells. Specifically, we related the fire occurrence data of Lafon and Grissino-Mayer (2007) to the number of consecutive days without precipitation in at least one of four climate stations in the region. The number of consecutive dry days was calculated for the fire season (defined here as March through November) by using daily precipitation data obtained from the dynamic climate normal product of the National Climatic Data Center (NCDC) for the years 1970–2001. Fires occurred on 673 of the 8,800 days in the record, or about 8 percent of all days, suggesting that for any given day there is a probability of 0.08 that fire will occur somewhere within the

1,058,241 acres of National forest land. The fire probability for each day actually varies greatly, however, depending on the number of preceding rain-free days (see fig. 2.03) using equation (1):

$$P(F) = 0.0124D + 0.0231 \qquad (1)$$

where $P(F)$ is the probability of fire and D is the number of consecutive dry days. As evident from the y-intercept, the predicted probability of fire on a day when precipitation occurs (i.e., zero consecutive dry days) is approximately 2.3 percent. In cases with one rain-free day (i.e., a single day that has no precipitation but when precipitation occurred the previous day), the predicted probability of fire on that single rain-free day is 3.6 percent. Similarly, on a dry day preceded by 9 consecutive rain-free days (i.e., 10 consecutive rain-free days in total), the predicted probability of fire is 14.7 percent. This strong positive relationship underscores the importance of dry fuels to wildfire occurrence in the humid Appalachian Mountains and also suggests that it would be instructive to conduct a detailed study of Appalachian fire weather.

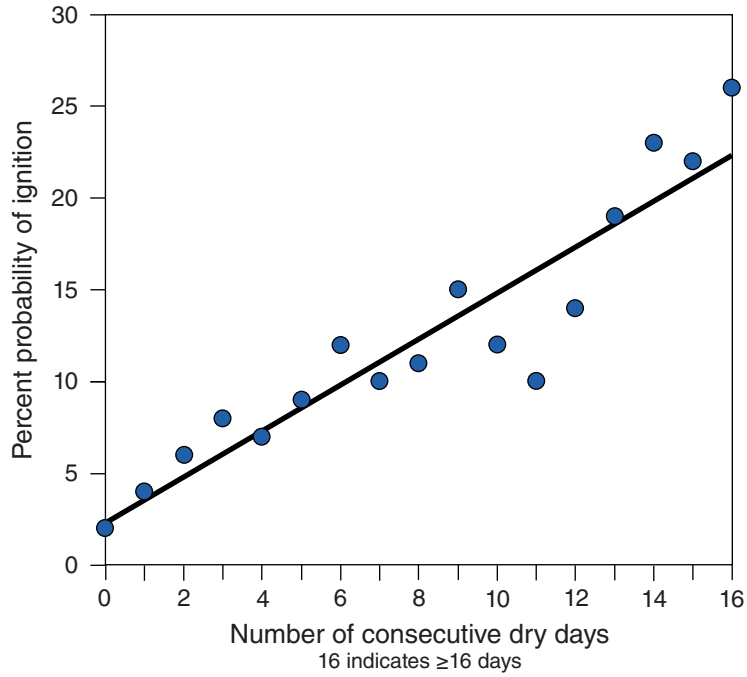


Figure 2.03—Probability of ignition in the National forests in the Ridge and Valley province, West Virginia and Virginia, 1970–2001. Model $R^2 = 0.89$, $F = 115.0$ (df = 1), $P < 0.001$. Probability of ignition increases with the number of consecutive dry days.

Of particular importance to fire weather are the broad, synoptic-scale atmospheric systems that contribute to rain-free days and strong winds. The classic synoptic work on fire weather in the United States is Schroeder and Buck's (1970) handbook, *Fire Weather: A Guide for Application of Meteorological Information to Forest Fire Control Operations.* For regions east of the Rocky Mountains, Schroeder and Buck identified the periphery of surface high pressure systems as providing the most favorable fire weather because they combine dry weather and strong winds. Such weather is most commonly associated with Pacific Highs, which bring mild air masses that originate over the Pacific Ocean but lose much of their moisture by the time they have crossed the continent and arrived in the Appalachian region. The gusty weather at the leading edge of these air masses, along a dry cold front, is particularly favorable for fire. Fire weather can also accompany the cold, dry highs that originate in Canada. Additionally, the subtropical Azores High is especially important in the Southeastern United States, including the southern Appalachian Mountains, because of its tendency to stagnate over the region for a long period. When the Azores High extends westward to Texas, Gulf of Mexico moisture is cut off from the Eastern United States and prolonged drought can develop.

A more detailed synoptic study for the State of West Virginia (Takle and others 1994) identified eight surface patterns common in the Eastern United States and investigated the association of each pattern with fire. Again, periods associated with high pressure were shown to be important, particularly the windy "back-of-high" situation as the high drifts eastward. A terrain interaction occurs under the back of the high with orographic lifting of easterly winds over the eastern slopes of the Appalachian Mountains and drying/warming as air descends the western slopes into West Virginia. Consequently, this synoptic pattern accompanies the most extensive burning in the State. The pattern would not necessarily promote fire in eastern parts of the Appalachian region, however, because the orographic lifting sometimes generates rainfall along the eastern mountains. Additional studies of this sort are needed to understand the fire weather for other parts of the Appalachian region, particularly the Blue Ridge and the Ridge and Valley provinces where most of the federally managed lands are found.

Synoptic weather configurations are embedded in longer-term climatic patterns, and therefore the year-to-year variations in climate alter the occurrence of weather conditions that favor burning. Interannual climatic variations are often associated with global-scale circulation patterns, such as the El Niño–Southern Oscillation (ENSO) phenomenon. Considerable research has been focused on the links between fire activity and ENSO or other circulation patterns in the Western United States

(e.g., Grissino-Mayer and Swetnam 2000) and parts of the Southeastern United States (e.g., Brenner 1991). In Florida, for example, burning often peaks during La Niña years, when dry-season rainfall is below normal (Beckage and others 2003, Brenner 1991, Goodrick and Hanley 2009, Harrison 2004). El Niño years, in contrast, are wetter and less conducive to fire. Analyses of such relationships have largely been lacking for the Appalachian region, but a preliminary investigation for the southern Blue Ridge Mountains (Baker 2009) suggested that anthropogenic fires burn more extensively during La Niña than El Niño years. This finding may reflect the abnormally wet weather that typically accompanies El Niño years in parts of the southern Blue Ridge Mountains (Climate Prediction Center 2016). However, the finding may not apply to other parts of the Appalachian region, where the fall-winter-spring of El Niño years is usually drier and often warmer than normal (Climate Prediction Center 2016).

Correlating interannual variations in fire with annual variations in the Palmer Drought Severity Index (PDSI) (Palmer 1965) underscores the importance of dry conditions for fire in the humid Appalachian Mountains. PDSI, which is calculated by using a water-balance approach, assumes negative values under dry conditions and positive values under wet conditions. Measures of Appalachian fire activity—number of wildfires, area burned, and fire intensity—are negatively related to PDSI, meaning that fire activity increases as PDSI declines toward drier conditions (Baker 2009, Lafon and others 2005, Mitchener and Parker 2005, Yaussy and Sutherland 1994). It is clear that temporal variations in climate and weather have an important influence on Appalachian burning, but more work is needed to gain a thorough understanding of the relationships among fire, drought, synoptic weather events, and global-scale atmospheric circulations.

IGNITION SOURCE AND SEASONALITY

Whether fires are ignited by people or lightning is of interest because it pertains to the question of what is "natural" and how "natural vegetation" is maintained. Does lightning ignite enough fires to maintain fire-dependent vegetation such as pine and oak stands? Or are such communities merely artifacts of past human logging and burning?

These are difficult questions that cannot be fully answered with the data that are currently available. The questions connect to a larger debate about the role of aboriginal burning prior to European settlement (e.g., Denevan 1992, Vale 1998). Subsequent chapters on fire history offer partial glimpses, whereas this chapter provides context by reporting what is known about ignition sources today.

The foregoing discussion of present fire cycles indicates that anthropogenic fire cycles are shorter than those for lightning-ignited fires, primarily because a handful of the anthropogenic fires grow larger than any of the lightning-ignited fires. Anthropogenic ignitions also outnumber lightning ignitions and account for nearly all fires in some areas. Across the State of West Virginia, for example, 99.9 percent of all fires ignited between 2001 and 2008 were caused by people (Lynch and Hessl 2010). Similarly, a study of all the National forests in the Ohio Valley (Illinois, Indiana, Kentucky, Missouri, Ohio, and West Virginia) found that 99 percent of the acreage burned was a result of anthropogenic fires (Yaussy and Sutherland 1994).

Lightning ignitions are a significant part of the fire regime in some parts of Appalachia, however. Lightning seems especially important on the eastern escarpment of the Blue Ridge and along some parts of the western escarpment and Ridge and Valley province (Baker 2009, Lafon and Grissino-Mayer 2007). An analysis of spatial patterns of fire (Lafon and Grissino-Mayer 2007) in the Virginia–West Virginia study area noted above (Lafon and others 2005) revealed that lightning ignitions accounted for a greater proportion of wildfires along the eastern edge of the study area than in the west: 24 percent of fires in the Blue Ridge Mountains, compared with 18 percent in the Ridge and Valley province and only 8 percent on the Appalachian Plateau.

Most lightning-ignited fires and anthropogenic fires alike burn out before growing to a large size, but as discussed above, a few anthropogenic fires grow quite large, and therefore anthropogenic fires contribute more heavily to the fire cycle calculations. Fire seasonality helps explain why anthropogenic fires are responsible for most of the burning in Appalachia. Most anthropogenic fires burn during early to middle spring or in the fall, whereas lightning ignitions largely occur from mid-spring through summer (Baker 2009, Barden and Woods 1974, Lafon and others 2005, Yaussy and Sutherland 1994). The exact timing of the peaks in burning vary geographically over the region, but Appalachian fire regimes can be described generally as having a bimodal (spring/fall) anthropogenic pattern with a smaller unimodal distribution of lightning ignitions (fig. 2.04). The bimodal anthropogenic burning reflects the seasonal cycle of temperature, humidity, wind, precipitation, and plant phenology, which dictate the availability and flammability of fuels (Lafon and others 2005). The two peaks in fire activity coincide with the periods of the year when relative humidity is at its lowest and wind speeds are at their highest. Also, after the deciduous trees shed their leaves, sun and wind can penetrate to the forest floor and dry the dead litter, which is abundant and fluffy in fall and

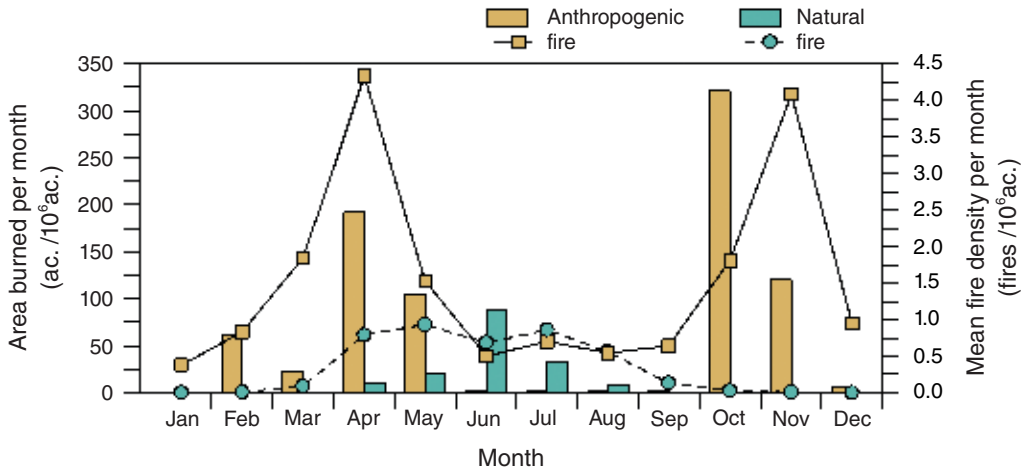


Figure 2.04—Average number of fires (anthropogenic and natural) and area burned per month on federally managed lands of eastern West Virginia and western Virginia, 1970–2003. Based on data from Lafon and others (2005). The occurrence of anthropogenic fires is bimodally distributed, with peaks during spring and fall, whereas the incidence of natural, lightning-ignited fires is unimodally distributed with a peak in late spring-early summer.

spring but less so in summer, when it has become more decayed and compacted. Some of the dead material is derived from herbaceous plants, and by summer much of this dead matter has also decayed and has been replaced by succulent green plants that do not readily burn.

Most lightning strikes occur during the summer when high humidity and closed forest canopy thwart drying of the litter on the surface and when vegetation is succulent and difficult to ignite (Lafon and others 2005). Lightning also usually accompanies rain, and therefore a lightning ignition would appear to require an unusually favorable combination of weather conditions (Lafon and Grissino-Mayer 2007), particularly if it is to spread and burn large acreages before it can be suppressed. Occasionally this happens, but not often. In contrast, people can light fires at any time of year, and therefore human ignitions dominate the spring and fall fire seasons when physical conditions most favor burning.

Lightning ignitions likely played a greater role in the past than at present because frequent burning would have maintained more flammable vegetation consisting of open woodlands with an understory of grasses and shrubs, such as blueberries (*Vaccinium* spp.) (cf. Harrod and others 2000). The fine understory fuels would have dried rapidly after rain, enabling fire to spread from ignition points such as dry snags. Snags commonly serve as ignition points today (Lafon and others 2005). They can hold fire for up to several weeks until the moisture conditions of the surrounding fine fuel become conducive to the spread of fire (see footnote 1). Snags are common in old-growth forests today (Hart and others 2012), particularly on dry sites (McComb and Muller 1983), and they likely were abundant across Appalachian landscapes before the logging episode of the late 19th and early 20th centuries. Consequently, the vegetation that covered Appalachian mountain slopes in the past would appear to have been more favorable to lightning-ignited fires than the present vegetation cover.

The exact combinations of weather conditions that favor lightning ignitions are not known. This is a topic where additional research is needed, especially to understand the possibilities for implementing "wildland fire use" or "fires managed for resource benefit," in which lightning-ignited ("natural") wildfires are not suppressed but are allowed to burn to promote ecosystem restoration or other management goals. The relatively high incidence of lightning ignitions along the Blue Ridge Mountains suggests that terrain may contribute in some way to the development of lightning flashes during weather that is dry enough for burning. Solar heating of the Blue Ridge Mountain slopes may induce atmospheric convection in the absence of other convection-forcing mechanisms such as fronts or vertical wind shear, when high pressure persists over the region (Lafon and Grissino-Mayer 2007). These are precisely the conditions that would promote the drying of fuel because rainless and often sunny weather would prevail. During such weather, diurnal heating of the slopes generates convection (Bach and Price 2013), which can produce isolated thunderstorm cells. These scattered cells would not wet the fuels as continuously as an organized band of thunderstorms, and therefore the lightning that originates within these storms likely has a greater chance of striking dry fuel.

A recent study of single-cell thunderstorms over two summers in the Appalachian Mountains indicated that lightning activity was greatest over steep terrain, especially on the east- and south-facing aspects in the lee of major ridges (Miller and others 2015). These findings suggest the importance of morning and midday heating along the east- and south-facing slopes. As the warm air rises, it converges with the synoptic wind from the north or west, resulting in convection along the lee side. These results are not confined to the Blue Ridge province, and therefore they do not pinpoint why the Blue Ridge Mountains have more lightning ignitions than elsewhere. The Blue Ridge Mountains may be especially favorable because of their high relief or because

they are exposed to incursions of humid, unstable air at low atmospheric levels from the Atlantic Ocean (Lafon and Grissino-Mayer 2007). By impeding the westward flow of this air, the Blue Ridge Mountains may also inhibit convection over the Ridge and Valley province and the Appalachian Plateau. These mechanisms must remain speculative for now, however, because no research has been conducted to clarify how synoptic-scale weather interacts with Appalachian terrain to enable lightning ignitions.

TOPOGRAPHIC PATTERNS OF FIRE

Mountainous terrain can also lead to local-scale variations in disturbance frequency or severity because of topographic differences in runoff and exposure to precipitation, wind, and sunlight (Flatley and others 2011, Harmon and others 1983). In a humid region, where fuel production is not as limiting to fire as fuel moisture, fires might be expected to burn more frequently or severely on dry topographic positions (e.g., ridgetops or south-facing slopes) than in moist positions (e.g., valleys or north-facing slopes) (fig. 2.05).

Work in the Appalachian Mountains largely confirms that fires occur most frequently on dry sites, although it should be noted that topographic gradients of fire occurrence have been explored for only certain parts of the region—the National forests and National parks along the southern Blue Ridge Mountains of Tennessee and North Carolina (Barden and Woods 1974, Flatley and others 2011, Harmon and others 1983) and a section of the central Appalachians of Virginia and West Virginia spanning the eastern Appalachian Plateau, the Ridge and Valley province, and the Blue Ridge Mountains (Flatley and others 2011, Lafon and Grissino-Mayer 2007). Elevation is especially important, with fire most common at low elevations where the climate is relatively warm and dry and human access is easiest. In fact, lightning ignitions show a weaker relationship to elevation than anthropogenic ignitions.

Aspect and slope position also influence fire frequency; as expected, more fires occur on south- or west-facing slopes and on ridgetops than on other aspects (Flatley and others 2011, Harmon and others 1983, Lafon and Grissino-Mayer 2007). However, these patterns are not entirely consistent between study areas or are not statistically significant. Further, the strength of the topographic influence depends on the broad climatic setting. A spatial analysis of fire perimeter data for the two major Appalachian National parks revealed terrain influences under wet climatic conditions but not under dry conditions (Flatley and others 2011). This interaction was manifested in two ways. First, topographic patterns were stronger in the relatively wet Great Smoky Mountains National Park than in the drier Shenandoah National Park. Second, at each park, topographic patterns were relatively strong during abnormally wet years but not during dry years. Dry climatic conditions appear to render most of the landscape flammable and permit fires to spread readily across the landscape. Wet climatic conditions, on the other hand, confine burning more narrowly to the driest sites.

Figure 2.05—View toward the west slope of the Blue Ridge Mountains in Virginia, where a lightning-ignited wildfire killed large patches of forest during the dry summer of 2001. This fire was unusually severe because most Appalachian fires cause relatively little overstory mortality. In this photograph, taken toward the south-southeast in summer 2003, the remaining live trees are clearly visible in moist topographic positions. These moist sites include valley bottoms, ravines, and north-facing slopes, which face toward the viewer and slightly toward the left of the photograph.

Local topographic influences on fire occurrence likely scale up to affect the overall fire regime of an entire landscape or region. A landscape with a drier climate should see larger fires because more of the terrain is flammable and therefore does not impede the spread of fires. Comparing Shenandoah and Great Smoky Mountains National Parks confirms such a pattern (Flatley and others 2011). The fire size distribution showed a stronger positive skew in Shenandoah, resulting in larger mean fire size (105 acres as compared to 63 acres) and shorter fire cycle (204 years as compared to 1,197 years).

Fire intensity and severity seem to follow similar topographic patterns as fire frequency, and they may be more ecologically important. Although fires often spread widely across terrain and encompass many topographic positions (e.g., Flatley and others 2011, Wimberly and Reilly 2007), they show topographic variations in both intensity (e.g., flame length, temperature) and severity (e.g., percent of plants killed, forest floor consumption). Studies of field data and remotely sensed images indicate that fires generally burn with greatest intensity and severity on dry ridges and upper slopes and on south- or west-facing aspects (Barden and Woods 1976, Hubbard and others 2004, Rush and others 2012, Vose and others 1999, Wimberly and Reilly 2007). These terrain patterns apparently reflect not only the topographic effect on fuel moisture but also the influence of the vegetation itself because stands dominated by flammable yellow pines cover the driest landforms. Even though yellow pines are more fire resistant than most other Appalachian tree species, they often sustain high mortality because of the intense burning in those stands. In turn, relatively severe burning usually benefits pine recruitment (Barden and Woods 1976, Harrod and others 2000, Jenkins and others 2011, Waldrop and Brose 1999, Welch and others 2000, Wimberly and Reilly 2007), thereby reinforcing topographic heterogeneity in vegetation and fire behavior.

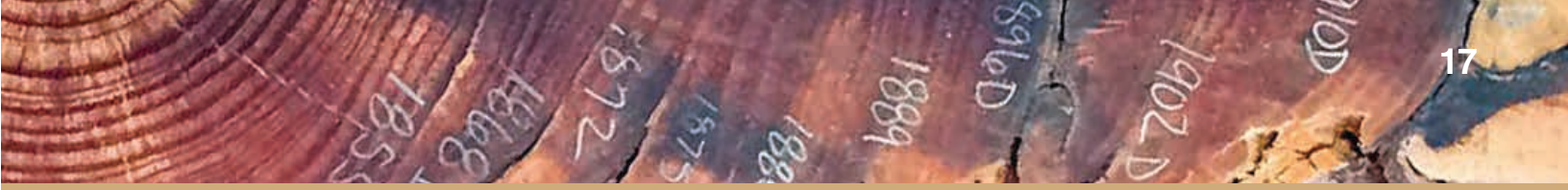
Positive feedbacks of this nature probably operated in the past, when fire was a more important component of Appalachian landscapes. Although frequent burning would have limited the accumulation of woody fuels in the open pine stands, it would have fostered the thick growth of flammable grasses and shrubs in the understory (Harrod and others 2000). The regular burning of this combustible understory vegetation and pine litter would have thwarted the establishment of fire-sensitive tree species and perpetuated the existence of the open pine–grass structure, as seen in other ecosystems including the longleaf pine (*Pinus palustris*)–wiregrass (*Aristida stricta*) of the Coastal Plain (Christensen 2000), shortleaf pine (*Pinus echinata*)–little bluestem (*Schizachyrium scoparium*) of the Ouachita-Ozark Highlands (Hedrick and others 2007), and ponderosa pine (*Pinus ponderosa*)–bunchgrass of the Rocky Mountains (Peet 2000). If this interpretation is correct, the Appalachian yellow pine stands, which currently occupy upper slopes and south- and west-facing aspects, testify to a history of frequent burning in the past.

CONCLUSIONS AND IMPLICATIONS

The current fire regime appears inadequate to maintain pine stands, oak stands, and other fire-favored communities over the long term. Fire cycles are on the order of hundreds to thousands of years, even on landscapes dominated by flammable vegetation such as oak and pine forests. This means that fire return intervals for individual points and forest stands are also long. These long fire intervals differ greatly from those hypothesized for the past, when fires are thought to have occurred about once per decade in Appalachian oak forests (e.g., Brose and others 2001).

Analyses of the present fire regime contextualize and clarify the proxy records to be examined in subsequent chapters. The importance of fire size is particularly evident. Fire cycles—and fire intervals—are mostly determined by a handful of the largest fires, and because the fire size distribution is skewed more strongly in some parts of the Appalachian region than in others, certain landscapes witness much more burning than others. The Blue Ridge Mountains are especially favorable for large fires. This physiographic province has a variable precipitation regime with long dry spells that apparently enable fires to spread widely and burn large areas. The Blue Ridge province is also prone to lightning ignitions. These ignitions suggest that terrain-induced convection may initiate lightning strikes during relatively dry periods that permit fires to ignite and grow, although more study of this topic is needed before any firm conclusions can be reached. On the Appalachian Plateau, in contrast, the fire regime seems more strongly dominated by anthropogenic factors, such as cultural uses of fire in the coal fields.

Temporal patterns of burning largely reflect variations in weather and climate. Fire is associated with dry periods, whether at the time scale of days (e.g., synoptic weather configurations), seasons (spring and fall), or years (droughts, ENSO). These fire-climate associations suggest relationships to look for using proxy records of past fire regimes. As will be discussed in chapter 4, fire-scarred trees provide seasonally or annually resolved data that are informed by the relationships evidenced by current fire regimes.



Chapter 3. Forest Composition and Fire Before European Settlement as Inferred from Witness Tree Records

INTRODUCTION

European settlement activities significantly altered the disturbance regimes of forests across the Appalachian region (Dyer 2001, Foster and others 1998). During the 19th century, settlers cleared these forests at least once for timber and crop production or to make way for livestock grazing (Flatley and Copenheaver 2015). Many of the forests we observe today are actually second- or third-growth forests that developed after this initial clearing. A better understanding of forest composition before extensive clearing and settlement can help guide resource management and can also provide clues about the role of fire in shaping the vegetation. Some information about "presettlement" vegetation can be gained from surveyor records of "witness trees," or "bearing trees" (Abrams and Ruffner 1995, Anderson and others 2006, Black and Abrams 2001, Black and others 2002, Bourdo 1956, Foster and others 2004).

Initial surveys of the Eastern United States during the colonial period (pre-1785) followed the metes-and-bounds system (Black and Abrams 2001). Survey routes and property boundaries often conformed to stream banks, trees, ridgelines, trails, and courses easily navigable across the landscape (Black and Abrams 2001, Thomas-Van Gundy and Strager 2012). This created a network of irregularly shaped property units across the original 13 colonies. The metes-and-bounds surveys were conducted gradually as settlers filled the lands that had been surveyed. As these lands became more densely settled over time, some existing parcels were split into smaller parcels to accommodate the growing population, and new parcels were carved from unsettled tracts of land. This gradual parceling of the land over time produced a record of continuous landscape change, which Flatley and Copenheaver (2015) compared to movies, i.e., "moving pictures as settlers moved west and divided up the land over time." Most of the Appalachian region was surveyed by using the metes-and-bounds system.

Beginning in 1785, Congress enacted a series of ordinances whereby surveying was executed along a rectangular system and its subdivisions known as the township and range system. This survey—the U.S. Public Land Survey System (PLSS)—was completed in the early 1900s (Liu and others 2011). Each 6-mile by 6-mile grid cell, or township, was further divided into 36 one-square-mile sections (Anderson and others 2006, Liu and others 2011). Each section consists of four corners and lines connecting each corner. Each line is also bisected by a quarter-corner (Anderson and others 2006, Manies and Mladenoff 2000). At each of these intersections, surveyors placed posts or stones in the ground. In addition, they blazed two to four trees nearest each corner. These trees were known as bearing trees or witness trees. Surveyors identified these bearing trees to species, measured their diameter at breast height, and measured the distance between the trees and the corners. Surveyors were also instructed to make note of the general vegetation characteristics, such as abundance, transitions between vegetation types, burned areas, and suitability for cultivation (Batek and others 1999). This provided information about vegetation composition at intervals of one-half mile along any of the four cardinal directions (Anderson and others 2006) or about 24 trees per square mile (Black and others 2002). However, the rules for designating these trees changed through about 1850, likely leading to inconsistencies in the application of the rules and the development of possible biases (Bourdo 1956). These surveys were conducted over a short period of time, leading Oswald and Foster (2014) to refer to them as providing "snapshots," in contrast to the "movie" that is available from metes and bounds.

Despite their utility, survey records regarding witness trees represent an unintentional, nonrandom, and non-impartial sampling effort. As a result, scientists have documented significant evidence for error, biases, and outright fraud in the survey records. Bourdo (1956) noted that field notes were often

fictitious or described township lines and corners that were never established. Notes also suggested that the time expended to establish the survey lines and mark the witness trees was too short to have been possible if the surveyors had actually followed the rules that were required. Survey lines may have deviated considerably from their intended route due to the use of improper or faulty equipment such as compasses. Black and Abrams (2001) suggested that surveyors often incorrectly identified tree species or interchangeably used common and uncommon names. Because surveyors were required to choose witness trees based upon their perceived economic value, size, age, abundance, and the ease with which they could be blazed, surveyors may have preferentially identified healthy or long-living trees rather than those actually near the survey lines or corners (Anderson and others 2006, Bourdo 1956). For example, Dyer (2001) suggested that in the northern portion of the Appalachian region, surveyors would have likely been biased to beech trees because their thin, smooth bark facilitated blazing. As a result, beech may have been interpreted as more abundant than it actually was.

Although witness tree records were not conducted to assess ecological communities, researchers have used these records to reconstruct characteristics of historic vegetation (e.g., Black and Abrams 2001, Liu and others 2011, Mladenoff and others 2002, Radeloff and others 1999, Schulte and Mladenoff 2005, Schulte and others 2002, Wang 2007). This has been accomplished at a variety of spatial scales, ranging from a local/county scale to a statewide scale (e.g., Friedman and Reich 2005). Based upon abundances of fire-dependent genera such as pine and oak, we can also use these records as an indirect means to assess the presence of fires. When complemented with direct evidence of fire from fire-scarred trees (chapter 4) and soil and sediment charcoal (chapter 6), the records allow us to paint a clearer picture of the role of fire.

Researchers have used witness trees for both "environmentally independent" and "environmentally dependent" analyses of past forest composition (Black and others 2002). Environmentally independent analysis relies solely on spatial patterns of witness tree records without direct regard for landscape features. Early studies using this approach were laborious because of the tedious efforts required for translating witness tree records onto maps. The laborious nature of the work limited the spatial extent of studies, but today the widespread availability of GIS (geographic information systems) software permits researchers to readily digitize records and to expand the spatial extent of the analyses using interpolation techniques (Black and others 2002, Thomas-Van Gundy and Strager 2012). This has allowed for a more objective analysis of relationships between community data and underlying environmental variables (Batek and others 1999) as well as the development of spatially continuous representations of forest communities (Manies and Mladenoff 2000, Thomas-Van Gundy and Strager 2012).

Environmentally dependent analysis may be used to establish species-site relationships using variables such as topography (e.g., slope, aspect, elevation, and landform type), soils, and hydrography. Through a statistical analysis associating species with these variables, researchers are able to assess potential controls on community composition. The drawback to this approach is that researchers must choose these variables *a priori*. As a result, these chosen variables may not be the most significant controls on community composition (Black and others 2002).

OBJECTIVES AND METHODS

In the following sections, we briefly review studies that used witness tree records to reconstruct past forest composition in the Appalachian region (fig. 3.01, table 3.01). We compiled and reviewed peer-reviewed studies conducted over the past 35 years. These studies used environmentally independent analysis, environmentally dependent analysis, or both. More studies were conducted for the Appalachian Plateau than for the other provinces. Some studies included multiple sites, which are treated separately in the graphs presented below. These studies encompass a range of areas, from local watersheds of 10 square miles to multiple counties exceeding 15,000 square miles. In addition, these studies examine historic forest composition across a wide range of elevations and actual witness trees transcribed (1,000–22,000).

This is perhaps the first quantitative synthesis of these studies, and our intent here is to offer a first-cut look at commonalities across them that will provide a resource for land managers. It is important to recognize that in our efforts to provide understandable generalizations, we have had to avoid extensive discussions regarding localized nuances as a consequence of micro-environmental and geological conditions.

We extracted data from these studies and grouped the study sites by physiographic province. Many of the studies report data on the total number of trees and on the percent of trees composed of each species. We used this information to calculate the total number of individuals of each species. We then aggregated the taxa into broad groups (pine, oak, other), because the fire-dependent pines and oaks are of particular interest for managers today. Several older studies only report percent composition, instead of both percent composition and abundance of each taxon, and consequently our aggregations for those datasets may be less accurate than for the other studies. Some studies also appear to include errors that prevented the species groupings from summing to 100 percent.

Several studies also use witness tree records in association with archaeological sites of Native American settlements to infer localized effects of anthropogenic activity on forest composition. We provide a brief review of the findings of these studies.

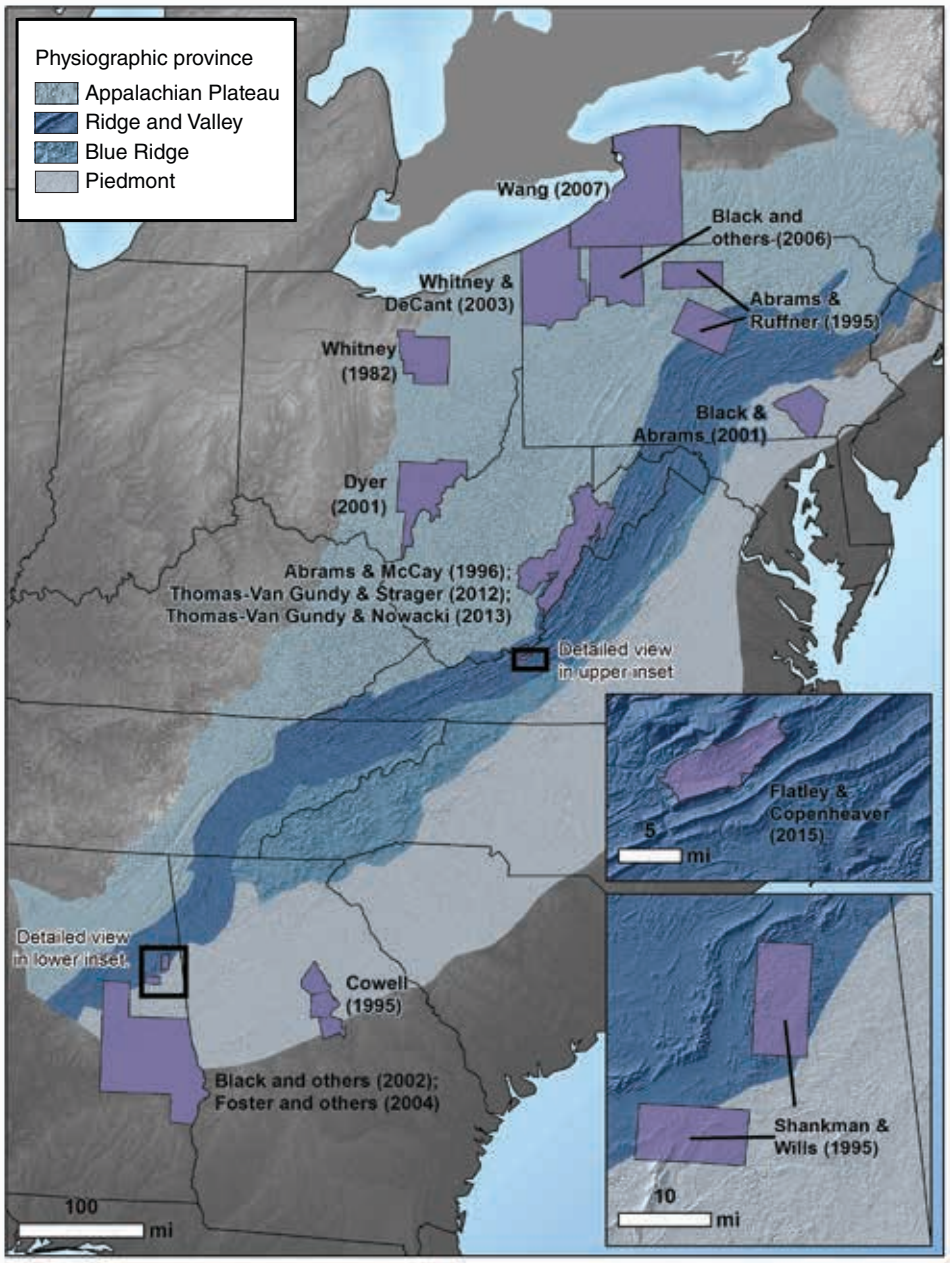


Figure 3.01—Witness tree sites reviewed in this report. Purple polygons indicate areas across the Appalachian region in which corresponding witness tree records were analyzed; sources are listed beside the locations.

Table 3.01—Summary of information derived from studies reviewed in this chapter

Source	State	Physiographic province	Study area size	Elevation	Number of witness trees	Warrant map dates
			square miles	*feet*		
Abrams and Ruffner (1995)	PA	AP	15,158.70	750 - 2,570[b]	1,184	1765-1798
		RV	737.2	530 - 1,930[b]		
Abrams and McCay (1996), Thomas-Van Gundy and Strager (2012), Thomas-Van Gundy and Nowacki (2013)	WV	AP, RV	2,662[a]	945 - 4,860[b]		1752-1899
Black and Abrams (2001)	PA	PD	968.5[a]	80 - 1,200[b]	9,880	1715-1725, 1735-1765
Black and others (2002), Foster and others (2004)	AL	RV, PD	13,000[a]	120 - 1,920[b]	43,610	1830-1850
Black and others (2006)	PA	AP	1,865	1,000 - 2,400[b]	166	1790-1820
Cowell (1995)	GA	PD	982.55	200 - 830[b]	11,511	1804, 1806
Dyer (2001)	OH	AP	4171[a]	500 - 1,100[b]		1788-1789, 1796-1802
Flatley and Copenheaver (2015)	VA	RV	10.02	1,909 - 3,825	3,774	1786-2000
Shankman and Wills (1995)	AL	RV	144.74	1,634 - 4,902	1,057	1832
Wang (2007)	NY	AP	5,560	230 - 2,550		1797-1814
Whitney (1982)	OH	AP	1,405.65	800 - 1,400[b]	8,000+	1810-1831
Whitney and DeCant (2003)	PA	AP	3,219.26	540 - 1,900[b]	6,000+	1785-1840

Notes: Some studies (e.g., Abrams and Ruffner 1995) included multiple sites. In other cases, a single site was the subject of two studies (e.g., Black and others 2002, Foster and others 2004).
AP = Appalachian Plateau, RV = Ridge and Valley, PD = Piedmont.
[a] Values reported in this table were obtained by using geographic information systems-based analysis and 30-m digital elevation data.
[b] Values either not reported explicitly by the study or only roughly estimated.

COARSE-SCALE INFERENCES REGARDING PRESETTLEMENT FOREST COMPOSITION

The percent composition of pine, oak, and other species are presented in fig. 3.02A–C. The sites are arranged on these graphs according to the physiographic provinces in which they were primarily located (some sites overlapped partially into a second province). Pine was relatively uncommon on the Appalachian Plateau (fig. 3.02A), but oak was relatively abundant (fig. 3.02B). White oak (*Quercus alba*) was especially common (Dyer 2001, Whitney 1982, Whitney and DeCant 2003). However, the "other" category represented the predominant tree group on the Appalachian Plateau (fig. 3.02C). Particularly important were sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), yellow-poplar (*Liriodendron tulipifera*), and black cherry (*Prunus serotina*) (e.g., Abrams and Ruffner 1995, Dyer 2001, Wang 2007). These results suggest that oak stands were intermixed with mesophytic forest, with oaks most common on the drier, less fertile soils and on fire-prone sites (e.g., Whitney and DeCant 2003). The high abundance of mesophytic species on the Appalachian Plateau probably reflects, in part, the relatively unfavorable fire environment (e.g., wetter climate) of the plateau compared to the other physiographic provinces (chapter 2). Geographic patterning of fire in the past will be considered further in chapter 4.

Fire-tolerant pines and oak were more prevalent in the Ridge and Valley and Piedmont physiographic provinces than on the Appalachian Plateau (fig. 3.02A and B); mesophytic species, in turn, were less common in the Ridge and Valley and the Piedmont than on the Appalachian Plateau (fig. 3.02C). The greater abundance of pine and oak and the limited number of mesophytic trees likely resulted from the relatively dry climate of the Ridge and Valley and the Piedmont provinces. A drier climate would have favored xerophytic species directly through the physiological adaptations of the species to low moisture and indirectly by promoting frequent and widespread burning. The terrain in these two provinces may also have created larger fire compartments than those on the plateau. In a study of the Georgia Piedmont, for example, Cowell (1995) found that pine and oak were common irrespective of topographic position, a finding that suggests fires burned widely across the landscape and enabled xerophytic species to occupy mesic sites from which they would have been competitively excluded in the absence of fire.

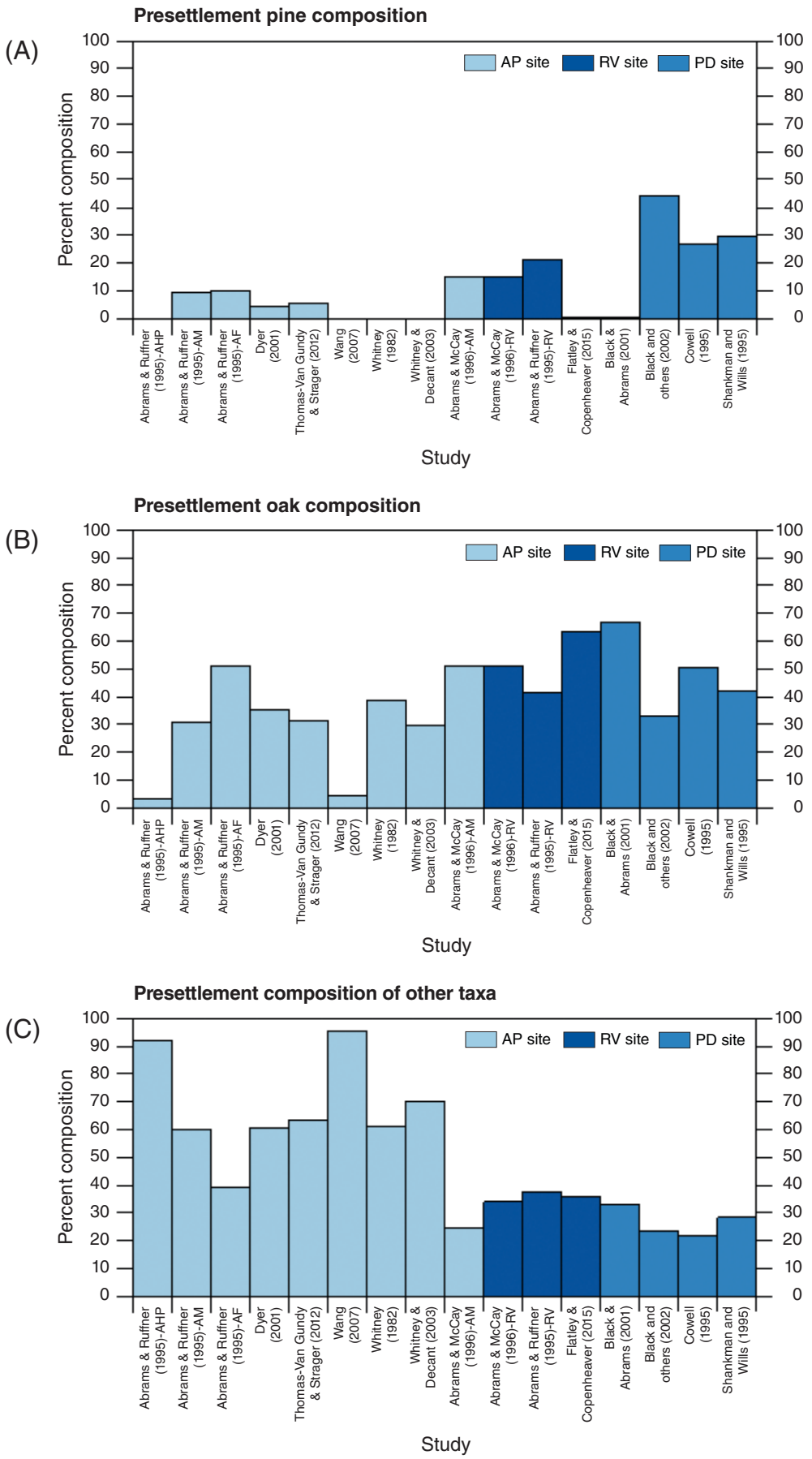


Figure 3.02—Estimated presettlement forest composition across the physiographic provinces for (A) pine, (B) oak, and (C) other taxa. AP = Appalachian Plateau; RV = Ridge and Valley; PD = Piedmont. The x-axis indicates the data sources, where AF = Allegheny Front, AHP = Allegheny High Plateau, and AM = Allegheny Mountains.

LOCAL INFLUENCES OF ANTHROPOGENIC ACTIVITIES ON FOREST COMPOSITION AND FIRE ACTIVITY

Several of the studies we reviewed looked for relationships between anthropogenic activities and vegetation in areas around Native American settlements. The concern here is not with extensive burning that might have contributed to the widespread abundance of oaks, as considered above. Rather, the interest of some researchers has been in the more localized alterations in the abundance of fire-tolerant species in the vicinity of Native American settlements.

Black and others (2006) examined witness tree records in northwestern Pennsylvania in an effort to assess the impact of Native American influence on the presettlement landscape. Drawing on archaeological literature, they surmised that Native American influence was constrained to a radius of a few miles extending from a village. This suggestion reflects documented activities of clearing and burning for agricultural field development as well as for foraging and hunting. The human impact diminished as a function of distance, owing to the limitations of walking. These bits of information allowed Black and others (2006) to develop an index reflecting Native American influence that could then be statistically analyzed in association with forest composition. The authors found that high levels of human activity were associated with localized areas of high oak abundance. Clearing of the forest likely favored oaks due to their early successional traits, adaptions to fire, and ability to recruit rapidly. However, Black and others (2006) acknowledge that it is difficult to establish a causal relationship. Did Native Americans preferentially chose sites with fire-tolerant species as a source of wood, or did their activities promote the development of oak?

In Alabama, Foster and others (2004) found a relatively low abundance of pine around Native American settlements, and elevated levels of early-successional species such as elm and cedar. This evidence suggested that Native Americans favored pine wood for construction. The heavy use of pine apparently offset any benefits that pines would have gained from the elevated burning near settlements.

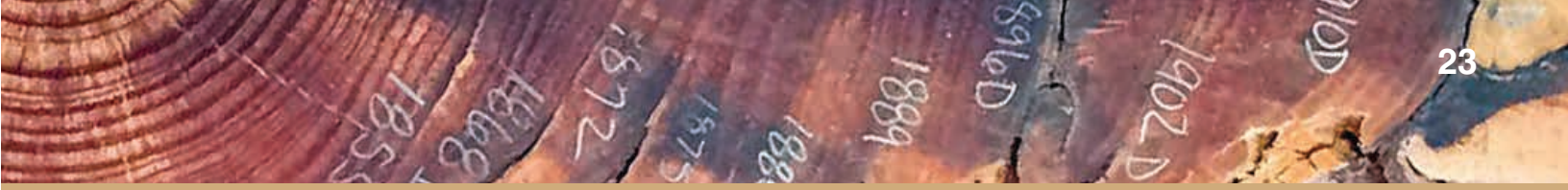
CONCLUSIONS AND IMPLICATIONS

Witness tree studies reveal vegetation patterns that are broadly consistent with the geographic patterns of forest composition and fire observed today (e.g., chapter 2). Xerophytic, fire-favored taxa (oak and pine species) were common in the Ridge and Valley and the Piedmont physiographic provinces, whereas mesophytic species were abundant on the Appalachian Plateau. These spatial patterns show the direct influence of climate and terrain on moisture availability for plants. Additionally, variations in moisture across the region would have influenced flammability and thereby would have contributed to geographic patterns of fire and fire-adapted plants.

These interpretations of spatial patterning in vegetation across the physically diverse Appalachian region are bolstered by work conducted in neighboring regions surveyed under the PLSS. Witness tree analyses for those areas indicate that the distribution of fire-adapted tree species—such as longleaf pine on the Gulf Coastal Plain (Predmore and others 2007), shortleaf pine on the Ozark Plateau (Batek and others 1999), and jack pine (*Pinus banksiana*) in the Midwest (Radeloff and others 1999)—corresponded with environmental gradients (e.g., moisture and topography) that would have influenced susceptibility to fire. Other, more fire-sensitive species showed opposing patterns along those same environmental gradients. Moreover, the PLSS records allow estimates of structural attributes such as tree density and diameter distributions. These estimates suggest that frequent burning maintained open woodlands or savannas with large, widely spaced trees (Batek and others 1999, Cox and Hart 2015, Predmore and others 2007, Radeloff and others 1999).

A recent study using witness trees to identify spatial patterns of vegetation across an Appalachian landscape in eastern West Virginia (Thomas-Van Gundy and Nowacki 2013) classified tree species into two broad groups, “pyrophilic” and “pyrophobic.” Mapping the distributions of these groups by extrapolation from survey points indicated a shift from pyrophilic dominance in lower elevations and rain shadow environments to pyrophobic dominance in higher elevations and areas with orographically enhanced precipitation. Although this and other Appalachian studies rely on the metes-and-bounds survey system, and therefore cannot portray floristic and structural details, their results are broadly consistent with the work conducted in other regions; thus, these studies appear to offer reliable indications about the role of fire before widespread European settlement of the Appalachian region. Witness trees hold considerable promise for improving our understanding of Appalachian vegetation across the large sections of the region that remain to be investigated using these records.

At a local scale, presettlement species composition appears to have reflected the influence of Native American burning and land clearance near villages. Burning and cutting favored oaks in particular. However, it is not clear whether oaks were abundant during occupation of the villages or if instead they colonized after the villages were abandoned, when reduced fire frequency would have enabled oak sprouts to become established.



Chapter 4. Appalachian Fire History as Reconstructed from Fire-Scarred Trees

INTRODUCTION

Fire-scarred trees are one of the best sources of fire history information for understanding vegetation dynamics and guiding resource management (fig. 4.01). Scars offer direct evidence of past fires, including the year and often the season of burns and where the fires occurred. A fire-scar record compiled from multiple trees permits estimates of fire-free intervals (i.e., the elapsed time between successive fires), including how the intervals responded to land use change or climatic variations. Fire scars also provide information about fire extent and geographical variations in fire frequency. They offer a glimpse of fire regimes that existed decades or centuries before the industrial logging and fire exclusion eras.

A fire scar forms when a tree is injured by fire, but not killed (Craighead 1927, Dieterich and Swetnam 1984, Smith and Sutherland 1999, Weaver 1951). As new wood curls over the wound in subsequent growing seasons, the scar becomes embedded within the wood and the tree trunk. Multiple scars may accumulate within a tree over its lifetime if nonlethal surface fires are common. The scars form a distinctive, triangular-shaped feature termed a "catface" by foresters, extending from the tree base up the tree trunk (Arno and Sneck 1977) (fig. 4.02). By sawing through the catface of a living tree or snag to obtain a full or partial cross-section from the tree (fig. 4.03), the researcher captures the fire scars and can date them to their exact year of formation using the annual growth rings and dendrochronological techniques.

Vegetation scientists exploited this record of fire history as early as 1910, when Frederic Clements (1910) sawed cross-sections from fire-scarred lodgepole pines to reconstruct fire history back to 1707 in the Rocky Mountains of Colorado. Foresters and ecologists knew the importance of these fire-scar records early in the 20th century (Leopold 1924, Presnall 1933, Show and Kotok 1924), but it was not until the 1950s–1970s that researchers began applying tree-ring dating techniques to other coniferous forests of western North America (Houston 1973, McBride and Laven 1976, Wagener 1961, Weaver 1951) as the

Figure 4.01—Fire-scarred pine, George Washington National Forest. Each vertical ridge on the uphill side of the tree was formed as wood curled over the portion of the tree wounded by a fire. Many fire-scarred trees, as this one, bear wounds received from multiple fires.

Figure 4.02—Henri D. Grissino-Mayer sawing a fire-scarred pine snag, Jefferson National Forest. The distinctive triangular catface is visible at the base of the snag.

ecological importance of fire became evident to western forest managers. These researchers sought evidence from fire history studies to learn more about the role of fire and eventually inform management personnel to help guide the prescribed burning programs they were initiating. By the late 1970s, the utility of fire scars for reconstructing fire history had become widely recognized. Particularly important for this recognition was the detailed description of fire-scar sampling and analysis, published by the USDA Forest Service as General Technical Report INT-42, *A Method for Determining Fire History in Coniferous Forests of the Mountain West* (Arno and Sneck 1977).

Subsequent decades have seen an explosion of fire history research in the American West. Until about 15 years ago, however, little such work had been conducted in eastern North America. The paucity of studies on eastern fire history probably reflects several factors. First, little impetus existed to search for fire-scarred trees because fire was not widely considered to have played an important role in the temperate hardwood and mixed hardwood-conifer forests of eastern North America. Second, the dominance by hardwoods means that the fire history techniques developed in the West were not directly transferable to the East because hardwoods record scars less clearly and reliably than conifers. Several hardwood-based studies have been conducted (e.g., Hutchinson and others 2008, McEwan and others 2007), but conifers, especially pines, are superior recorders of fire history. Third, the humid climate found in the Eastern United States promotes rapid wood decay, which probably destroyed many dead trees that had contained fire scars. The decay problem is especially pronounced in hardwoods, many of which have catfaces that have rotted (fig. 4.04). In contrast, many pines saturate the wound with resin, which improves the resistance of the wood to future decay and extends the time for which the record of fire history is preserved. Well-preserved pine logs, especially the wounded portion saturated with resin, can remain on the forest floor for decades (fig. 4.05). Fourth, forest

(A)

(B)

Figure 4.03—Fire-scarred cross-sections. (A) Henri D. Grissino-Mayer sawing a cross-section from a fire-scarred snag, George Washington National Forest. (B) A sanded and dated cross-section cut from a living pitch pine tree on the George Washington National Forest. The scars on this cross-section record 13 different fires between 1845 and 1921.

Figure 4.04—Decayed catface at the base of a beech tree, Jefferson National Forest.

Figure 4.05—Dead pine remnant (foreground) with fire scars, Great Smoky Mountains National Park. Many of these old, toppled pines still have dateable fire scars. The live pine in the background shows the wide base that may indicate a catface on the opposite side of the tree. (photo by Lisa B. LaForest)

clearance in the Eastern United States probably destroyed many fire-scarred trees such that researchers had to scour often rugged terrain to find stands with old trees that were not logged during the industrial logging episode. Finally, because many eastern tree species have shorter lifespans than their western counterparts, the lengths of the fire histories would be shorter and perhaps offer only limited information on the role of past fires.

Fortunately, however, field sampling conducted in eastern North America over the past 20 years has uncovered many sites across a broad geographic area of the Eastern United States that contained dead and living trees with considerable numbers of fire scars. The trees include pines in the Appalachian Mountains that preserve a record of fire history dating back to the 17th and 18th centuries. These pine-based fire chronologies are complemented by a few additional ones of similar length based on oaks. Together, the Appalachian fire chronologies form a fire-scar network (fig. 4.06) that portrays fire regimes across several physiographic provinces and over multiple land-use phases—beginning in several locations before European settlement and continuing through settlement, industrial logging and mining, and fire suppression.

Before synthesizing these results, however, we discuss the methods that are used to obtain them. It is critical to understand how the data are obtained and how reliably they can be used for estimating fire intervals or other fire regime parameters that are useful to resource managers.

FIELD SAMPLING FOR FIRE HISTORY

A fire-scarred tree preserves a record of at least some of the fires that burned at a specific point on the landscape. However, an individual tree may not record all the fires that occurred in its proximity. The reliability of individual trees for recording past fires is not well understood or quantified, but it is generally known that thin-barked trees are more sensitive to fire than trees with thick bark because their cambium is not as well insulated from heat (Brose and others 2014). A tree is therefore most susceptible to scarring when young. Once scarred, the tree remains susceptible to subsequent scarring because the bark sloughs off the scarred portion of the trunk and leaves it unprotected (Speer 2010), even as its diameter increases.

If a tree escapes scarring when small, it may become highly resistant to scarring as it grows larger and its bark thickens. A young tree could have escaped scarring for a number of reasons in the past, even if fires occurred at short intervals. For example, the tree might have been established in an unusually long fire-free interval, during which it attained a large enough size to avoid scarring when frequent burning resumed. Moreover, fuel conditions might not have supported fires that would scar the tree, particularly if the tree were surrounded by sparse fine fuels or if the understory had a grass component that burned rapidly without attaining the prolonged high temperatures needed to scar the tree. The process of scar formation is too poorly understood to know whether trees grew into a “scar-proof” stage, but some evidence exists for it in the Appalachian region, where many old pine trees lack fire scars even in stands where neighboring trees have been scarred. Additionally, recent prescribed fires have created scars on scarred small-diameter pines while leaving larger ones unscathed.

Because of questions about the susceptibility of trees to scarring, researchers should sample in forest stands that contain numerous fire-scarred trees to improve the likelihood of capturing a thorough record of past fires. Increasing the number of fire-scarred samples increases the likelihood that a complete or near-complete census of fires is captured in the fire-scarred record. One study (Kou and Baker 2006) suggests that a sample size of at least 20 trees should be sought, but van Horne and Fulé (2006) found that a sample size approaching 50 randomly sampled fire-scarred trees would result in more accurate estimates of the census fire frequency. In the Appalachian region, dense clusters of fire-scarred trees are not available in many locations. However, our experience has shown that many Appalachian slopes have only one or a few fire-scarred trees. In some cases, one or two of these trees contain numerous scars, but such a small sample size for the stand is insufficient for thoroughly reconstructing fire history.

One strategy for enlarging the sample is to collect fire-scarred trees from a larger area. However, this strategy potentially introduces another bias because the larger area may capture additional fires that did not encompass the entire area, resulting in a decrease of the mean fire interval, the standard metric for quantifying fire frequency. It therefore may overstate the

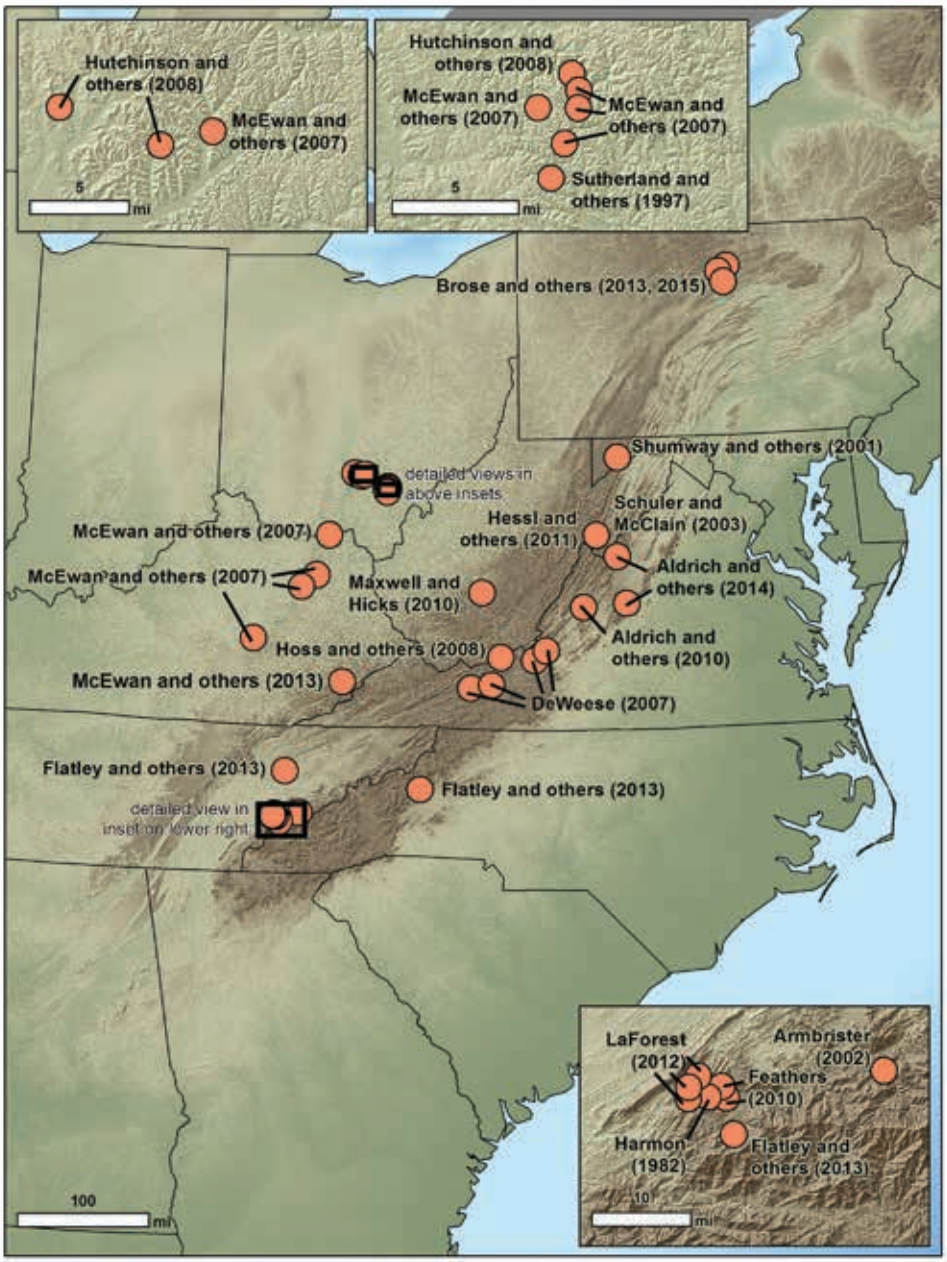


Figure 4.06—Locations of fire-scar network (shown as orange circles) across the Appalachian region reviewed in this report; sources are listed beside each location.

amount of burning within individual forest stands. In fact, if a large enough area were sampled—an entire national forest, for example—fires would probably be recorded every year, but it would be incorrect to conclude that all those fires affected an individual stand, which is often the initial spatial level of interest to land management agencies.

Consequently, to minimize both types of errors—missing fires that actually occurred or falsely attributing fires to points where they did not burn—Kou and Baker (2006) recommend collecting a large number of cross-sections (from approximately 20 trees) within a small area (approximately 2.5 acres, or 1 ha), where the researcher could be reasonably confident that all the recorded fires actually occurred within that small area. However, van Horne and Fulé (2006) found that as few as 40 fire-scarred trees would capture the complete record of fires in a 247-acre (1-km^2) area using a technique called targeted sampling, whereby the researcher samples only from the best fire-scarred trees instead of sampling them randomly. Probably more important than the absolute size of the sampled area is whether the area sampled represents a single fire compartment (*sensu* Frost 1998) that had continuous fuels through which fires could have spread, unimpeded by firebreaks, to all the sampled trees.

In practice, it can be impossible to find such concentrations of fire-scarred trees, and the studies synthesized below follow these recommendations to varying degrees. In some cases, the researchers were only permitted to sample opportunistically in a manner that precludes such a strategy. In an old-growth forest of eastern Kentucky, for example, McEwan and others (2014) were not allowed to cut any living trees, and therefore they based their fire history on 35 downed hardwood trees scattered over a 60-acre area. Even though the study departed from the recommended minimum number of samples, it clearly made a valuable contribution, and in fact, the entire 60-acre site likely represents a single fire compartment. Restricted sampling opportunities should not discourage fire history studies in such locations, but we should recognize the potential limitations they impose, especially for comparing between studies that used different sampling strategies. In our synthesis below, we note the limitations to provide the reader with the best possible interpretations of the data that are available.

PROCESSING SAMPLES AND DATING FIRE SCARS

A primary means to reconstruct fire events is through dendrochronology, or tree-ring dating. To obtain accurate dates for each tree ring involves crossdating the rings by matching the tree-ring sequences of multiple trees in an area to ensure all rings are accounted for because individual trees may have locally absent rings or false rings caused by intra-annual ring density differences (Stokes and Smiley 1968). All trees in a region should display a similar pattern of ring-width variation over time because all are affected by the same regional climatic variations that operate year to year (Fritts 1976). A regional drought, for example, will induce slow tree growth, and hence a narrow annual ring will form in all trees. Over time, the trees establish a specific and recognizable sequence of wide and narrow rings that corresponds to changes in climatic favorability from year to year. By comparing the tree-ring series of multiple trees in a sample, the researcher can identify and correct any dating errors for an individual tree (Grissino-Mayer 2001a, Speer 2010). Even a dead tree (e.g., a log, standing snag, or smaller remnant sections of wood) can be dated by matching its outermost tree-ring series with the innermost ring patterns obtained from living trees (Stokes and Smiley 1968, Swetnam and others 1985). Dead trees found as standing snags or downed sections with catfaces are especially valuable for fire history because they usually contain the oldest fire scars at a site.

In the field, the researcher cuts cross-sections containing the fire scars from dead trees by using a chain saw and following established sampling techniques (Arno and Sneck 1977). Further, some smaller sections can be carefully cut from selected living trees to ensure that the record of most recent fire events is obtained (Heyerdahl and McKay 2001). In addition to these few fire-scarred living trees, researchers also core multiple trees from the same area (fig. 4.07) because these living trees ensure development of a chronology of tree-ring patterns that overlaps with the patterns obtained from the dead trees. Later, in the laboratory, the surface of each core and cross-section is smoothed by sanding with progressively finer-grit sandpaper to enhance the visibility of the tree-ring structure (Orvis and Grissino-Mayer 2002). The tree rings for each specimen then are crossdated under a low-power boom-arm stereo-zoom microscope by using unusually narrow rings as markers by which to crossdate the specimen against the others. Graphical techniques of crossdating, such as skeleton plots (Swetnam and others 1985), are especially useful but many times the list method (Phipps 1985, Yamaguchi 1991) can be used, especially in the Eastern United States. To verify and refine the crossdating, most dendrochronologists also measure the tree rings and statistically crossdate the ring-width series by using the program COFECHA (Grissino-Mayer 2001a, Holmes 1983). For dead trees, which have unknown dates, COFECHA matches the ring-width series against the living trees to assign the actual calendar year to each ring (Grissino-Mayer 2001a).

Figure 4.07—Students Steven Tarpley (left) and Will Flatley (right) removing increment cores from the base of a pine in Great Smoky Mountains National Park. (photo by Lisa B. LaForest)

Fire seasonality and potential ignition sources can be inferred from the location of the scar within an annual growth ring (Baisan and Swetnam 1990, Dieterich and Swetnam 1984, Lafon 2010, Swetnam 1990, Swetnam and others 1999). Scars situated within the earlywood portion of the annual ring indicate fires that occurred during the early portion of the growing season, whereas middle-earlywood, late-latewood, and latewood scars may indicate summer burns, depending on the latitude and elevation of the study area. A scar situated between two annual rings is categorized as a dormant-season fire because the tree was not growing when the fire occurred. It is unclear, however, which year a dormant-season fire occurred. For example, a dormant-season scar between the rings for 1800 and 1801 could have formed in late 1800 or early 1801. Because these fires must be assigned to only one calendar year, researchers are informed by the current fire season and can assign one of the two years accordingly. For example, in the American Southwest, a dormant season fire is assigned the year after the fire scar because fires can occur in the dry months prior to onset of the North American Monsoon in early summer (Baisan and Swetnam 1990).

DEVELOPING A FIRE HISTORY

The creation of the FHX2 program between 1992 and 1995 represented an important step in fire history research. FHX2 and its successor FHAES enable the researcher to enter and archive fire history data in the internationally accepted fire history exchange (FHX) format (Grissino-Mayer 2001b) and display the fire events in a composite fire chart (figs. 4.08 and 4.09). The main benefits of FHX2, however, are the many statistical analyses that can be performed on the fire history data once entered to gain more information on the overall fire regime. The program calculates several fire interval statistics, including the widely used mean fire interval (MFI), which is the average of all the fire intervals in the sample. Additionally, because fire interval data often are not normally distributed, FHX2 fits a Weibull distribution to the fire interval data and calculates the Weibull median interval (WMI, also called the Weibull median probability interval, or WMPI), which is considered a better estimate of the typical fire interval (Grissino-Mayer 1995, 1999, 2001b).

Measures of central tendency in fire interval data, such as the MFI and WMI, are not the only metric that matters when evaluating a fire regime. The variation in interval length can have important implications for understanding the role of fire events on tree establishment patterns. For example, an occasional long interval between successive fires may be needed for tree seedlings to grow tall enough to survive subsequent fires. FHX2 calculates several measures of variability, including standard deviation (SD), range of observed intervals, and the lower exceedance interval (LEI) and upper exceedance interval (UEI) (Grissino-Mayer 1999). LEI and UEI represent the bounds between which most intervals would be expected to fall,

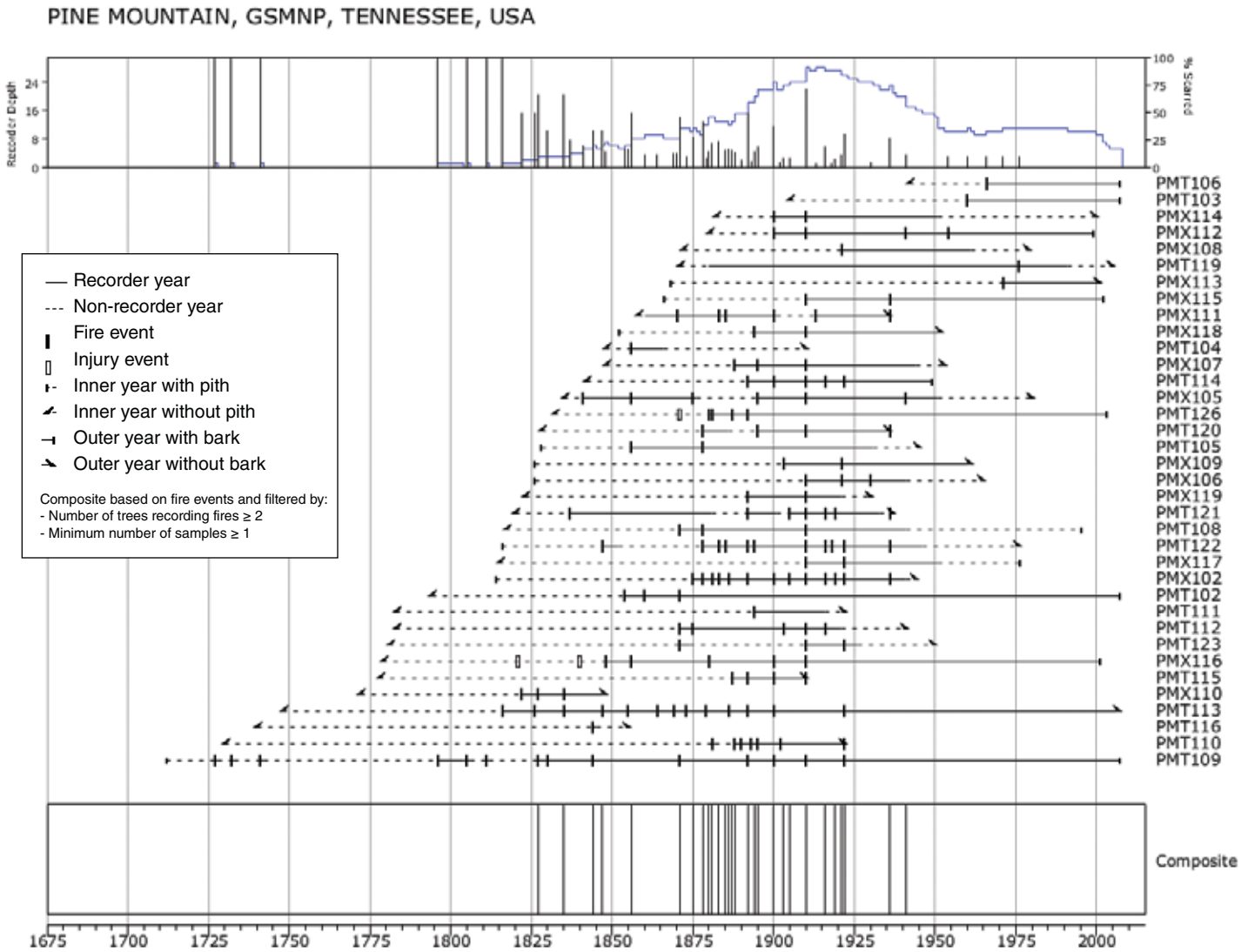


Figure 4.08—Fire chart for Pine Mountain, Great Smoky Mountains National Park (LaForest 2012), created with the FHAES program. Each horizontal line represents the years covered by an individual tree. Dashed portions of the lines represent non-recording years, whereas solid portions represent recording years. Short vertical lines intersecting each horizontal line represent individual fire events. The vertical lines on the "Composite" axis at the bottom of the chart represent the record of all fires recorded by all trees at the study site.

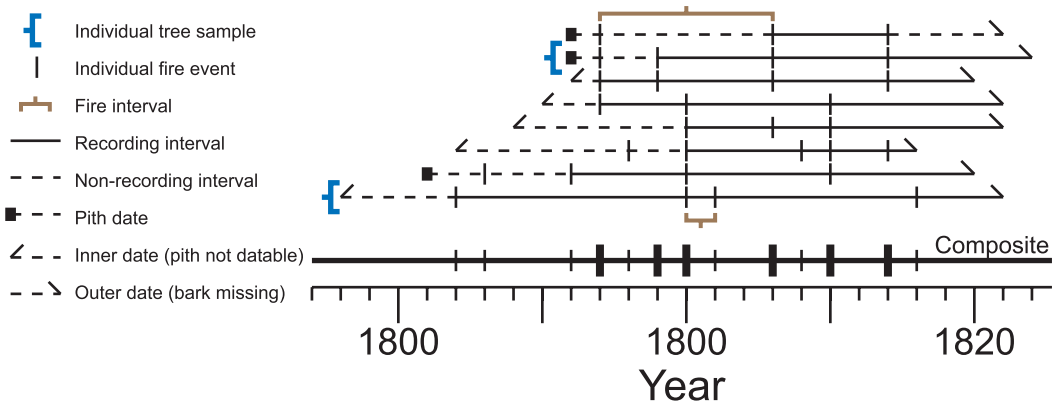


Figure 4.09—Portion of an idealized fire chart illustrating how to interpret the symbols. Each individual horizontal line (two of which are marked by blue brackets) represents the time spanned by an individual tree sample. Solid black portions of a line indicate recording years in which the tree is considered to have been susceptible to scarring. Dashed portions represent non-recording years. Short vertical lines indicate years with dated fire scars. The time elapsed between fires (marked by brown brackets) is the fire interval. The point mean fire interval (MFI) is calculated by averaging the fire intervals across all trees for recording years. The bottom line labeled "Composite" shows every year in which a fire was recorded by one or more sampled trees in the study site. The composite MFI is calculated by averaging the intervals between fires represented on the composite axis. The filtered composite MFI is calculated by averaging the intervals between "major" fires that are recorded on the composite axis. Major fires in this example are indicated by heavy vertical lines on the composite axis. These major fires include only those for which the following two criteria are met: at least two recording trees are scarred in a single year, and at least 25 percent of all recording trees are scarred that year.

according to the Weibull-modeled distribution of fire intervals. Most studies use the FHX2 default of 75 percent to define the LEI and UEI; i.e., 75 percent of all fire intervals would be expected to fall between the LEI and UEI. Of the remaining 25 percent of intervals, the 12.5 percent below the LEI are the unusually short intervals, and the 12.5 percent above the UEI are unusually long for the site (see Brose and others 2013, 2015; Grissino-Mayer and others 2004).

An important issue concerns the metrics used to evaluate the overall fire regime for an area because these metrics are influenced by the number of fire-scarred trees sampled and the overall area represented by the trees. For example, was the sample size too small, in which case the calculated fire intervals may be too long? Were the samples collected from a large geographic area, in which case the fire intervals would be atypically shorter? Basically, how can we compare metrics for fire interval data between sites with different sample sizes and different areal coverage?

Especially critical in fire history studies is accounting for the "imperfect recorder" problem when analyzing fire scars because otherwise the interval length could be grossly overestimated. For a given tree, only certain years are considered "recorder" years and should be designated as such when entered in FHX2/FHAES (Grissino-Mayer 2001b). Recorder years refer to those rings that developed in the years after an initial scar and are therefore capable of recording subsequent fires. This initial scar increases the susceptibility of that tree to subsequent scarring (see recorder intervals in fig. 4.09). Because many pines and oaks have thick, protective bark, they may have endured many fires before the first scar; therefore, no fire interval exists before the first scar. Similarly, if the tree heals over the wound, the years after the last fire scar formed prior to closure are no longer considered recorder years. Finally, tree rings of a fire-scarred cross-section that are obscured by burning or decay, whereby one cannot tell if a fire scar could have been present, are also not considered recorder years (figs. 4.09 and 4.10). By limiting the analyses to recording intervals, the researcher ensures that calculations are based only on periods that are covered by fire-scar data. Yet the imperfect recorder problem cannot be fully surmounted as even the designated recording intervals likely fail to record some fires.

Researchers have learned that important information on fire regimes can be gained by analyzing fire history at the individual tree point level. The "point fire interval" involves no compositing, i.e., consolidating all fire interval data from many trees into one time series. Fire intervals are calculated at the level of the individual tree, and the MFI, WMI, etc., for all these intervals are calculated (fig. 4.09). When considering a broader geographic area, however, fire-interval lengths will be overestimated, and the point fire interval will yield the most conservative estimate of fire frequency. It represents the longest possible fire interval for an area.

More often, though, the fire history researcher will composite the fire events in multiple ways and report fire interval statistics (MFI, WMI, SD, range, LEI, and UEI) for each level of compositing. The "composite fire interval" provides a way to compensate for the imperfect recorder problem by combining the fire record for all the trees at a site into one composite time series (fig. 4.09). The more trees sampled, the lower the likelihood of missing a fire. As long as the trees were sampled within a small area, i.e., a single fire compartment, the composite fire record

should yield the most reliable estimates of metrics that define the fire regime. Many researchers also calculate the composite fire interval by using any of several "filters" that will include only fire years in which a minimum number of recorder trees (usually two trees) and a minimum percentage (usually 10 percent or 25 percent) were scarred (Grissino-Mayer 1995, 2001b; Grissino-Mayer and others 1995; Swetnam 1990). The resultant "filtered composite fire interval" may characterize the typical interval for fire compartments on a landscape if fire scars were sampled from multiple fire compartments. For example, van Horne and Fulé (2006) performed an exhaustive census of fire-scarred trees from a 247-acre (1-km^2) area of ponderosa pine forest in northern Arizona and found that the 25-percent filter offered the most reliable fire interval estimates. By reporting multiple fire interval calculations, including the point fire interval, the composite fire interval, and filtered composite fire intervals, a researcher can provide a range of estimates that cluster around the actual fire interval. Despite attempts to capture a complete inventory of fire events for an area, it is nonetheless impossible to know how many past fires were not recorded because they did not scar any trees in the sample. As such, fire interval metrics always provide a maximum length between successive fires for the study area. Should methods be found later that could reveal such "invisible" fire events (e.g., by using chemical changes of wood in the tree-ring record), then these newly discovered fire events will actually serve to further reduce the average time between successive fires.

In considering the fire history results reported below, we note that many fire history studies conducted in the Eastern United States have not followed these standard sampling and reporting protocols. Many did not distinguish or tally recorder and non-recorder years, for example, which would bias any estimates of fire interval metrics and affect the overall description of the local fire regime. Some used only one compositing method while others did not include a fire chart. The inconsistency and incompleteness have limited some of the analyses we attempted for this synthesis and therefore have constrained our interpretations.

Figure 4.10—Pine cross-section with scars damaged by fire. A few dateable scars are present on this cross-section, but others may have been destroyed.

FIRE INTERVALS RECONSTRUCTED FOR THE APPALACHIAN REGION

We identified 19 studies reporting analyses of pre-exclusion fire history in the Appalachian region (table 4.01). Of the 44 sites included in these studies, 21 had fire interval data extending back before 1850, but for the remaining sites fire intervals cover only the late 19th century through the 20th or early 21st century. The fire interval statistics reported in these studies—or that we calculated from them—indicate that fires burned frequently across the Appalachian region before pervasive anthropogenic fire exclusion practices disrupted these fire regimes (table 4.02).

Composite fire intervals were calculated and reported for nearly all the study sites (table 4.02). The composite MFI varies between 1.9 years for a study site in the Great Smoky Mountains of Tennessee, which was dominated by pitch pine and chestnut oak (LaForest 2012), and 19.5 years for a northern red oak-dominated site in the Ridge and Valley section of eastern West Virginia (Schuler and McClain 2003), with an average of 6.8 years across all sites. However, the statistical distribution of these composite MFI estimates is positively skewed (fig. 4.11A), and therefore the median value (5.4 years) better represents the central tendency. These composite MFI estimates indicate that in the most frequently burned location, fires burned at least part of the study site about once every 2 years. Whether fires encompassed the entire study site that frequently cannot be determined from the composite fire-scar record because it combines all the scars from the entire study site into a single record, as described above (fig. 4.09). The composite WMI is similar to the MFI and ranges between 1.7 and 17.1 years across the various sites, with an average of 5.6 years.

Some of the reported differences in estimates of fire interval appear to result from differences in sample size. Shorter fire intervals are estimated for fire history sites with large sample sizes than for those with small sample sizes (fig. 4.12A). This relationship probably reflects the ability of larger samples to capture more fires, although the scatter among points indicates that differences in reconstructed fire intervals do not merely reflect sample size but also show the influence of actual controls, such as climate and terrain.

Table 4.01—Fire-scar studies and study sites synthesized in this report

Source	Site name	Phys. Prov.	Elevation	Topo. pos.	Genus	*N*	Record length
			feet				*years*
Aldrich and others (2010, 2014)	Kelley Mtn.	BR	3050-3310	W	*Pinus*	92	1638-2005
	Mill Mtn.	RV	2260-2950	W		63	1704-2003
	Reddish Knob	RV	2070-2950	W		76	1671-2005
Armbrister (2002)	GSMNP	BR	2280-3800	SW	*Pinus*	9	1860-2001
Brose and others (2013, 2015)	Long Branch Hill	AP	1700-1800	NW	*Pinus*	35	1633-2010
	Slate Run		1750-1900	NW		30	1623-2010
	Upper Dry Run		1550-1830	NW		28	1635-2010
DeWeese (2007)	Brush Mtn.	RV	2790-2950	W & SW	Pinus	36	1758-2002
	Griffith Knob		3610-3770	W		36	1764-2004
	Little Walker Mtn.		2620-3020	N		23	1778-2004
	North Mtn.		2200-2490	NW		18	1742-2003
Feathers (2010)	CRX	BR	2000-2030	SE	*Pinus*	15	1735-2008
	CRT			SE rdg. top		20	1720-2008
Flatley and others (2013)	House Mtn.	RV	1700-2000	Ridge top/ upper slopes	*Pinus*	82	1763-2009
	Licklog Ridge	BR	2300-2950	S & SE		116	1729-2009
	Linville Mtn.		3180-3660	S & W		44	1725-2009
Harmon (1982)	GSMNP	BR	850-3090	—	*Pinus*	43	1856-1979
Hessl and others (2011)	Pike Knob	RV	4100-4300	S & W	*Pinus*	25	1868-2008
						11	1887-2010
					Quercus	16	1885-2001
Hoss and others (2008)	Peters Mtn.	RV	2000-2690	W	*Pinus*	73	1794-2005
Hutchinson and others (2008)	REMA2	AP	820-1050	E, S	*Quercus*	29	1877-2000
	REMA3					22	1878-2000
	Zaleski2					24	1870-2000
	Zaleski3					25	1914-2000
	Tar Hollow 2					22	1883-2000
	Tar Hollow 3					17	1900-2000
LaForest (2012)	Gold Mine	BR	1510-1970	W	*Pinus*	45	1728-2007
	Rabbit Creek		1640-1970	NW		36	1763-2008
	Pine Mtn.		1640-1970	W		36	1727-2007
Maxwell and Hicks (2010)	Endless Wall	AP	1900	S	*Pinus*	21	1914-2005
McEwan and others (2007)	Eagle Mill	AP	660-1310	N, E, S, W	*Quercus*	26	1917-2005
	Watch Rock					33	1936-2005
	Ball Diamond					22	1878-2002
	Arch Rock					31	1900-2005
	Raccoon Creek					25	1889-2005
	Shawnee					20	1889-2005
	Road Branch					20	1885-2002
	Dickerson Hollow					20	1893-2002
	Silver Creek					28	1879-2005
McEwan and others (2014)	Big Everidge Hollow	AP	1050-1970	E	*Quercus*	21	1678-2009
Schuler and McClain (2003)	Pike Knob	RV	4270	E	*Quercus*	20	1869-2002
Shumway and others (2001)	Big Savage Mtn.	AP	1970-2200	S & E	*Quercus*	20	1616-1997
Sutherland (1997)	REMA	AP	790	N	*Quercus*	14	1871-1995

Note: The Genus column indicates which genus of trees was sampled for fire scars. The N column indicates the number of scarred trees in the sample.
— = no data reported from study.
Phys. prov. = physiographic province; Topo. pos. = Topographic position; AP = Appalachian Plateau; BR = Blue Ridge; RV = Ridge and Valley; GSMNP = Great Smoky Mountains National Park; CRX = Cooper Ridge "Near" site; CRT = Cooper Ridge "Far" site; REMA = Raccoon Ecological Management Area.

Table 4.02—Calculations of fire interval for the study sites described in table 4.01

Source	Site name	Composite		10 percent filter		25 percent filter		Point		Decadal fire index
		MFI	WMI	MFI	WMI	MFI	WMI	MFI	WMI	
		years								
Aldrich and others (2010, 2014)	Kelley Mtn.	3.9	3.7	—	—	5.8	5.5	7.1	7	0.9
	Mill Mtn.	5.4	5.1	—	—	7.8	7.5	11.1	10.2	0.7
	Reddish Knob	4.8	4.6	—	—	8.2	7.4	12.5	11.3	0.7
Armbrister (2002)	GSMNP	7.5	6.8	—	—	—	—	5.6	—	0.7
Brose and others (2013, 2015)	Long Branch Hill	19.4	11.2	—	—	—	—	22.1[a]	—	0.2
	Slate Run	14	9.4	—	—	—	—	25.4[a]	—	0.2
	Upper Dry Run	10.9	6.3	—	—	—	—	13.3[a]	—	0.3
DeWeese (2007)	Brush Mtn.	4.1	3.3	9.8	8.1	—	—	11.9	—	0.7
	Griffith Knob	2.3	1.9	5.8	4.3	—	—	13.4	—	0.6
	Little Walker Mtn.	2.8	2.6	4.6	4.1	—	—	8.9	—	0.7
	North Mtn.	3.2	2.6	7.7	6.5	—	—	11.5	—	0.8
Feathers (2010)	CRX	6.2	5.6	—	—	—	—	8.1	—	0.5
	CRT	3.4	3	—	—	—	—	10.7	—	0.4
Flatley and others (2013)	House Mtn.	2.6	2.1	—	—	7.9	6.5	9.8	8.1	0.8
	Licklog Ridge	2.2	2	—	—	4.6	4.4	9.1	8	0.7
	Linville Mtn.	4	3.4	—	—	6.5	5.8	13.1	11.1	0.6
Harmon (1982)	GSMNP	—	—	—	—	—	—	12.7	—	—
Hessl and others (2011)	Pike Knob	—	—	7.1	6.3	—	—	14.1	—	0.4
		—	—	9.4	7.9	—	—	15.8	—	0.4
		—	—	—	—	—	—	49.8	—	—
Hoss and others (2008)	Peters Mtn.	2.5	2.2	—	—	12.5	12.3	18.4	16.7	0.6
Hutchinson and others (2008)	REMA2	9.3	9.1	—	—	—	—	—	—	—
	REMA3	9	9.2	—	—	—	—	13[a]	—	0.1
	Zaleski2	14.5	11.3	—	—	—	—	—	—	—
	Zaleski3	—	—	—	—	—	—	—	—	—
	Tar Hollow 2	—	—	—	—	—	—	—	—	—
	Tar Hollow 3	—	—	—	—	—	—	—	—	—
LaForest (2012)	Gold Mine	2.1	1.8	2.6	2.2	5	4.2	10	—	0.6
	Rabbit Creek	1.9	1.8	3.1	2.6	5.6	5.2	10.3	—	0.7
	Pine Mtn.	2.4	2.1	3	2.6	7.3	6.7	9.7	—	0.4
Maxwell and Hicks (2010)	Endless Wall	4.5	3.2	—	—	—	—	13.7[a]		0.2
McEwan and others (2007)	Eagle Mill	2.1	1.7	—	—	—	—	—	—	—
	Watch Rock	8.4	8.2	—	—	—	—	—	—	—
	Ball Diamond	6.6	6.3	—	—	—	—	12.1[a]	11.6	0.5
	Arch Rock	9	8.1	—	—	—	—	—	—	—
	Raccoon Creek	6.4	5.7	—	—	—	—	—	—	—
	Shawnee	5.3	4.7	—	—	—	—	5.3[a]	5.3	0.5
	Road Branch	8.6	6.7	—	—	—	—	7[a]	7	0.4
	Dickerson Hollow	12.2	11.1	—	—	—	—	15.6[a]	14.6	0.4
	Silver Creek	—	—	—	—	—	—	—	—	—
McEwan and others (2014)	Big Everidge Hollow	9.3	—	—	—	—	—	34.7	—	0.2
Schuler and McClain (2003)	Pike Knob	19.5	17.1	—	—	—	—	35[a]	—	0.1
Shumway and others (2001)	Big Savage Mtn.	8.2	7.6	—	—	—	—	29.6[a]	—	0.3
Sutherland (1997)	REMA	5.4	3.6	—	—	—	—	10.2[a]	—	0.2

Note: The column labels at top indicate the scar data on which the fire intervals were calculated (e.g., composite intervals were based on the composite record of all scars at the study site).
MFI = mean fire interval; WMI = Weibull median interval; GSMNP = Great Smoky Mountains National Park; CRX = Cooper Ridge "Near" site; CRT = Cooper Ridge "Far" site; REMA = Raccoon Ecological Management Area.
— = no data reported in the study.
[a] = Estimated by us from the fire chart but not reported in the study.

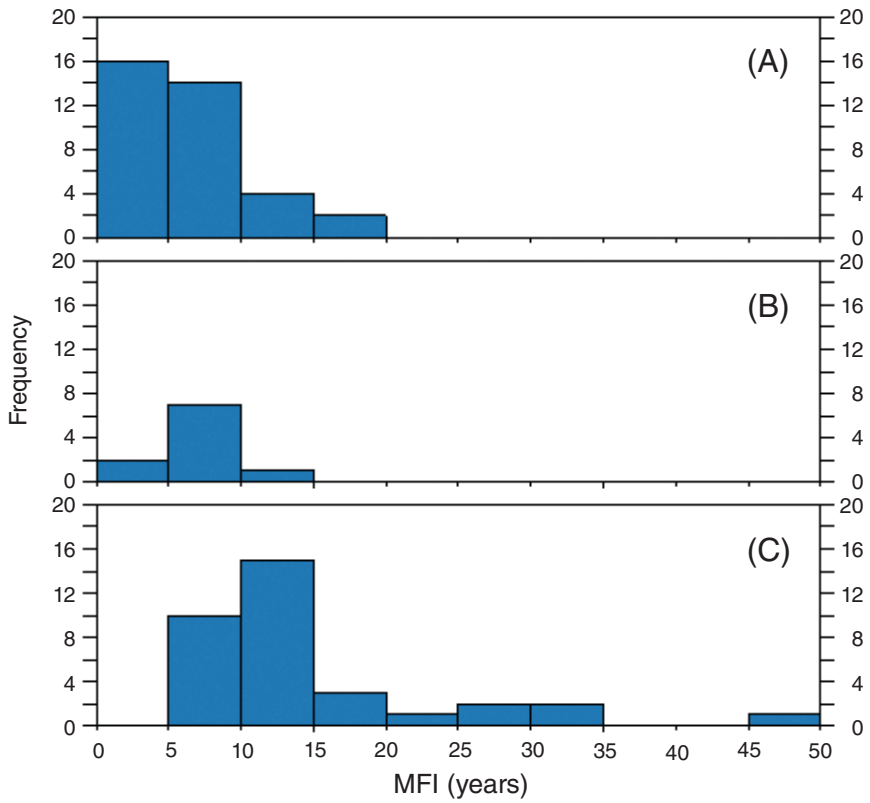


Figure 4.11—Distribution of fire intervals among the studies reported in table 4.02: (A) composite mean fire interval (MFI), (B) filtered composite MFI (25 percent), and (C) point MFI.

The influence of these controls can be minimized by comparing among neighboring stands within a study site (fig. 4.12B–D). Each study site included four separate pine stands on a mountain slope (Aldrich and others 2010, 2014), and each stand contained a different number of fire-scarred trees. Because fire frequency probably was similar among the stands on a single mountainside, the observed differences in MFI likely reflect differences in the completeness of fire history records, with larger samples generally having a fuller record than smaller samples. Sample size appears to influence the estimates of fire interval. The trends suggest, in fact, that the site-level composite MFI (i.e., the MFI for all four stands combined) may offer the best portrayal of fire interval because it is the most thorough. Whether compositing across an entire site is appropriate, however, depends on how widely fires spread over the landscape. If fires routinely encompassed multiple pine stands, it would mean that the entire study site was part of a single fire compartment and should be analyzed as such.

We will consider fire size and spread in more detail in a later section, but because the actual sizes of the fire compartments are not certain, it is important to analyze fire intervals through multiple measures to bracket a potential range. Unfortunately, few Appalachian fire history publications report filtered composite fire intervals (Aldrich and others 2010, 2014; Flatley and others 2013; DeWeese 2007; LaForest 2012). Of those applying the 25-percent filter (table 4.02; fig. 4.11B), MFI ranges between 4.6 and 12.5 years, with an average of 7.1 years and median of 6.9 years across the 10 sites for which it is reported. The corresponding WMI values are 4.2–12.3 years, with an average of 6.6 years. These results indicate that major fires burned a substantial portion of each study site at intervals of roughly 4–13 years with an average of about 7.0 years (Grissino-Mayer 2016).

The estimates for the point fire interval are longer (table 4.02; fig. 4.11C), with MFI of 5.3–49.8 years (average 15.0 years) and WMI of 5.3–16.7 years (mean 10.1 years). For studies that do not report point MFI, we calculated it from the published fire charts and included it in table 4.02. These estimates are probably biased toward long fire intervals because some studies do not distinguish between recording and non-recording intervals. Nonetheless, even these conservative estimates indicate a quite high fire frequency for most study sites. At the most frequently burned Shawnee site in Ohio (McEwan and others 2007), fires can be interpreted to have occurred at every point on the landscape at about a 5-year interval, at least during the four decades (1889–1931) represented at the study site. These decades encompass the period of frequent, severe burning associated with industrial land use, and unfortunately the Shawnee record does not extend further back in time. However, even some of the older fire chronologies have short intervals, as seen at Kelley Mountain in Virginia (Aldrich and others 2014), with a point MFI of 7.1 years for the period 1725–1921.

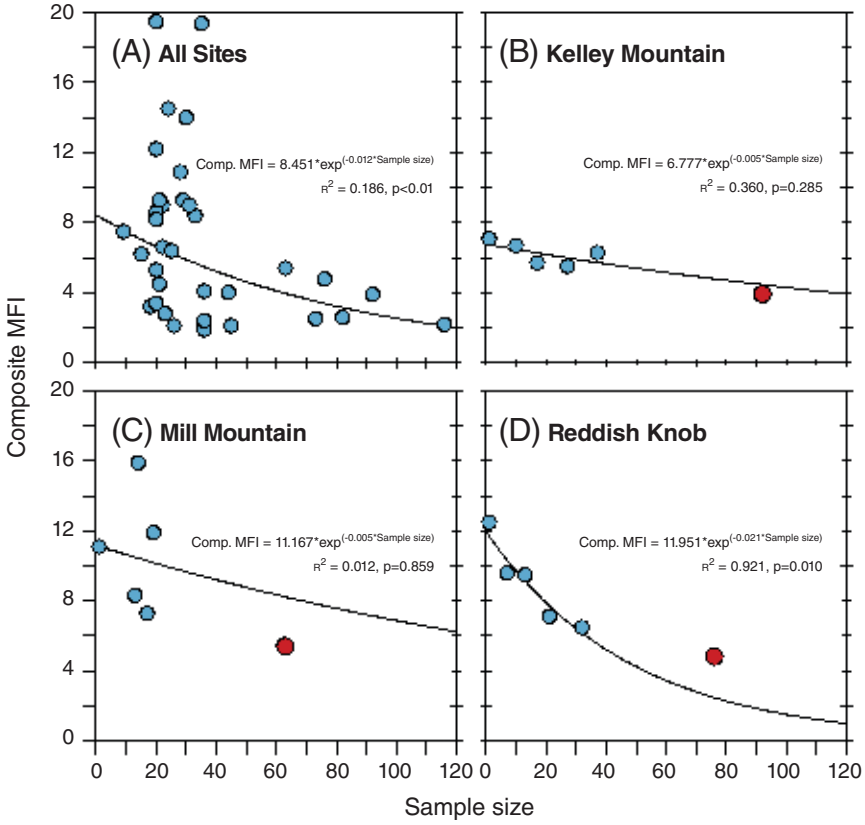


Figure 4.12—Relationship between composite fire interval and sample size for (A) all studies reviewed in this report and (B–D) pine stands at three fire history study sites on the George Washington National Forest (Aldrich and others 2010, 2014). For B–D, the trend lines were fitted to the blue points, which indicate the composite mean fire interval (MFI) for the four individual stands at each study site. One of the blue points also indicates the point fire interval, which represents the sampling level of a single tree (i.e., fire scars were not composited and therefore the sample size is entered as one tree). Red points indicate site-level composite MFI, for reference; these points were excluded from the trend lines to avoid the assumption that an entire study site functioned as a single fire compartment.

VARIABILITY IN FIRE INTERVALS

Care should be taken, while focusing on MFI and WMI, not to overlook variations in fire interval, given that (1) the occasional long interval can have important consequences for plant regeneration, and (2) very short intervals between two or more successive fires can reduce the density of tree seedlings and saplings and thereby shape the forest/woodland structure that develops. For the studies reporting filtered composite fire intervals, the LEI and UEI indicate that intervals exceeding about 10–15 years could be expected occasionally (table 4.03). At the Reddish Knob site, for example, 12.5 percent of the fire intervals are predicted to exceed 14.4 years (and 12.5 percent should be less than 2.7 years; also see fig. 4.13A–C).

From the modeled Weibull distribution, we can also estimate the probability of any specific interval. For example, oak seedling establishment may require an interval of at least 10–40 years to enable the seedlings to grow large enough to survive subsequent fires (Brose and others 2014). The broad range of 10–40 years suggests that the precise requirements for seedling establishment are uncertain. The requirements undoubtedly vary among oak species and depend on such factors as fuel load, fire behavior, and site productivity. For argument's sake, we will assume a critical interval of 10 years. Using the Reddish Knob fire interval data, we find that 31.9 percent of the filtered composite fire intervals, or roughly one-third of them, would exceed this critical length (fig. 4.13D).

Table 4.03—Variability in fire interval based on the filtered composite fire-scar record

Source	Site name	Lower exceedance interval	Upper exceedance interval	Range
		---------- *years*	----------	
Aldrich and others (2010, 2014)	Kelley Mountain	2.5	9.5	2-15
	Mill Mountain	3.6	12.4	2-17
	Reddish Knob	2.7	14.4	2-26
DeWeese (2007)	Brush Mountain	2.3	18.6	1-29
	Griffith Knob	1	11.7	1-19
	Little Walker Mountain	1.5	7.9	1-12
	North Mountain	2	14.5	1-21
Flatley and others (2013)	House Mountain	1.9	14.9	1-26
	Licklog Ridge	1.9	7.6	2-12
	Linville Mountain	2.1	11.7	2-24
Hoss and others (2008)	Peters Mountain	6.9	18.2	4-20
LaForest (2012)	Gold Mine	1.3	9.2	1-13
	Rabbit Creek	2.1	9.4	2-10
	Pine Mountain	2.7	12.4	2-15

Would this fire regime, where one in three intervals exceeded the critical length, have been suitable for oak establishment? To find out, we would need to know how many years are required for three fire intervals to pass because one of those three intervals should exceed the 10-year threshold (on average). Reddish Knob had a filtered composite MFI of 8.2 years, so it burned three times every 25 years, on average (i.e., 8.2 years × 3 intervals ≈ 25 years). This means that during every 25-year period, one interval was long enough to enable oak seedlings or sprouts to become established and attain a fire-resistant size: the fire regime appears to have provided ample opportunities for oak establishment. Because oak trees live more than 25 years, an oak population could have been maintained indefinitely under such a fire regime, with younger oaks regularly replacing old ones that died.

In contrast, if oaks actually require a 40-year interval without fire, the past fire regime was unsuitable—only about 0.001 percent (or 1 in 100,000) of the fire intervals would have been that long (fig. 4.13D). That is, only one interval in 820,000 years would have permitted oak establishment (i.e., 8.2 years × 100,000 intervals = 820,000 years). An oak population could not persist on a site without one or more seedling establishment episodes during the typical lifespan of the trees, or about 50–100 years for the shortest-lived Appalachian oak species [scarlet oak (*Quercus coccinea*) and black oak (*Q. velutina*)] and 300 years for the longest-lived species [white oak (*Q. alba*) and chestnut oak (*Q. montana)*] (Loehle 1988).

In truth, it would be impossible to identify a critical fire interval that applies to all oak species on all sites. Whether an interval provides enough time for oak establishment would depend in part on the fire resistance of each oak species and how rapidly a seedling or sprout could grow. On a site with favorable growing conditions (e.g., good soil), 10 years might be long enough for a particular species, but it could be insufficient on a droughty site where the seedlings grow slowly.

Interrelationships between plant growth and fire likely account for many of the vegetation patterns on Appalachian landscapes. For example, oak-hickory forests occupy moderately moist north- or east-facing mountain slopes, while the more fire-resistant pines cover drier south- or west-facing slopes and ridges (fig. 4.14). On these dry slopes, only a few old oaks can be found scattered among the pines, suggesting that oak seedlings and sprouts generally did not establish and grow to a fire-resistant size during even the longest fire intervals. Moreover, fires may have burned hotter on the dry sites (see chapter 2), so a longer fire interval

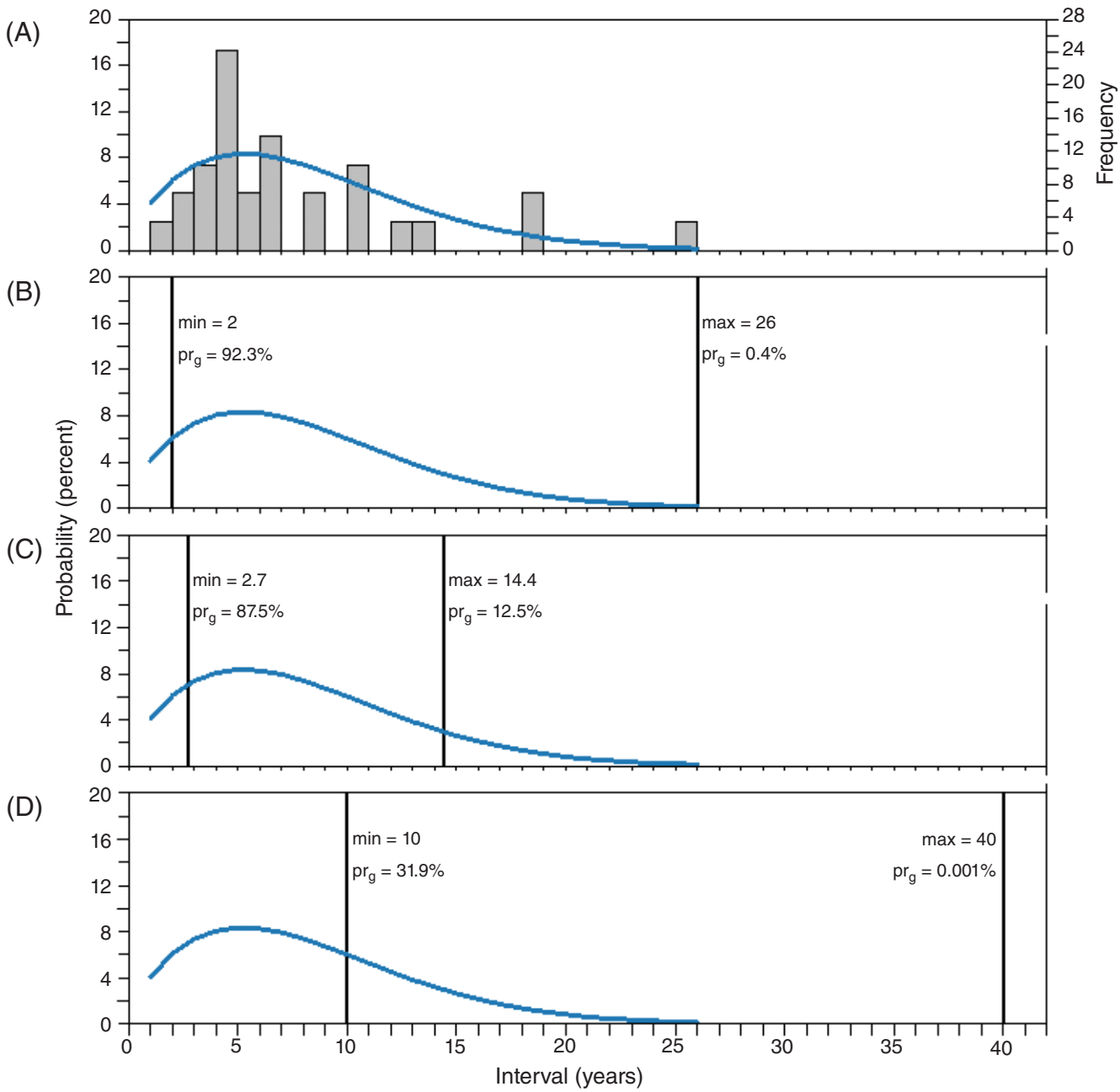


Figure 4.13—Weibull distribution of filtered composite fire interval data from Reddish Knob, VA (Aldrich and others 2014), demonstrating (A) the actual frequency distribution of fire intervals (gray bars) with the modeled probability distribution superimposed (blue line), (B) the modeled probabilities of the minimum (2 years) and maximum (26 years) fire return intervals recorded at the site, (C) the modeled probabilities of the lower (LEI) and upper (UEI) exceedance intervals, and (D) the modeled probabilities of a 10-year and 40-year fire return interval.

would have been necessary for oaks to have attained a large enough size to enable them to withstand the high temperatures by developing thicker bark or more expansive roots around the base where little fuel could accumulate.

The persistence of pines on dry slopes apparently reflects the fire resistance of even fairly small seedlings. Some pines survived burning at ages as young as 4–7 years, according to fire-scar data, and at stem diameters as small as 0.6–4.5 cm. These are the minimum ages and diameters at which trees recorded their first scar at three sites in western Virginia (Aldrich and others 2010, 2014), and they correspond with the ages (5–10 years) at which Table Mountain pine trees can bear cones (Gray and others 2002). To be sure, it is unusual to find fire scars on such small trees, but even the average age at first scarring was quite young, between 12.6 and 19.7 years among the three sites, and average stem diameter was only 5.1–7.4 cm. Clearly, the Table Mountain and pitch pines are adapted to a rigorous environment (fig. 4.15) where poor, droughty soils constrain growth and fires recur at short intervals.

(A)

(B)

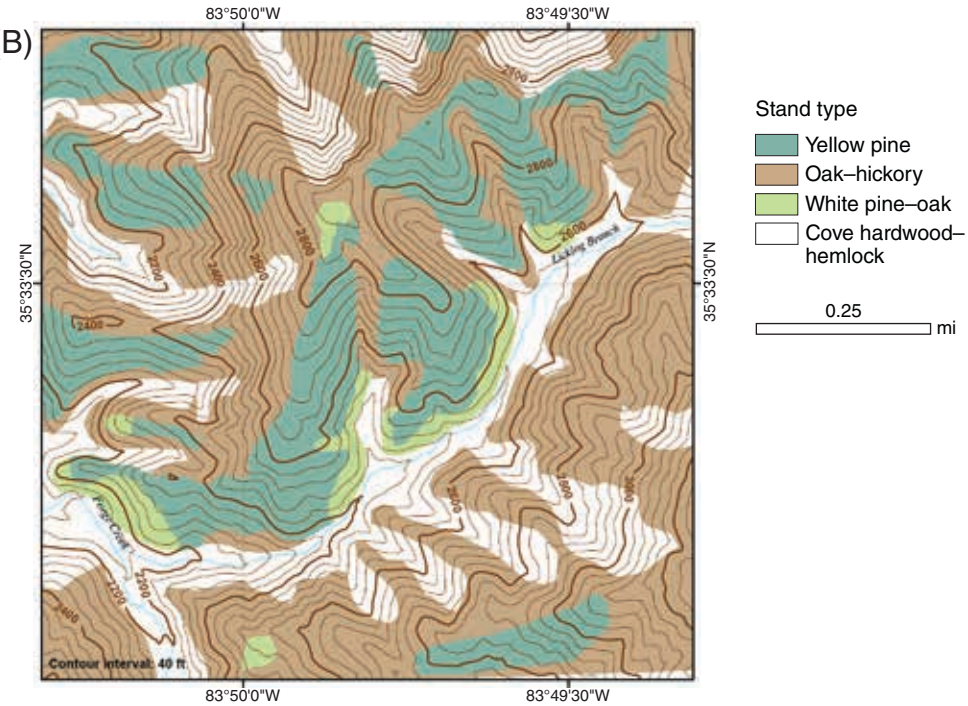


Figure 4.14—Vegetation distribution on Appalachian slopes. (A) View of the north slope of Brush Mountain, Jefferson National Forest. The view is toward the south, and pine stands are visible as the dark patches covering the west-facing slopes of spurs and surrounded by hardwood forest matrix. (B) Topographic distribution of forest types in a portion of Licklog drainage basin, Great Smoky Mountains National Park (Flatley and others 2013, 2015).

Figure 4.15—Dry oak-pine stand in the Blue Ridge Mountains, Jefferson National Forest.

TEMPORAL CHANGES IN FIRE FREQUENCY

An important question arising from the fire interval analyses is how well they represent the preindustrial fire regime. It is the earlier fire regime(s) that are of most interest, especially to guide prescribed burning when attempting to restore and maintain fire-dependent vegetation. Therefore, if the industrial logging period had an anomalous fire regime, as suggested by the conceptual model presented in fig. 1.02 and repeated here in fig. 4.16, it would be useful to calculate fire intervals separately for the earlier periods to characterize the fire regime before the industrial impact was manifest. In this section, we look for temporal variations in the fire-scar records to ascertain how fire frequency varied under changing land uses.

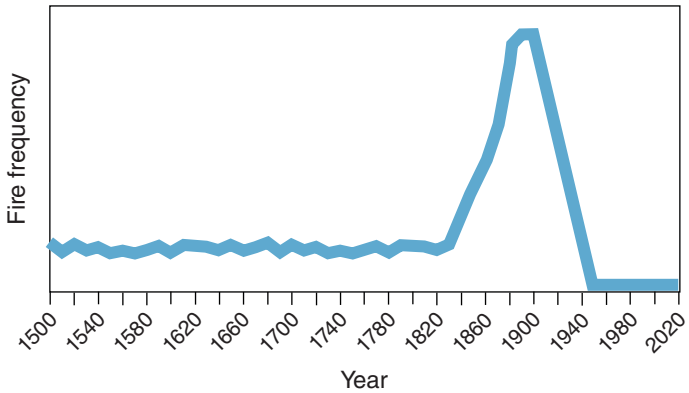


Figure 4.16—Conceptual model of Appalachian fire history, after Brose and others (2001). According to this model, fires occurred regularly during aboriginal habitation and European settlement before spiking in frequency during the industrial logging episode of the late 1800s. The spike was followed by a rapid decline in fire frequency during the fire exclusion era that began in the early to mid 1900s.

To make such comparisons, we use a fire frequency index first calculated by Hoss and others (2008), referred to in this report as the decadal fire index (DFI). The DFI is calculated by first summing the number of fire scars recorded during each decade. This sum is then divided by the number of trees that are represented during that decade by at least one recorder year; dividing by the number of recording trees standardizes the fire-scar sum to permit comparison between decades with different sample sizes. When the DFI is graphed, it displays decade-to-decade variations in fire frequency and reveals long-term trends in fire occurrence (fig. 4.17). This index offers a conservative estimate of fire frequency because it does not composite the fire scars.

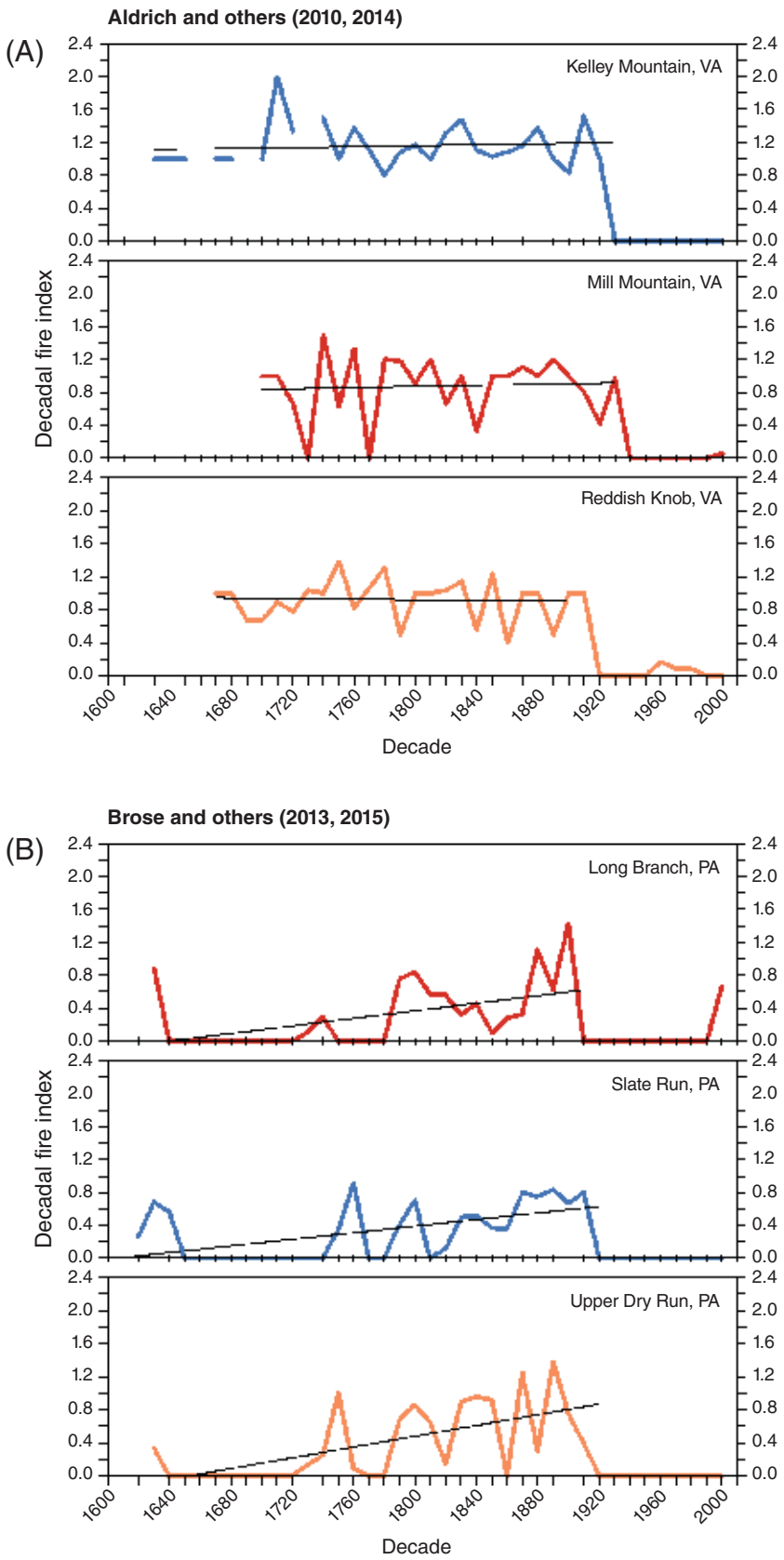


Figure 4.17—Temporal variations in the decadal fire index (DFI, thick colored lines) for (A) three study sites on the George Washington National Forest, Virginia, (Aldrich and others 2010, 2014) and (B) three study sites on the Tioga and Tiadaghton State Forests, Pennsylvania (Brose and others 2013, 2015). The thin black lines are regression lines fitted to the pre-exclusion decades.

The DFI has been reported for several fire history sites (Aldrich and others 2014, Flatley and others 2013, Hoss and others 2008). Additionally, for this synthesis we have calculated DFI for the remaining Appalachian fire history sites based on scar and recording tree data obtained from the published fire charts. Where studies do not distinguish recording versus non-recording years, we had to assume that every sampled tree was recording continuously for every year of its life. This assumption is unrealistic, and therefore the calculations for these cases will be biased toward less fire activity than actually occurred. After obtaining DFI for all the fire history sites, we regressed DFI against time for the pre-exclusion era to look for long-term trends in fire frequency before the exclusion era (table 4.04; fig. 4.17). If fire frequency rose over the course of European settlement and industrialization, positive relationships should emerge.

The DFI analyses suggest two general conclusions. First, fire frequency declined sharply with the advent of fire exclusion and remained low thereafter (fig. 4.17). Second, little evidence exists for a peak in fire frequency during the industrial phase or for a long-term rise in fire frequency, as positive trends are lacking for most fire history sites (table 4.04). Only in one area, the northern Appalachian Plateau in Pennsylvania, did fire frequency exhibit a positive trend across multiple study sites [fig. 4.17B and Brose

Table 4.04—Summary of regression models analyzing trends in decadal fire index (DFI) over time

Source	Site name	Decades covered	Number of decades	R^2	Trend
Aldrich and others (2010, 2014)	Kelley Mtn.	1630–1929	27	0.006	0
	Mill Mtn.	1700–1939	24	0.004	0
	Reddish Knob	1670–1919	25	0.003	0
Brose and others (2013, 2015)	Long Branch Hill	1600–1909	31	0.349	+
	Slate Run	1600–1919	32	0.321	+
	Upper Dry Run	1600–1919	32	0.425	+
DeWeese (2007)	Brush Mtn.	1730–1939	21	0.142	0
	Griffith Knob	1750–1939	17	0.151	0
	Little Walker Mtn.	1770–1939	17	0.038	0
	North Mtn.	1750–1939	19	0.197	0
Feathers (2010)	CRX	1730–1939	21	0.031	0
	CRT	1720–1939	22	0.284	+
Flatley and others (2013)	House Mtn.	1760–1959	20	0.07	0
	Licklog Ridge	1720–1919	20	0.056	0
	Linville Mtn.	1720–1939	20	0.001	0
Hoss and others (2008)	Peters Mtn.	1790–1949	16	0.1	0
LaForest (2012)	Gold Mine	1740–1939	15	0.001	0
	Pine Mtn.	1720–1939	18	0.304	–
	Rabbit Creek	1760–1939	18	0.053	0
McEwan and others (2014)	Big Everidge Hollow	1670–1940	28	0.111	0
Schuler and McClain (2003)	Pike Knob	1850–1969	12	0.005	0
Shumway and others (2001)	Big Savage Mtn.	1600–1949	35	0.105	0

Note: the Trend column indicates sites for which the DFI shows a statistically significant rise (+), a statistically significant decline (–), or no statistically significant trend (0).
CRX = Cooper Ridge “Near” site; CRT = Cooper Ridge “Far” site.

and others (2013, 2015) sites in table 4.04]. Nearly all the other sites were characterized by temporal trends resembling those shown in fig. 4.17A—fire frequency remained fairly constant over the various land-use phases before exclusion but varied around this level from decade to decade.

The long-term stability of fire activity differs from interpretations found in some fire history papers. For example, McEwan and others (2014) stated that for a site in eastern Kentucky they "detected many fewer fires in the 1700s and early 1800s than in the period from 1875 to 1950. Studies conducted in deciduous forests that have access to fire scars from prior to 1850 largely support these findings" (2014: 318). The problem with such an interpretation, as McEwan and others acknowledge, is that sample size varies temporally—the early part of the record is represented by fewer fire-scarred trees than the later part. Because trees are imperfect recorders of fire history, the change in sample size will inevitably yield an apparent change in fire interval even if no such change actually occurred. Only by compensating for the varying sample size, as through the decadal fire index used here, can fire history be represented more accurately.

In light of the analyses reported here, it appears that previous conceptual models of Appalachian fire history should be revised, at least for areas covered primarily with oak- and pine-dominated forests and other flammable vegetation such as savannas (fig. 4.18). Fires burned frequently during all land-use phases except fire exclusion. Burning was common even on landscapes with little human presence, as seen where aboriginal depopulation preceded European settlement. Frequent burning would have required some minimum density of ignitions, but the required density might have been quite low if fires grew large enough on the unfragmented landscapes of the past to spread regularly through many forested stands and grasslands, including the fire history study sites that have been sampled.

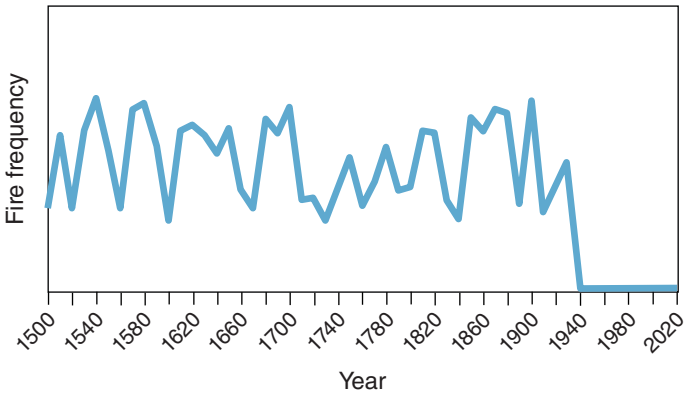


Figure 4.18—A revised conceptual model of fire history for Appalachian landscapes covered with flammable vegetation such oak- and pine-dominated forests. Following observed patterns of decadal fire index (DFI), the model portrays decadal variability in fire frequency prior to the fire-exclusion era but no long-term change until the fire-exclusion era. Notably, the model does not depict an anomalous rise in fire frequency during the industrial period of the late 19th and early 20th centuries.

As for the industrial logging era, some fires may have been unusually severe owing to heavy fuel loads, but the intervals between fires were not atypical. This finding possibly indicates that fire intervals were controlled not by ignition density or by the amount of heavy fuels but by the recovery of fine fuels that carried fires over the landscape. A scarcity of such fuels likely explains the anomalous rising trend in fire frequency on the Appalachian Plateau of Pennsylvania (fig. 4.17B). At these study sites, Brose and others (2013, 2015) sampled fire-scarred red pines and pitch pines on dry upper slopes that were surrounded in the past by eastern hemlock–white pine–northern hardwood forest. This mesophytic vegetation would not have carried fire as readily as the oak- and pine-dominated forests to the south, and therefore fires apparently were unable to burn frequently until the advent of European settlement and logging in the 19th century.

The picture that seems to emerge from the multicentury fire-scar studies conducted in oak- and pine-dominated landscapes is that ignitions occurred at sufficient densities to maintain stable fire regimes regardless of human land use. Therefore, the short fire intervals reported in table 4.02 appear to represent a stable, multicentury fire regime, not one that applies only to a brief industrial episode. Frequent burning extended from presettlement/early European settlement until it was ended by fire prevention and suppression in the 20th century. This interpretation can be made with greatest confidence for the parts of Appalachia covered by the longest fire histories—the core of the region encompassing the Blue Ridge province and the Ridge and Valley province of Tennessee, North Carolina, and Virginia, as well as the eastern Appalachian Plateau in Kentucky and Maryland. These areas have the greatest extent of publicly managed land in the region, and therefore they offer the best opportunities to reintroduce fire at levels that influenced vegetation development for at least two or three centuries before the era of fire exclusion.

FIRE–CLIMATE RELATIONS

Although the influence of human land use on past fire regimes has received much attention in the Eastern United States, climatic variability can also affect burning, as demonstrated by numerous fire history studies in the American West (e.g., Grissino-Mayer and others 2004, Heyerdahl and others 2002, Kitzberger and others 2007, Veblen and others 2000) and by fire–climate relationships observed in the Appalachians today (chapter 2). Because fires currently burn more frequently during dry years than at other times, it is reasonable to hypothesize that a similar relationship existed in the past.

Evidence for such a relationship is limited, however. The authors of fire-scar studies reported in this chapter have compared fire and drought for 20 study sites (in some studies, the analyses were combined across multiple sites) where drought was characterized using the Palmer Drought Severity Index, or PDSI (Palmer 1965). Negative PDSI indicates dry conditions, but fire is not strongly linked to negative PDSI at any Appalachian sites except for Mill

Mountain and Reddish Knob on the George Washington National Forest, Virginia (Aldrich and others 2014). The climate relations for these two sites, one of which is indicated in fig. 4.19, were established using superposed epoch analysis (SEA), a technique based on averaging annual PDSI values for all fire years to look for anomalously high or low values during or before the year of fire (Grissino-Mayer 2001b, 2016). A few other sites exhibit weak evidence for a similar relationship, but in general, most data indicate that fire showed little response to interannual climate variations.

The weak response to climate may stem from the overwhelming influence of human activities (McEwan and others 2007). For example, people could have intentionally avoided burning in drought years and instead targeted favorable burning windows during normal or even wet years, with the result that fire activity was not strongly tied to dry years. If this interpretation is correct, the strong climate relationship for the two sites in George Washington National Forest may reflect their remoteness from human influences (Aldrich and others 2014). To tease out the climate influence for sites with a stronger human impact would require a different analysis technique (Grissino-Mayer 2016). One promising approach is bivariate event analysis (BEA), which can be used to determine whether fire tends to occur in synchronicity with a climate process. Grissino-Mayer (2016) found that for the Brush Mountain fire history site, fires were synchronous with positive phases of the El Niño–Southern Oscillation and the North Atlantic Oscillation. These conditions bring relatively warm, dry winters that would facilitate the drying of fuels and would therefore increase the likelihood of extensive burning during the subsequent spring.

At the time scale of seasons, the annual climate cycle seems to have controlled fire occurrence in the past. Dormant-position scars prevail at most study sites (table 4.05), making up 71.5 percent of the scars, on average. The dominance of dormant-position scars is consistent with fire seasonality today, where fire activity peaks during spring and fall (chapter 2). These seasons generally present the best opportunities for widespread burning on humid landscapes dominated by deciduous forest—humidity is lower than usual, wind is strong, and no canopy is present to block the wind and sun from drying the fine fuels on the forest floor.

Earlywood scars also make up a substantial proportion (mean 24.6 percent) of the total at some locations, especially the Ridge and Valley province, but latewood scars are more rare (mean 8.3 percent) (table 4.05). Because earlywood scars formed in spring, they may be explained by the same springtime weather that accounts for the dormant scars. In fact, some individual fires are recorded by dormant-position scars on certain trees and by earlywood scars on others (Aldrich and others 2010), suggesting that the fire occurred just as trees were ending their dormancy. Of the dormant scars formed in spring (instead of fall), they probably belong with earlywood scars in a single, multimonth spring fire season, as seen at present (chapter 2). Any further specifications as to the months or portions of months that correspond with dormant versus earlywood scars would require greater knowledge about tree-ring phenology. This topic deserves future research, including investigations into how phenology varies with respect to latitude, terrain, and climate change.

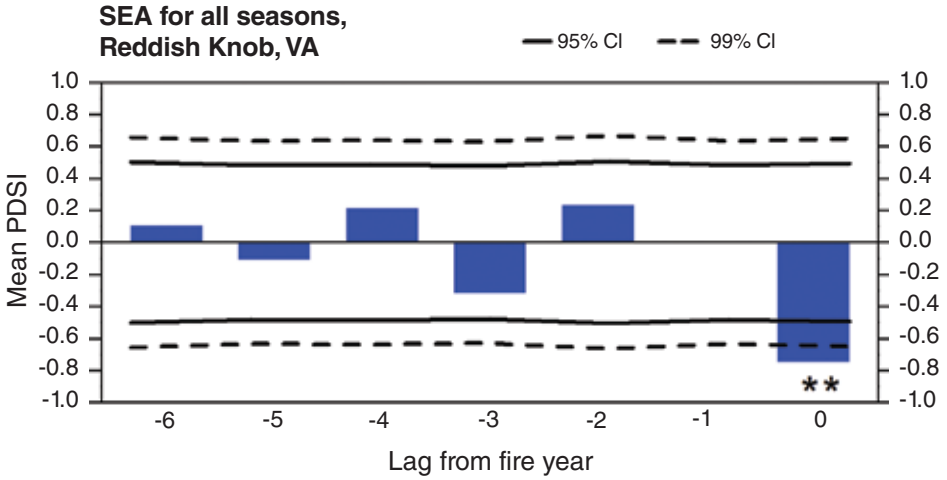


Figure 4.19—Results of superposed epoch analysis (SEA) for the Reddish Knob study site, George Washington National Forest, Virginia (Aldrich and others 2014). SEA was used to determine if fires were associated with anomalous Palmer Drought Severity Index (PDSI) during the year of fire or during the six preceding years. Fires at Reddish Knob were associated with drought (indicated as a negative PDSI value) during the year of fire. Asterisks indicate a statistically significant association. CI = confidence interval.

Table 4.05—Fire-scar seasonality for each study site, calculated as the percentage of all scars at the site for which seasonality could be determined

Source	Site name	Season		
		Dormant	Early	Late
		----------percent----------		
Aldrich and others (2010, 2014)	Kelley Mtn.	86.1	13.9	0
	Mill Mtn.	89.6	9.7	0.7
	Reddish Knob	56.5	37.1	6.4
Armbrister (2002)	GSMNP	>50	—	—
Brose and others (2013, 2015)	Long Br. Hill	100	0	0
	Slate Run	91.3	8.7	0
	Upper Dry Run	50	50	0
DeWeese (2007)	Brush Mtn.	84	14.2	1.8
	Griffith Knob	29.7	67.6	2.7
	L. Walker Mtn.	35.1	60.8	4.1
	North Mtn.	76.3	22.4	1.3
Feathers (2010)	CRX	91.7		8.3
	CRT	87		13
Flatley and others (2013)	House Mtn.	75.4	23.7	0.9
	Licklog Rdg.	90.6	9	0.4
	Linville Mtn.	75.2	24.8	0
Hessl and others (2011)	Pike Knob	16	56	28
		12	53	35
		89	11	0
Hoss and others (2008)	Peters Mtn.	93.6	1.8	4.6
Hutchinson and others (2008)	All sites combined	85.7	14.3	0
LaForest (2012)	Gold Mine	61.7		38.3
	Rabbit Creek	84.1		15.9
	Pine Mtn.	83.8		16.2
Maxwell and Hicks (2010)	Endless Wall	100	0	0
McEwan and others (2007)	All sites combined	84	13	3
Shumway and others (2001)	Big Savage Mtn.	91	2.9	6.4
Sutherland and others (1997)	REMA	69	25	6

Note: For two studies (Feathers 2010 and LaForest 2012), the dormant- and early-season scars were reported together, and we have indicated these combined-season values by placing them between the Dormant and Early columns.
— = no data reported.
GSMNP = Great Smoky Mountains National Park; CRX = Cooper Ridge “Near” site; CRT = Cooper Ridge “Far” site; REMA = Raccoon Ecological Management Area.

IGNITION SOURCE: PEOPLE OR LIGHTNING?

Fire seasonality links to the question of ignition source—did people start most fires in the past as they do today? Or did lightning play a greater role when landscapes were less fragmented and fires could spread more readily from sparse ignition points than at present? Fire scars potentially offer insights into these questions (Allen 2002). In general, the preponderance of dormant scars matches the seasonality of anthropogenic fires today and therefore suggests that humans also set most fires in the past. On the other hand, many of the dormant-season scars probably formed as trees were ending dormancy in spring, as discussed above, and therefore could reflect lightning-ignited fires.

A further clue would be provided if scar seasonality varied over time—for example, if the proportion of dormant-season scars increased as human land use intensified over the course of White settlement and industrialization. However, no discernible or consistent shift in seasonality emerges among fire history sites in the Ridge and Valley or Blue Ridge provinces of Virginia and Tennessee (Aldrich and others 2014, DeWeese 2007, LaForest 2012) or in the Appalachian Plateau of Maryland or Pennsylvania (Brose and others 2013, Shumway and others 2001). The constancy in scar seasonality may indicate that people remained the dominant ignition source, even during periods with little human presence in the 17th and 18th centuries. On the other hand, it is conceivable that lightning ignitions compensated for anthropogenic ignitions during periods of low human activity.

Some western U.S. researchers have attempted to discern the relative importance of lightning and anthropogenic ignitions by looking for temporal changes in fire frequency that coincided with known changes in human land use. Where these changes coincided, they may indicate human control over ignitions (Allen 2002). In the Appalachians, however, temporal changes in fire frequency were generally absent (e.g., figs. 4.17A, 4.18), possibly indicating a compensating role of lightning ignitions, at least in some places. Scar seasonality is not inconsistent with lightning ignitions because the lightning fire season overlaps the spring anthropogenic fire season.

Therefore, fire scars do not fully answer the question of ignition source. They record only the occurrence of a fire, not its cause. A reasonable guess is that human-ignited fires predominated in the past as at present, but that lightning-ignited fires contributed more strongly than at present because of open vegetation and continuous fine fuels that would have favored the ignition and spread of these fires (see chapter 2). Lightning was probably an important ignition source in areas where growing-season scars are most abundant and lightning ignitions remain fairly common today (e.g., parts of the Blue Ridge Mountains and the Ridge and Valley province). These areas also have a greater extent of fire-adapted vegetation than the Appalachian Plateau, including oak and pine forests with endemic plants that display fire adaptations such as thick, fire-resistant bark, serotinous cones, and smoke/heat-induced germination. These adaptations are thought to imply a long history of lightning-ignited fires (Frost 1998, Noss 2012).

SPATIAL PATTERNS OF FIRE

Geographical Variations in Fire Frequency Across the Appalachian Region

Regardless of ignition source, an important consideration is whether fire intervals varied geographically across the Appalachian region, given the differences in climate, vegetation, terrain, and land use. This question is especially pertinent to fire management. Because resource managers implement prescribed burning on landscapes that lack detailed fire history studies, they need to know whether the published, site-specific fire histories conform to a general spatial pattern that reflects predictable relationships with climate or other factors.

In one attempt to delineate spatial patterns of fire, Frost (1998) mapped presettlement fire regimes for the entire coterminous United States. He obtained fire return intervals from fire scar studies or estimated them from vegetation characteristics, and then interpreted their relationships with terrain. Terrain dictates the size of fire compartments—large compartments burn more frequently than small ones, all else equal, because few ignitions are needed to burn an entire landscape that contains large fire compartments. Hence the Gulf and Atlantic Coastal Plains, with their vast expanses of uninterrupted uplands, are predicted to have had short fire intervals, whereas the broken Appalachian terrain would have seen longer intervals.

Frost (1998) suggested a pronounced geography of fire across the Appalachian region (fig. 4.20), with longest fire intervals (26–100 years) on the central and eastern Appalachian Plateau and shortest intervals (4–6 years) on the western Appalachian Plateau and parts of the Blue Ridge Mountains. Fairly short intervals (7–12 years) are also predicted for sections of the Ridge and Valley province and for the subdued terrain of the Piedmont east of the mountains. These estimates apply at a coarse resolution. That is, they lump an entire region into a single fire regime class based on the MFI for the most flammable parts of a landscape.

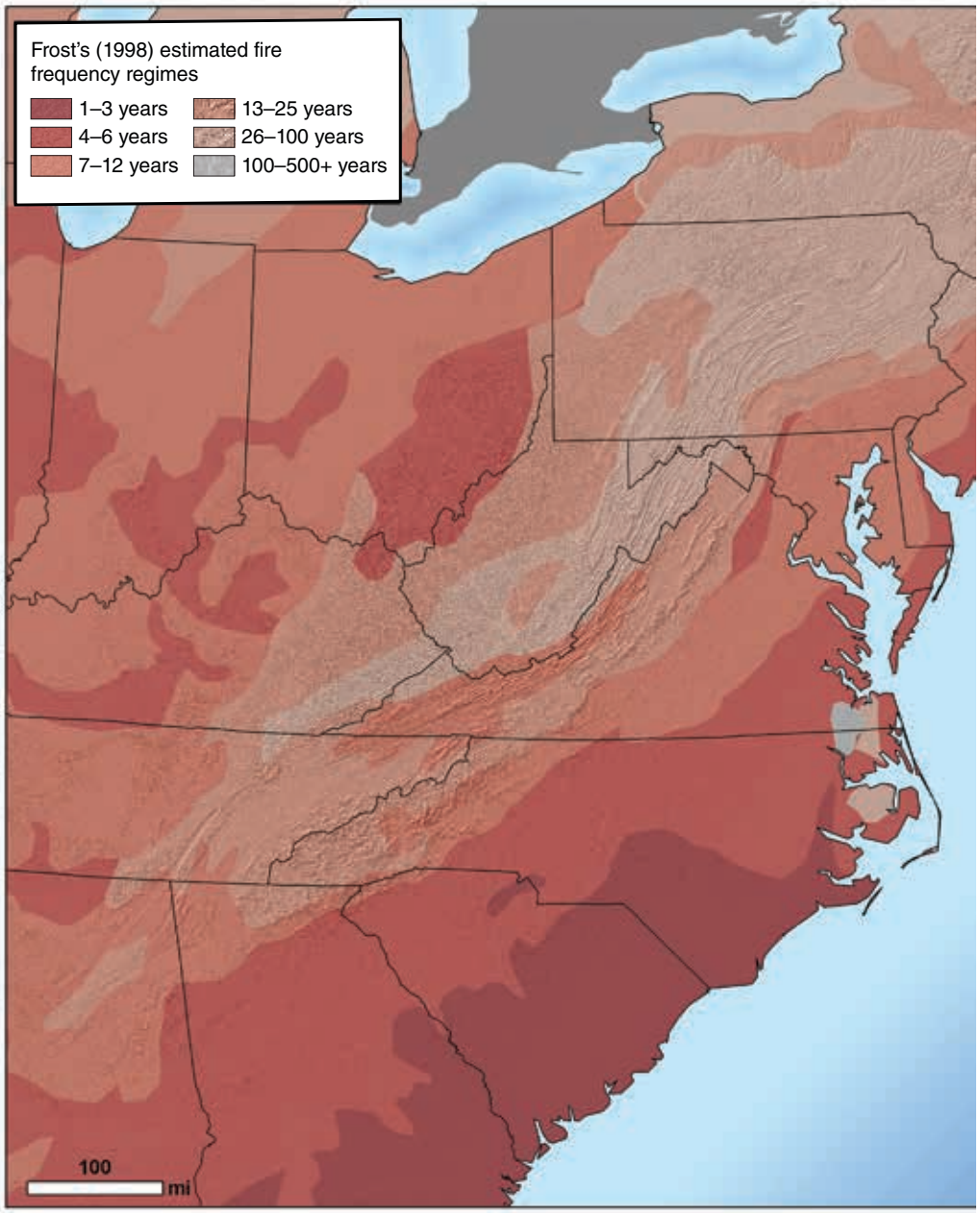


Figure 4.20—Frost's (1998) estimates of presettlement fire frequency in the Appalachian Mountains and surrounding areas. Frequency is highest along the coastal plain and interior lowlands, and lowest in the interior of the Appalachian region. Within the Appalachian region, the highest frequencies are along the eastern and western edges.

In a promising attempt to define a general, predictive model of past fire intervals at higher spatial resolution, Guyette and others (2012) developed a regression model that predicts pre-exclusion (1650–1850) MFI based on fundamental chemical processes controlled by climate in equation (2):

$$MFI = 0.232 + (2.62 \times 10^{-28} \times ARterm) + (52 \times PT_{rc}) \quad (2)$$

where *MFI* is the composite MFI in years for a 247-acre (1-km^2) area. In other words, the model predicts the interval at which fires will burn at least part of a 247-acre area. *ARterm* represents a separate equation that accounts for the effects of physical chemistry (reaction rate and requirements for ignition) as controlled by temperature and precipitation. It also includes oxygen concentration as a function of elevation. PT_{rc} represents fuel amount and moisture, based on precipitation and temperature. Because it is based on fundamental chemical processes, this model is robust in that it can be applied to any location in the United States (or elsewhere). The model was calibrated by using composite MFI for 170 fire history sites spanning a wide range of climates across North America, predominantly from the West but also from the East, including one or two locations in the Appalachian region. In calibrating to MFI, the model translates chemical reaction rate to likelihood of fire ignition and spread. The model predictions explain 80 percent of the variability in independent validation datasets.

To examine model predictions for the Appalachian region, we reproduced and mapped the predictions by using a 247-acre (1-km^2) grid for the region. The resultant map (fig. 4.21) suggests pronounced geographical variations that generally correspond to the patterns identified by Frost (1998): composite MFI of 6–10 years for the warmest, driest valleys, but 50 years or more for the cool, wet highlands of the Appalachian Plateau and Blue Ridge Mountains.

This predicted pattern generally corresponds with empirical estimates from the fire history studies discussed in this report. Study sites in the Blue Ridge Mountains and the Ridge and Valley province had short composite MFI (fig. 4.22, large circles), as did sites along the western edge of the Appalachian Plateau. The eastern section of the Plateau had longer intervals (small circles). It should be noted that this map includes both pine-based and oak-based fire histories, and that oak provides less reliable fire histories than pine. Therefore, to examine spatial patterns based solely on the best records, we mapped the pine-based studies alone (fig. 4.23). The resultant map excludes most of the Appalachian Plateau studies, but the pattern appears consistent with the previously mapped pattern in showing less frequent fire on the handful of Plateau sites than in the two provinces to the east.

Spatial patterns of MFI may also be distorted by the large differences in sample size among studies, and we therefore complemented the composite MFI maps by mapping two additional fire-frequency estimates that are insensitive to sample size: point MFI and the average decadal fire index for each site. However, both suffer from the recorder year problem, which means that fire frequency may appear comparatively subdued at sites for which we estimated the values from published fire charts that do not distinguish between recording and non-recording fire intervals (see table 4.02 for the sites where this consideration applies).

The mapped patterns (figs. 4.24, 4.25) are similar to those for composite MFI. The general pattern seems robust, therefore suggesting that an actual fire-frequency gradient existed in which fire activity was greatest in the Ridge and Valley province, the Blue Ridge Mountains, and possibly the western edge of the plateau. Fire was less common on the eastern Appalachian Plateau. The general agreement of this pattern with that predicted from the Guyette and others (2012) model suggests that past fire regimes were strongly influenced by the overall climate of a site and the resulting vegetation, even if—as discussed in the section on fire–climate relationships—temporal patterns of burning were not sensitive to climatic variations from year to year.

Despite the resemblances between predicted and observed spatial patterns, however, the model overestimates composite MFI for Appalachian sites. That is, the *relative* values of MFI correspond with predicted variations across the region, but their *absolute* values are shorter than predicted. When the observed and predicted MFI are compared for the 21 fire chronologies covering the preindustrial era (fig. 4.26), the predicted intervals are found to be 4.2 times longer, on average, than the observed intervals. Predicted MFI was near the observed interval for only two sites, both on the Appalachian Plateau. The other three plateau sites also show a reasonable correspondence in that predictions and

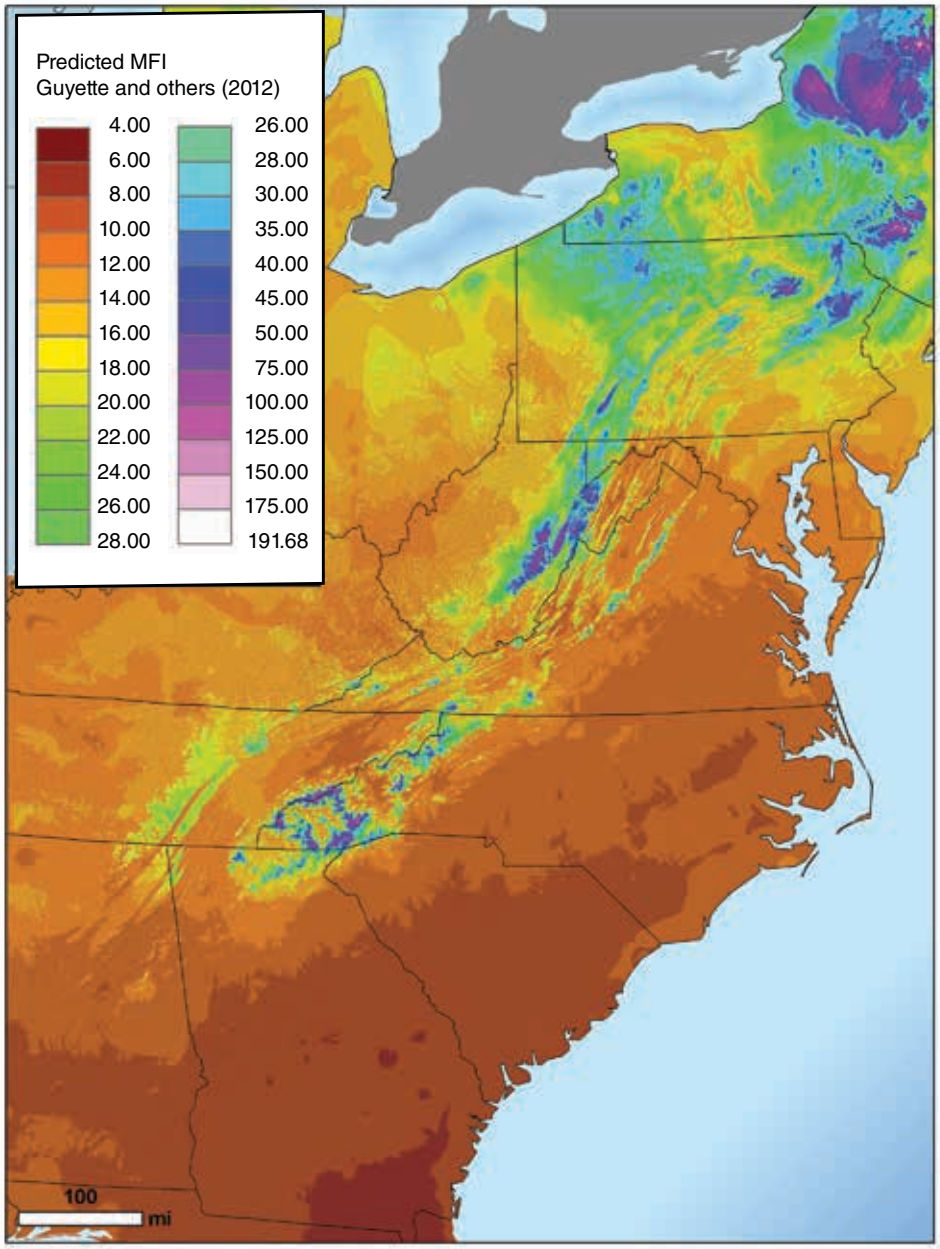


Figure 4.21—Pre-exclusion composite mean fire interval (MFI) predicted for 247-acre (1-km^2) grid cells by using the regression model of Guyette and others (2012). Fire frequency is highest on the southern coastal plain and decreases toward the cool, moist climates at higher latitudes and elevations.

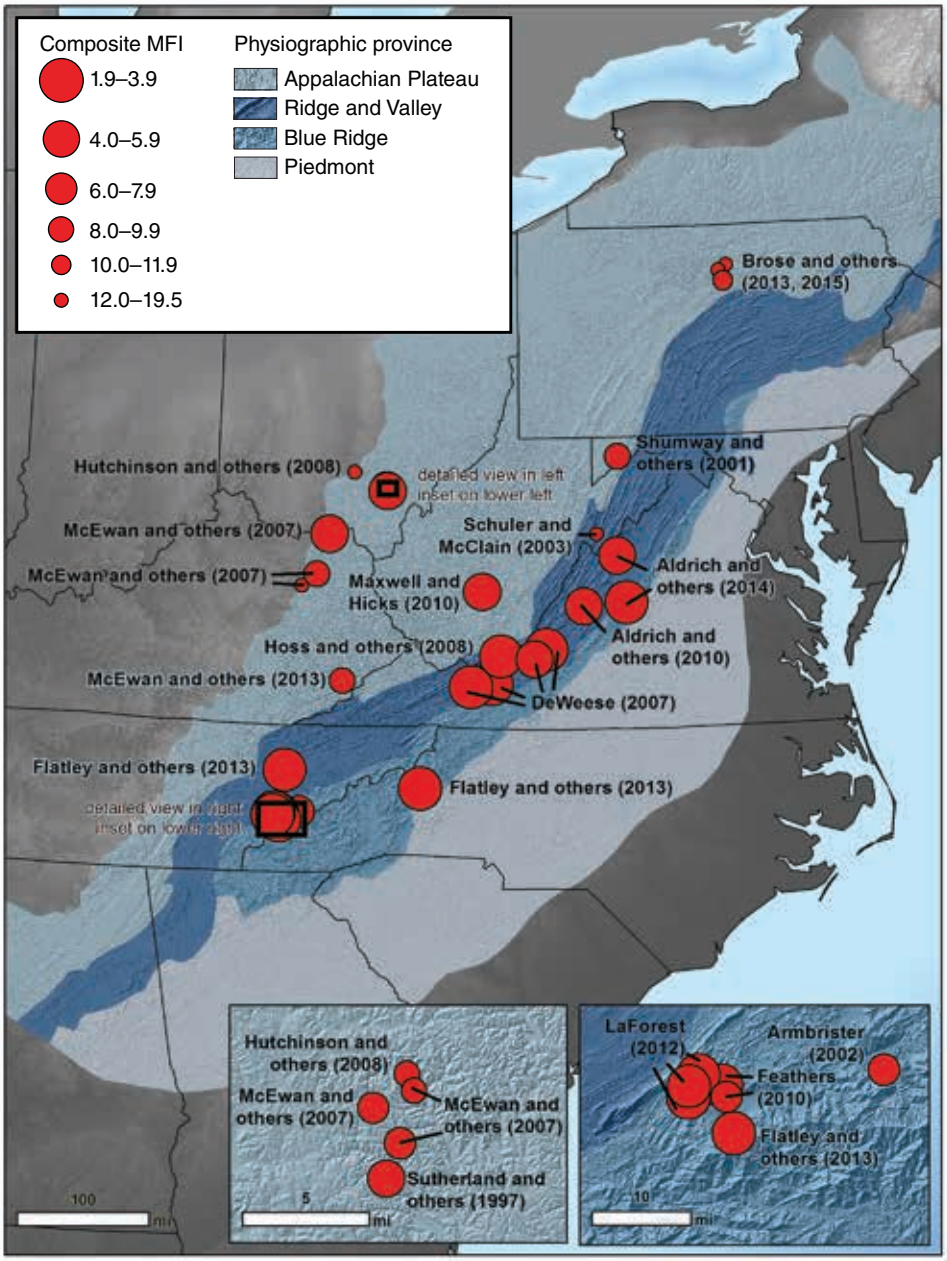


Figure 4.22—Composite mean fire interval (MFI) for all reviewed fire-scar studies in the Appalachian region. Fire intervals are represented using red graduated symbols, with larger symbols indicating shorter fire intervals. Sources are listed adjacent to study sites. Composite MFI is relatively short along the Ridge and Valley province and the Blue Ridge Mountains, short to moderate on the western Appalachian Plateau, and long on the eastern Appalachian Plateau.

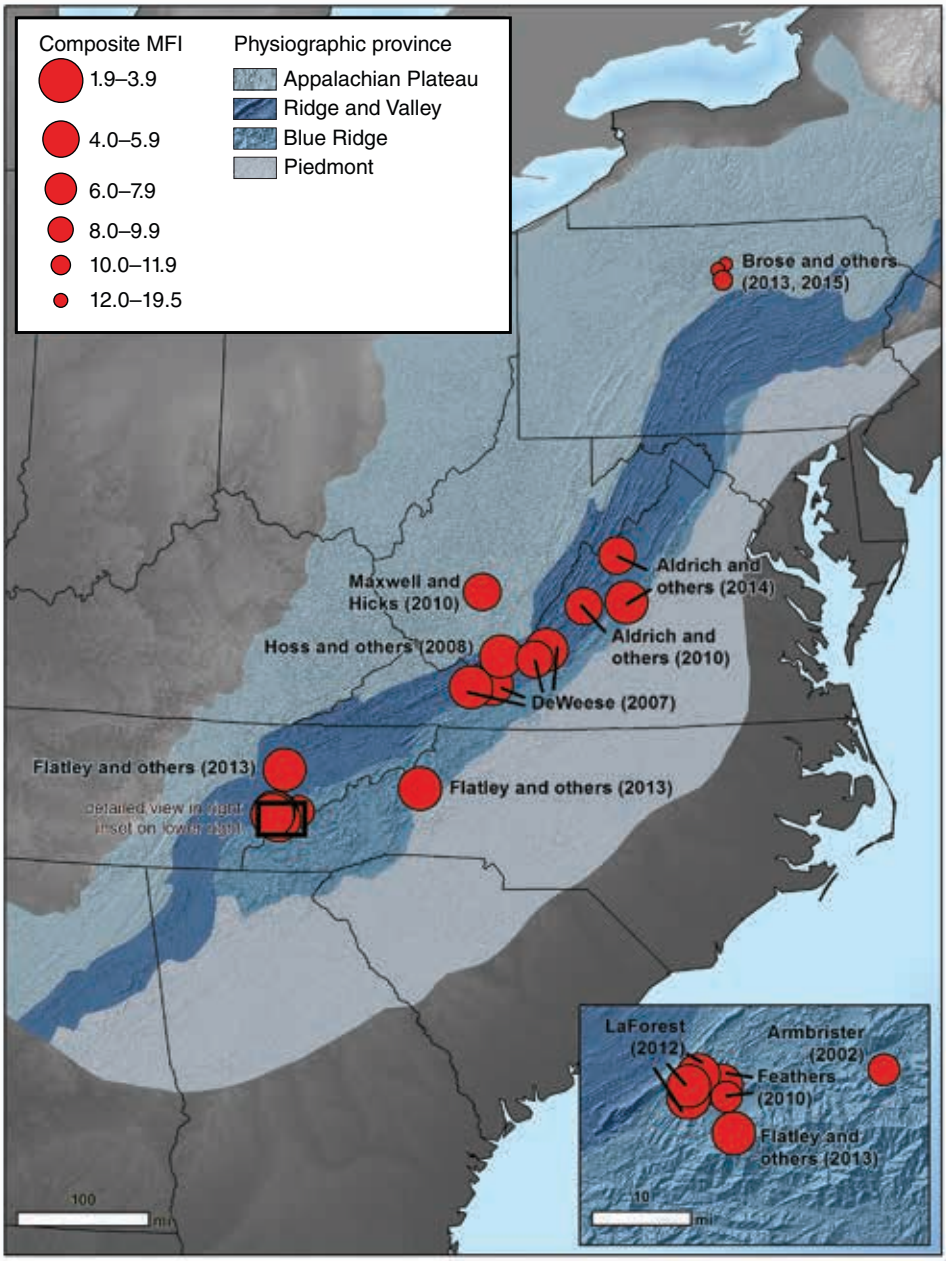


Figure 4.23—Composite mean fire interval (MFI) for all reviewed fire history studies based on fire-scarred pines in the Appalachian region. Fire intervals are represented using red graduated symbols, with larger symbols indicating shorter fire intervals. In general, composite MFI is consistent across the central and southern Appalachian region. The longest intervals are in the northern section of the Appalachian Plateau in Pennsylvania. Sources are listed adjacent to study sites.

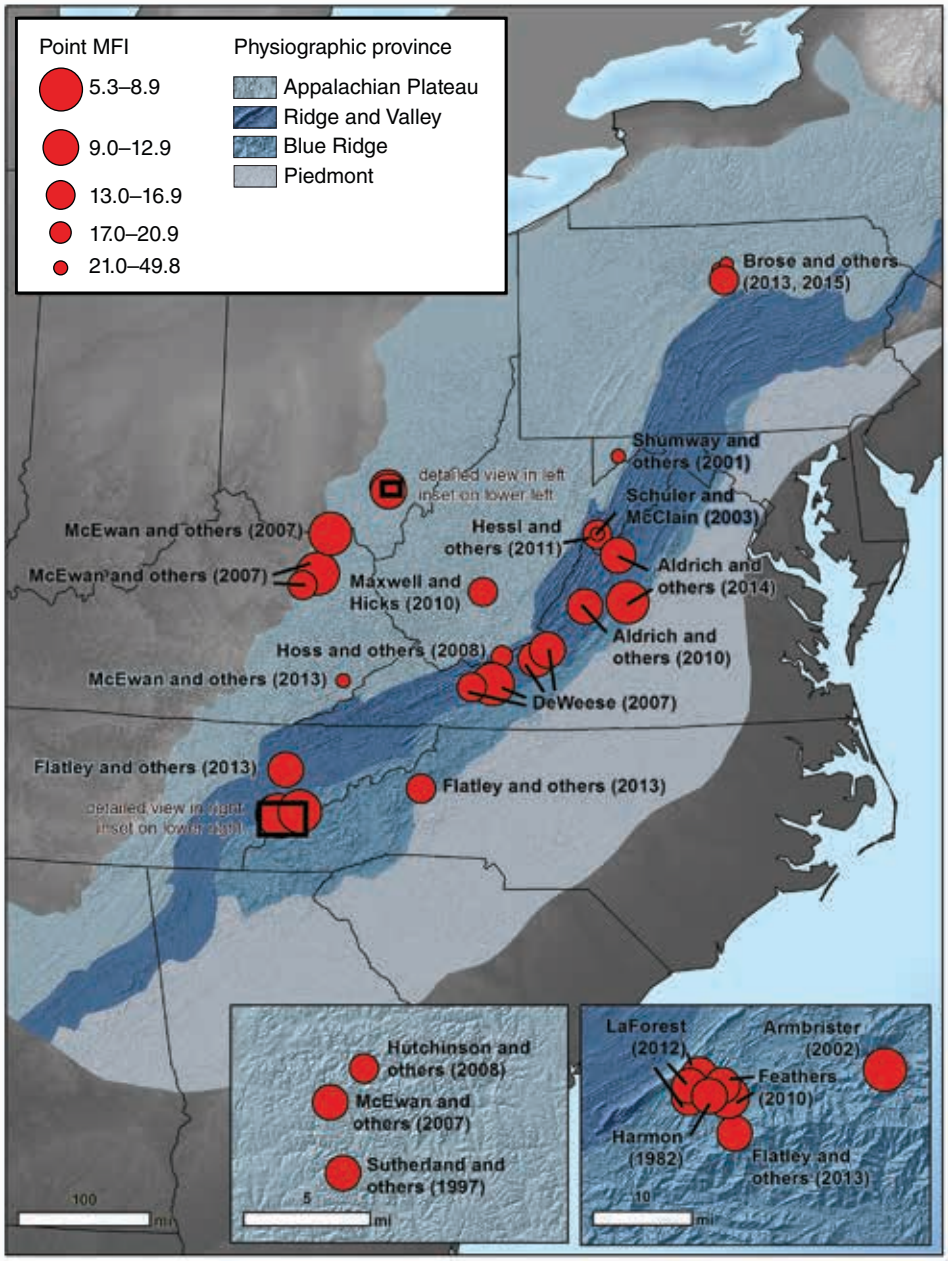


Figure 4.24—Point mean fire interval (MFI) for all reviewed fire-scar studies in the Appalachian region. Fire intervals are represented using red graduated symbols, with larger symbols indicating shorter fire intervals. Point MFI is relatively short along the Ridge and Valley province, the Blue Ridge Mountains, and the western Appalachian Plateau. Point MFI is long on the eastern Appalachian Plateau. Sources are listed adjacent to study sites.

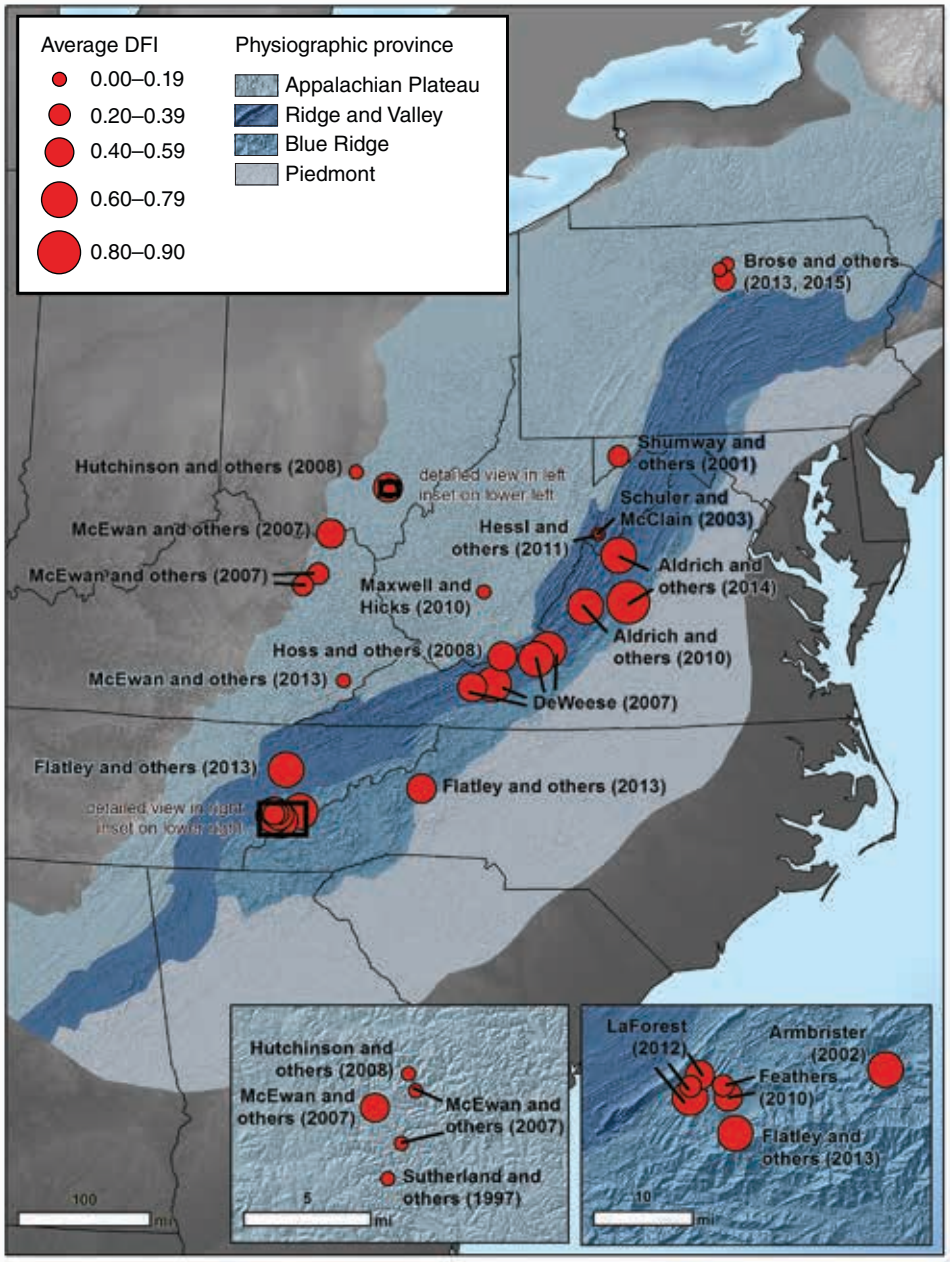


Figure 4.25—Decadal fire index (DFI) averaged across all pre-exclusion decades for all reviewed fire-scar studies in the Appalachian region. Shorter intervals are represented with gradually larger red circles. DFI is relatively short along the Ridge and Valley province and the Blue Ridge Mountains, short to long on the western Appalachian Plateau, and long on the eastern Appalachian Plateau. Sources are listed adjacent to study sites.

observations rise in concert, but model predictions are poor for sites in the Ridge and Valley province and the Blue Ridge Mountains, where the observed MFI falls within a narrow range of about 2–6 years even at relatively cool, moist, mid-elevation sites with much longer predicted intervals.

The discrepancies may reflect several factors. First, the model omits variables, such as ignition frequency and land use, that could have affected fire frequency. Second, it distills temporal variations in climate to the annual mean and reduces spatial variations in climate to a 247-acre resolution. However, these simplifying assumptions would not seem to bias MFI predictions systematically toward overestimates of fire interval length. The overestimates likely reflect additional factors that are not amenable to modeling. Two such factors are spatial contingencies and positive feedbacks.

Spatial contingencies arise because the area surrounding a point can play as great a role as conditions at the point itself (Phillips 2001). Contingencies weaken the predictability of many earth-surface phenomena, from soil development (Phillips 2001) to fire occurrence (Baker 2003). In the case of fire frequency, the long, high ridges in the Ridge and Valley province and the Blue Ridge Mountains connect to lower slopes and valleys with warmer and drier climates that make them susceptible to fire. Fires may have spread widely from more flammable to less flammable sites, elevating fire frequency to higher levels than would be expected from site conditions alone. Examining the location of fire history study sites in these two provinces (e.g., fig. 4.27) reveals the

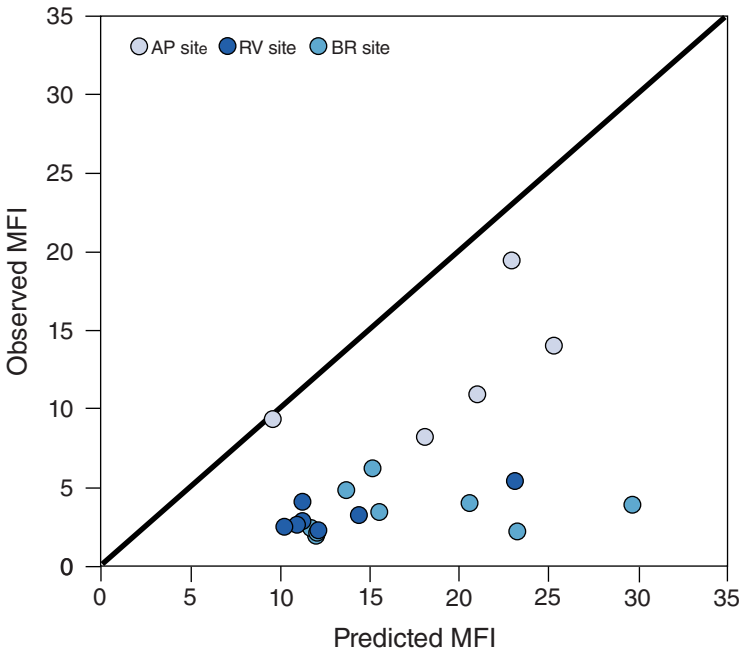


Figure 4.26—Scatterplot demonstrating the relationship between the observed mean fire intervals (MFI) at Appalachian study sites and the MFI predicted for those sites using the regression model of Guyette and others (2012). If observations matched the predictions perfectly, all the points would fall along the diagonal 1:1 line. Where points fall below the line, the model overestimated MFI (i.e., the model predicted less frequent fire than was observed). AP = Appalachian Plateau, RV = Ridge and Valley, BR = Blue Ridge.

proximity of the sites to broad, more fire-prone lowlands. In contrast, the Appalachian Plateau generally has lower relief and therefore less juxtaposition of warm, dry and cool, moist sites (fig. 4.27). Additionally, the slopes on the plateau do not connect to broad, dry valleys as in the other provinces but to moist, narrow stream valleys with relatively incombustible mesophytic forest.

Positive feedbacks probably also elevated fire frequency. Frequent burning would have promoted open forests and woodlands with a fairly continuous grass-shrub understory that, in turn, enabled fires to grow rapidly to large size (Harrod and others 2000). Moreover, the fire-favored oaks and pines shed flammable litter that augmented the continuous fuel bed. In these ways, contingencies and feedbacks likely amplified the basic regional variations in burning (e.g., Appalachian Plateau versus Ridge and Valley province) while diminishing the local differences between mountain slopes and adjacent lowlands.

The Spread of Fire Through Multiple Stands

The regular occurrence of large fires, fed by continuous fine fuels, could have supported frequent burning at individual fire history sites even if ignition densities were low, as in areas remote from human activities. Actual fire sizes cannot be ascertained from the fire-scar data currently available—such estimates would require hundreds of fire-scarred trees from many places on a landscape—but evidence from several study sites indicates that fires spread across the landscape to scar trees at some distance from each other. On the Appalachian Plateau in Pennsylvania, for example, Brose and others (2013) sampled old fire-scarred pitch pine and red pine trees scattered for a mile or more along upper slopes. Half or more of these pines were sometimes scarred in a single year. This synchronous scarring suggests that fires had spread along the top of the plateau and backed down into the gorges to scar trees on the upper slopes.

Synchronous scarring has also been observed on mountainsides in the Ridge and Valley province and the Blue Ridge Mountains (Aldrich and others 2010, 2014; Flatley and others 2013). Each fire history site included fire-scarred cross-sections collected from multiple pine-dominated patches separated by hardwood forest (fig. 4.14). Scar synchronicity among the pine stands implies that individual fires spread across the mountainsides to encompass both the pine-dominated patches and the intervening hardwood stands. The frequency of these synchronous fires has been estimated by using the MFI for "area-wide" fires, with an area-wide fire defined as an event recorded at all stands in a study site during a single year (Aldrich and others 2010, Fisher and others 1987). The area-wide MFI gives a conservative estimate of fire intervals because to calculate it requires matching fire dates across multiple stands with small sample sizes. The MFI calculations nonetheless yield relatively short intervals (table 4.06) and therefore indicate that frequent burning was not restricted to the pine stands from which the fire-scarred trees were sampled. Rather, fires commonly burned through the oak-pine mosaic that covers the mountain slopes of the Ridge and Valley

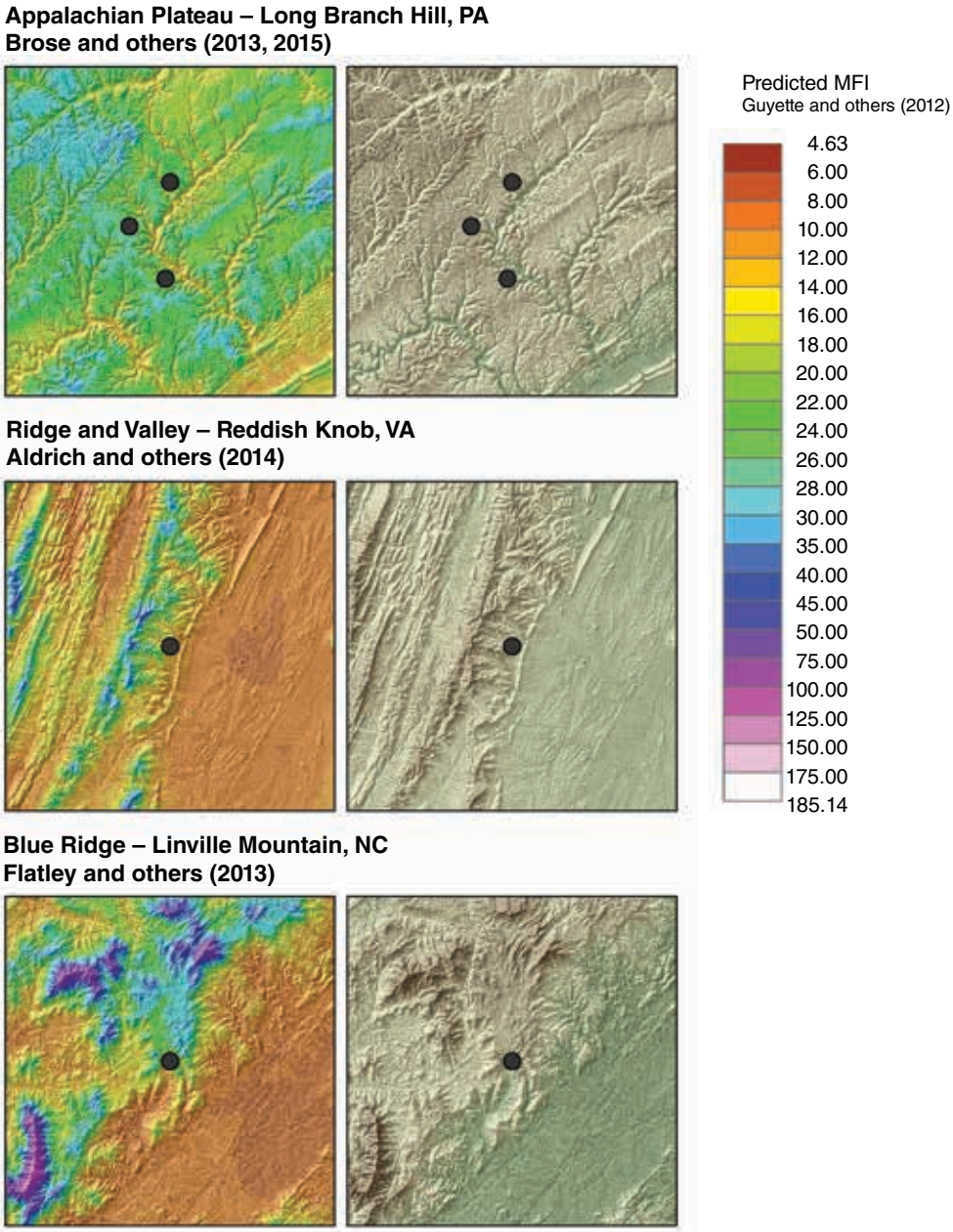


Figure 4.27—Locations of selected fire history sites (represented as black circles) relative to predicted mean fire interval (MFI) calculated by using the regression model of Guyette and others (2012). The Long Branch Hill sites of Brose and others (2013, 2015) are in close proximity to moist stream valleys containing relatively incombustible mesophytic forest, which may help explain why the fire intervals are relatively long. The Reddish Knob site of Aldrich and others (2014) and the Linville Mountain site of Flatley and others (2013) are in close proximity to broad, fire-prone lowlands, which may help explain the shorter fire intervals.

Table 4.06— Area-wide mean fire interval (MFI) in relation to current (1986–2009) ignition density on the National forest ranger districts in which the study sites are located

Source	Site name	Area-wide MFI	Study site size	Ignition density required to burn all stands separately in one year	Current ignition density by ignition source on ranger district		Ratio of required vs. current ignition density
		years	*acres*	*fires/M acres/yr*	*fires/M acres/yr*		
Aldrich and others (2010, 2014)	Kelley Mtn.	7.8	230	17,391	All	23.3	747
					Humans	13.2	1,319
					Lightning	10.1	1,722
	Mill Mtn.	17.3	230	17,391	All	10.4	1,670
					Humans	7.5	2,317
					Lightning	2.9	5,985
	Reddish Knob	8.8	120	33,333	All	26.1	1,275
					Humans	22.1	1,506
					Lightning	4	8,286
Flatley and others (2013)	House Mtn.	7.2	25	–	–	–	–
	Licklog Ridge	6.5	100	–	–	–	–
	Linville Mtn.	9.2	40	50,000	All	58.9	848
					Humans	40.8	1,225
					Lightning	18.1	2,759

Note: For the two study sites that are not on National forests, we have not included comparisons to current ignition density.
– = published data inadequate to provide calculation.

and the Blue Ridge provinces. These findings suggest that fire compartments were large enough to enclose entire mountainsides, perhaps stretching along the ridges for several miles.[2] These compartments probably also extended into adjacent valleys because small streams typically flow at a roughly perpendicular angle to the northeast-southwest trend of the ridges to join larger streams in the valleys. An ignition in a valley could therefore burn unimpeded to the mountain, run up the mountain slope, and then spread along the middle and upper slopes of the mountain where streams are absent or too small to stop the fire.

The Licklog watershed in the Great Smoky Mountains furnishes a good illustration of area-wide fires. This is an unlogged drainage basin from which 116 fire-scarred pines were sampled at three pine stands interspersed among other forest types covering a south-facing slope above Licklog Branch (fig. 4.14B). Area-wide fires burned across the slope with a MFI of 6.5 years (Flatley and others 2013), in the process scarring a few pines that stood in an oak stand situated between two adjacent pine stands. The fires also spread into the mesophytic cove forest in the valley, at least on occasion, as shown by fire-scarred hardwood and eastern hemlock trees growing to the edge of Licklog Branch at the base of the slope. The entire slope appears to represent a single fire compartment, therefore, in which case the unfiltered composite MFI of 2.2 years (table 4.02) may best approximate the past fire interval for the slope.

These widespread fires contradict recent assertions (e.g., Hart and Buchanan 2012, Matlack 2013) that burning was restricted to small ribbons of oak–pine forest growing on xeric ridgetops. This interpretation apparently reflects a misconception about vegetation distribution, namely, that oak- and pine-dominated stands are restricted to ridgetops. If that were true, fire histories based on oaks or pines might apply only to xeric ridgetops, where frequent burning reflected "microclimatic and edaphic peculiarities" that distinguished xerophytic oak–pine stands from a broader "mesic deciduous forest" that rarely burned (Matlack 2013). Only in close proximity to aboriginal villages could Matlack (2013) envision substantial burning of the prevailing mesic deciduous forest.

Actual conditions on Appalachian landscapes differ greatly from such interpretations. First, not all Appalachian fire history sites are located near former Native American villages (or those of European settlers), yet several sites evidence frequent burning even before the widespread European settlement and industrial logging of the 19th century (e.g., fig. 4.17A). Second, many fire history sites are not located on ridgetops but on mountainsides

[2] Personal communication. 2015. Cecil Frost, Consultant, Blue Star Consulting, 119 Potluck Farm Road, Rougemount, NC 27572.

covered with an oak-pine mosaic that was swept frequently by area-wide fires. Third, in a process known as spotting, wildfires may spread across drainages and ridges when sparks or embers are carried away from the main fire and ignite fuels downwind. Spotting has been observed to ignite patches up to one-half mile away in the Appalachian Mountains (see footnote 1). These circumstances strongly suggest that in the past, fires spread readily through the entire oak–pine complex to influence vegetation dynamics across the mountain slopes of the Ridge and Valley province and the Blue Ridge Mountains.

An area-wide fire event may perhaps represent separate small fires that burned neighboring pine stands synchronously without spreading through the intervening hardwood forest. If we assumed this were the case, it would mean that fire histories represent the pine stands but not the surrounding landscape. This is improbable, however. Synchronous small fires could not have occurred on the regular basis seen in the area-wide MFI calculations because they would have required an unrealistically high ignition density. Consider, for example, the four pine stands that make up the Reddish Knob fire history site on the George Washington National Forest. The ignition of four separate fires during the same year within the 120-acre study site would equate to 33,333 fires per 1,000,000 acres per year (table 4.06). This ignition density is 1,275 times greater than the present ignition density for the National forest ranger district on which the site is located, based on fire incidence data for 1986–2009 from the National Interagency Fire Management Integrated Database (Lafon and Quiring 2012, USDA Forest Service 1998). Such a high ignition does not seem plausible for a mountain slope that was isolated from Native American villages and European settlements until the late 18th century (cf. Aldrich and others 2014). All the more astonishing would have been the ignition of so many fires in small pine stands on the side of a ridge with no ignitions elsewhere, such as the more accessible valley bottom. Nor could lightning have been expected to strike numerous individual stands within a single year—that would require > 8,000 times the current density of lightning-ignited fires (table 4.06). Similar conditions apply to the other study sites reported in table 4.06.

The straightforward explanation for frequent area-wide fires is that the fires spread across the mountain slope to encompass multiple pine and hardwood stands. Exactly how large the fires grew is not yet evident from any fire history studies because none has been conducted at the scale necessary to make such a determination. But we can state confidently that fires were common within the entire oak-pine mosaic.

This mosaic is the primary vegetation feature on Appalachian ridges within the Ridge and Valley and the Blue Ridge provinces (fig. 4.28). It covers approximately 70–75 percent of all the land

Figure 4.28—Landscape in the Blue Ridge Mountains (James River Face Wilderness, Jefferson National Forest) on which the oak-pine mosaic is prevalent.

area within the George Washington, Jefferson, and northern Cherokee National Forests (Medlock 2012; Simon 2011, 2013). It also covers between 23 and 53 percent of the Pisgah and Nantahala National Forests, respectively (Simon and others 2005). In all cases, these are conservative estimates of the total proportion of pyrogenic vegetation because they exclude low-elevation shortleaf pine–oak, high-elevation red oak, and other stand types beyond the immediate vicinity of the mid-elevation oak–pine mosaics at the fire history study sites. The inescapable conclusion that emerges from the data at hand is that fires burned frequently and extensively across the various forest stands that cover most of the mountain slopes in the Ridge and Valley province and the Blue Ridge Mountains.

CONCLUSIONS AND IMPLICATIONS

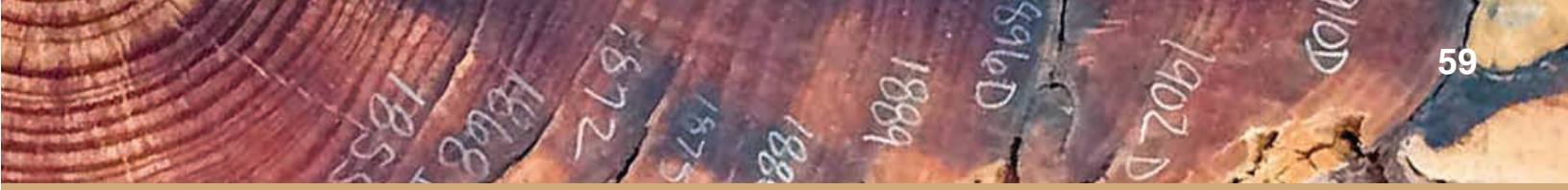
A picture of frequent burning emerges from the network of fire-scar sites that have been established over the past 15 years. This picture is clearest for portions of the Blue Ridge Mountains, Ridge and Valley province, and Appalachian Plateau where lengthy fire chronologies have been assembled from large samples of fire-scarred trees. At these sites, fires occurred frequently, from the beginning of the record in the 17th and 18th centuries until the advent of fire exclusion in the early to middle 20th century.

The reconstructed fire histories show considerable site-to-site agreement, especially within a physiographic province. The robustness of the results suggests that they provide adequate guidance for fire management on the core Federal, State, and private conservation lands within the Blue Ridge and the Ridge and Valley provinces of eastern Tennessee, northwestern North Carolina, and western Virginia. Additionally, the work on the Appalachian Plateau of central Pennsylvania is rounding out our understanding of fire history in the northern part of the study region. When combined with ongoing research in the Pennsylvania section of the Ridge and Valley province (Marschall and others 2016), these studies have application to the extensive State game lands in Pennsylvania.

Other areas are not as well represented by fire history studies, including much of the Appalachian Plateau, large sections of the southern Blue Ridge Mountains, and the Piedmont. Developing fire history studies for these and other underrepresented areas would benefit fire management and would also help contextualize the results from the more intensively sampled locations. For example, did the Piedmont have shorter fire intervals than the mountains, as predicted by the models of Frost (1998) and Guyette and others (2012)? Answering such questions depends on whether an adequate number of fire-scarred trees has escaped decay and destruction by the heavy land use that has characterized certain areas of the Appalachian region.

Just as important as filling these broad geographic gaps is to study fire history more intensively at a landscape scale. Recent debate about fire history largely collapses to the issue of fire extent on landscapes—were fires restricted to narrow ridgetop oak–pine stands, or did they extend broadly across the forested mountain slopes? The evidence at hand strongly suggests that fires burned through the entire oak–pine mosaic, but additional studies are needed to illuminate the full extent of individual fires. Doing so would require large samples of old fire-scarred trees arrayed in many clusters across a landscape. Such clustered sampling has already begun in many of the study sites; one or more of these sites could provide the nucleus for an expanded study.

Such work is labor intensive and time consuming. It is to be expected, therefore, that the expansion of the Appalachian fire-scar network will proceed at a modest pace, at best. Regardless, the studies completed to date have illuminated much that was previously unknown about Appalachian fire history. They support hypotheses (e.g., Abrams 1992, Day 1953, Lorimer 1984) that fire occurred frequently before fire exclusion, and they offer invaluable guidance to managers who implement prescribed burning to restore a fire regime comparable to that which prevailed before fire exclusion.



Chapter 5. Stand Age Structure and What it Indicates About Past Fire Regimes and Fire Effects on Vegetation

INTRODUCTION

Our interest in fire history largely reflects a broader interest in vegetation dynamics and disturbances, especially how fire influences vegetation and what happens to vegetation when fire is withheld from communities that burned frequently in the past. Knowledge about these issues has been built from various types of research, from witness-tree studies to studies of vegetation change after recent burns. Age structure analysis is another useful approach for learning about vegetation changes. By ageing the trees in a stand through tree-ring analysis, researchers obtain a snapshot of tree age distribution at a point in time, and this distribution, though static, permits inferences about stand dynamics and forest history, including the timing and effects of past disturbances (Didion and others 2007, Johnson and others 1994, LaForest 2012).

With respect to fires, the age structure yields two primary insights. The first concerns the fire regime itself, and the second concerns the effects of fire on vegetation. Regarding the fire regime, if a severe fire kills most or all trees in a stand, the forest that regenerates on the site will typically contain a primary age cohort that is reflected in a unimodal age distribution among the colonizing species. In fact, in a crown fire regime (such as is found in some boreal forest landscapes) the age structure is the primary data source for reconstructing fire history because few trees survive with scars that can be dated (Couillard and others 2012, Heinselman 1973, Johnson 1992). Ageing trees in different-aged patches over a landscape enables the researcher to characterize fire frequency by estimating the fire cycle, or the average number of years that would be required for the entire landscape to burn (Johnson and others 1999, Romme 1982).

A different situation applies in a fire regime once characterized by frequent fires, such as the Appalachian Mountains, where the fire interval can be more easily calculated from fire-scarred trees. In these fire regimes, the age structure yields information about the severity of past fires: were they all low-severity surface burns that only killed understory trees and shrubs, or did relatively severe fires occasionally open the canopy and permit unimodal age cohorts to establish in the stand? The latter scenario has been hypothesized by Frost (1998) for the Table Mountain pine–pitch pine stands of the Appalachian Mountains. Frost proposed that these stands developed under a "polycyclic" fire regime in which most of the pines established under the high light levels that followed relatively severe, canopy-opening fires, which burned at intervals of approximately 75 years. Lower-severity surface fires also swept the stands at short intervals, killing understory plants but not the overstory pines (Grissino-Mayer 2016). If this polycyclic or mixed-severity model is accurate, tree age distributions should reveal distinct age cohorts (Fulé and others 2003, Jenkins and others 2011).

The second insight to be gained from age structure concerns fire effects on vegetation. The current age structure reflects which species survived frequent burning in the past and whether less fire-resistant species have established under fire exclusion. In this type of analysis, age structure is used to infer changes in stand composition over time (Aldrich and others 2010, Brose and Waldrop 2010, Lafon and Kutac 2003, Waldrop and others 2003). It is sometimes augmented with vital information on the current stand structure and composition (i.e., percentage of seedlings, saplings, and mature trees). In other words, researchers can use age structure to evaluate concepts such as the fire-oak hypothesis and the mesophication process (Abrams 1992, McEwan and others 2011, Nowacki and Abrams 2008).

FIELD AND LABORATORY METHODS

The standard field approach used in studies of stand age structure and species composition is the establishment of plots in which all trees are identified to species and cored by using an increment borer (Speer 2010). For stands that have also been sampled for fire history reconstruction, pairing the fire history information with detailed plot-level data clarifies the manner in which vegetation responded to past changes in the fire regime (Flatley and others 2015).

At each plot, the field crew measures and records stem diameter and species identification of all living trees with stem diameters exceeding a certain size (commonly 2 inches, or 5 cm, at breast height). An increment borer is used to extract cores from these trees at their base, where the earliest rings can be captured for age structure analysis. As for smaller trees (seedlings and saplings

with stem diameter < 2 inches), they provide information about potential successional trends and are therefore tallied by species, but they are not aged because they are too small to core.

Tree cores are stored in small-diameter tubes, such as straws, for transportation to the laboratory. After drying, the cores are glued into wooden core mounts to be sanded and then dated following the same procedures as for fire-scarred cross-sections (chapter 4). When dated, each tree is assigned to an age-class bin, typically of 10 years in length. Finally, the age-class data for all trees in a plot or study site are aggregated to create a histogram depicting stand age structure.

SYNTHESIS OF AGE STRUCTURE ANALYSES IN THE APPALACHIAN REGION

Age Structure Data from the Appalachian Mountains

For this chapter, we synthesize the results of age structure analyses from 11 sites with yellow pine or yellow pine–oak-dominated stands (Aldrich 2011, DeWeese 2007, Flatley and others 2015, LaForest 2012). The yellow pines are the "hard" or diploxylon pines that make up the subgenus *Pinus* within the genus *Pinus* (Price and others 1998). We also synthesize results from four sites with oak-dominated stands (Aldrich 2011, Flatley and others 2015, Hoss and others 2008). The stands, which were sampled using rectangular plots of 0.247 acre (0.1 ha) in area, were collocated with fire history studies based on numerous old fire-scarred trees in Virginia and Tennessee.

Eight of the yellow pine sites were at middle elevations where stands were dominated by Table Mountain pine and pitch pine. The remaining three were low-elevation sites in western Great Smoky Mountains National Park with stands dominated by shortleaf (*Pinus echinata*), pitch, and Virginia pine (*P. virginiana*) mixed with oaks and white pine. Chestnut oak (*Quercus montana*) dominated the stands at the oak sites with northern red oak (*Q. rubra*), scarlet oak (*Q. coccinea*), and black oak (*Q. velutina*) also common in some stands.

Fire Severity

The age structure data from Table Mountain pine–pitch pine stands (Aldrich 2011, DeWeese 2007, Flatley and others 2015) provide support for a fire regime with occasional fires of moderate to high severity. Most of the age distributions include one or more distinct pine cohorts (e.g., fig. 5.01). However, the trees do not fall into strictly even-aged cohorts dating to a single decade; rather, they fall into broader peaks spanning two decades or more, suggesting that the stands did not recover immediately from severe disturbances.

The lifespans of Table Mountain and pitch pines are too short to permit the development of multicentury age structure analyses such as would be needed to identify several cohorts and verify the operation of a polycyclic fire regime. These pines rarely live beyond 200 years (Della-Bianca 1990, Little and Garrett 1990) but depending on species may live to 300–400 years (Eastern OLDLIST 2013). Most of them would have been killed at younger ages if crown fires recurred at intervals of about 75 years, as suggested by Frost (1998). Some lived longer, however, as evidenced by old fire-scarred trees that were sampled for fire history analyses in and around the plots. Because these fire-scarred trees were sampled from a larger area beyond the plot boundaries, it was possible to obtain enough of them to augment the plot-based age structures with remnants of earlier cohorts.

Graphing the establishment dates for these pines indicates multiple, distinct cohorts in some locations but not in others (fig. 5.02). In the particular case shown in figure 5.02, the

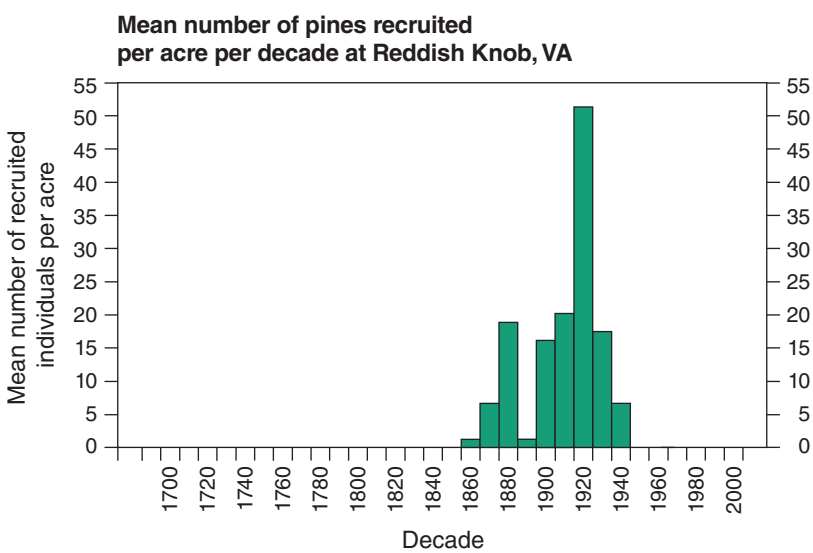


Figure 5.01—The mean number of pines recruited per acre per decade at the Reddish Knob, VA, site (after Aldrich 2011). Data from three pine stands analyzed by Aldrich (2011) are combined in this graph. The distinct pine cohorts that date to the late 1800s and early 1900s likely were established following relatively severe fires or other disturbances.

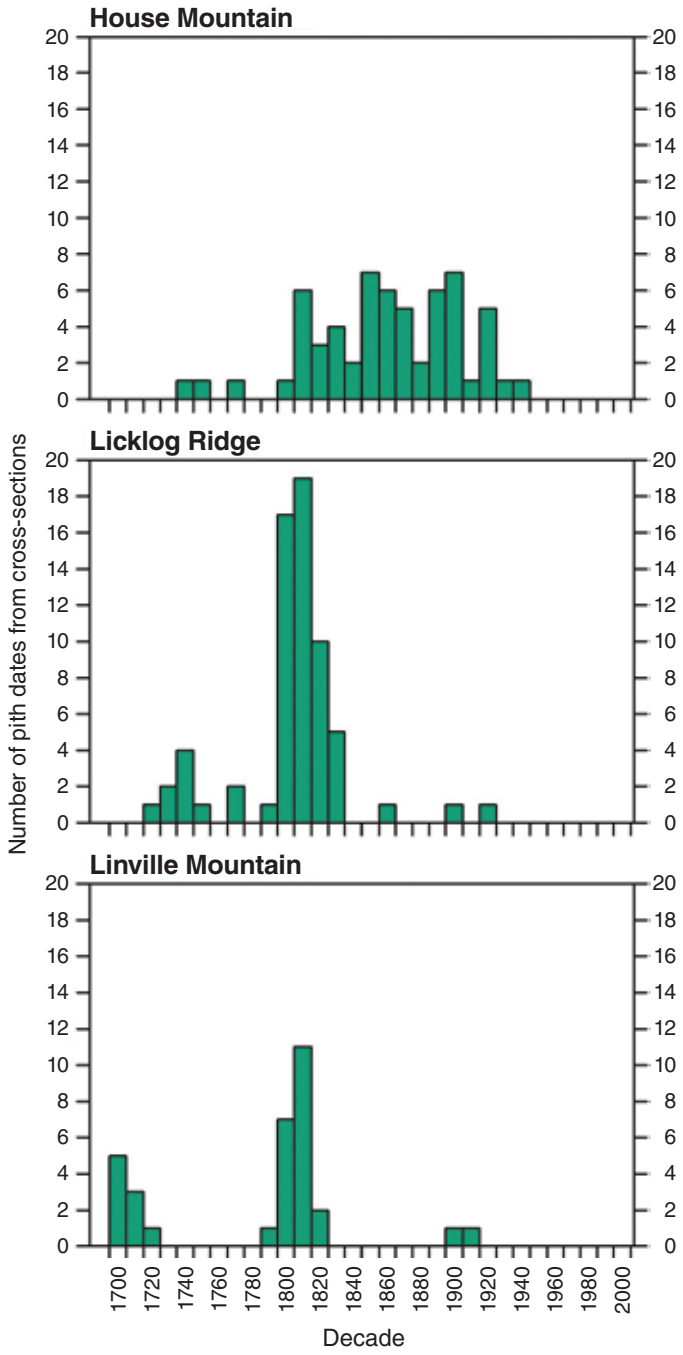


Figure 5.02—The number of pith dates by decade for fire-scarred yellow pine cross-sections at the House Mountain and Licklog Ridge sites in Tennessee and the Linville Mountain site in North Carolina (after Flatley and others 2013). The pine stands at House Mountain show an uneven-aged distribution that indicates the trees were established regularly, whereas Linville Mountain stands show distinct cohorts that indicate the trees were established within short windows of time, probably after severe fires. The Licklog Ridge pine stands also show fairly distinct cohorts, although pine recruitment does not appear to have been confined as strongly to short windows of time as at Linville Mountain.

uneven-aged structure is from a relatively low-elevation site (House Mountain) in the Ridge and Valley province of eastern Tennessee. At that site, fire history was reconstructed from scarred shortleaf, Table Mountain, and Virginia pines. In contrast, the most distinct cohorts were found in higher elevation Table Mountain pine–pitch pine stands at Linville Mountain along the eastern escarpment of the Blue Ridge in North Carolina (Flatley and others 2013). These varying age-structure patterns resemble the range of patterns discovered in a plot-based study of Table Mountain pine–pitch pine stands in different sections of the southern Blue Ridge Mountains (Brose and Waldrop 2006). Such variations suggest that disturbance regimes differed among pine stands (Brose and Waldrop 2006, Flatley and others 2013), with even-aged cohorts emerging where crown fires occurred periodically and uneven-aged structures developing where smaller gaps were present continuously because of frequent burning combined with scattered overstory-tree mortality.

Age structure likely reflects the interplay of fire with other disturbances, especially insect outbreaks and storms (Aldrich and others 2010, Brose and Waldrop 2006, Flatley and others 2013, Lafon and Kutac 2003). Even-aged stands would be particularly susceptible to outbreaks of southern pine beetle (*Dendroctonus frontalis*), which would have contributed to large gaps, heavy fuel loads, and severe fires that perpetuated the development of dense, even-aged cohorts. Such cohorts seem mainly to have developed in relatively pure Table Mountain pine–pitch pine stands (e.g., Aldrich 2011, Flatley and others 2013), whereas uneven-aged pine populations developed in lower-elevation stands containing shortleaf or Virginia pine and a sizable hardwood component (e.g., Flatley and others 2013, LaForest 2012). More data would be needed to confirm this observation, but it is reasonable to expect that the presence of hardwood trees would have reduced stand susceptibility to large gaps created by severe fires because hardwood trees and litter are less flammable than pines. Some hardwoods are also less vulnerable to disturbances such as ice storms (Lafon and Kutac 2003) and southern pine beetles, for which they are not hosts.

The relationship between fire and southern pine beetle is undoubtedly more complex than suggested from the brief foregoing synopsis. One dimension of the relationship that deserves more study is the potential role of fire in immunizing pines against beetle infestation. By maintaining relatively uncrowded pine stands, frequent burning would have promoted tree vigor and thereby enabled the trees to produce the heavy resin flows needed to resist beetle attack (Knebel and Wentworth 2007, Schowalter and others 1981). Moreover, exposure to fire appears to stimulate increased resin flow in Appalachian pines (Knebel and Wentworth 2007), and this elevated flow can be sustained for at least 18 months after the fire. When fires occurred at short intervals in the past, they likely abetted the resistance of pine stands to beetle outbreaks.

Age structure data reveal less about fire regimes of oak stands than pine stands in the Appalachian region. Only four study sites provide both age structure and fire history information (Aldrich 2011, Flatley and others 2015, Hoss and others 2008), and at three of the sites the oak stands appear to have been logged. Each of these logged stands is dominated by a large cohort of oaks and/or other species that were established at about the time of the last major fire. These fires coincided with logging, however, which suggests that a combination of fire and logging probably fostered the establishment of the dominant tree cohort.

To understand the pre-logging fire regime of oak forests requires data from unlogged stands. The best such information is from the Licklog Branch watershed in Great Smoky Mountains National Park, where a detailed fire history reconstruction indicates that fires occurred frequently until 1916, the date of the last major fire (> 25 percent of trees scarred; Flatley and others 2013). Here, the age structure of chestnut oak stands (fig. 5.03; Flatley and others 2015) reveals that oaks established through the 18th, 19th, and early 20th centuries, and it suggests that the moderate-sized gaps needed for oak regeneration were present on a regular basis. Whether these gaps were created by fires, storms, or other events—or from a combination of disturbance agents—cannot be determined from the age structure. Regardless, the uneven-aged oak distribution from Licklog Branch watershed indicates that the stands were not subjected to catastrophic mortality from fires or other events, even while the intermixed pine stands were occasionally burned more severely, as indicated by the lack of old pines in the plots and by the unimodal pine cohorts documented by the fire-scarred cross-sections (fig. 5.02). Most likely, fires burned fairly mildly through the hardwoods but sometimes flared into the crowns as they passed into the pine stands. This interpretation, of varying fire severity across the landscape, is supported by a remote-sensing study of a recent wildfire in Linville Gorge, North Carolina, where pine stands burned more severely than other forest types on the landscape (Wimberly and Reilly 2007).

Tree Establishment Under Changing Fire Regimes

Age structure analyses indicate that yellow pines and oaks recruited under the frequent burning of the pre-exclusion era, whereas a more diverse mix of species became established under fire exclusion (Aldrich 2011, DeWeese 2007, Flatley and others 2015, Hoss and others 2008, LaForest 2012) (e.g., fig. 5.03). To synthesize the results from multiple sites, we combined age structure data from all studies by aggregating the trees into three groups: yellow pines, oaks, and others. Next, for each species group, we stacked the decadal age bins from all study sites so as to align them by their first decade of fire exclusion. This alignment was necessary because effective fire exclusion did not occur synchronously among sites. For each study site, therefore, we designated the decade of the last major fire as decade 0.

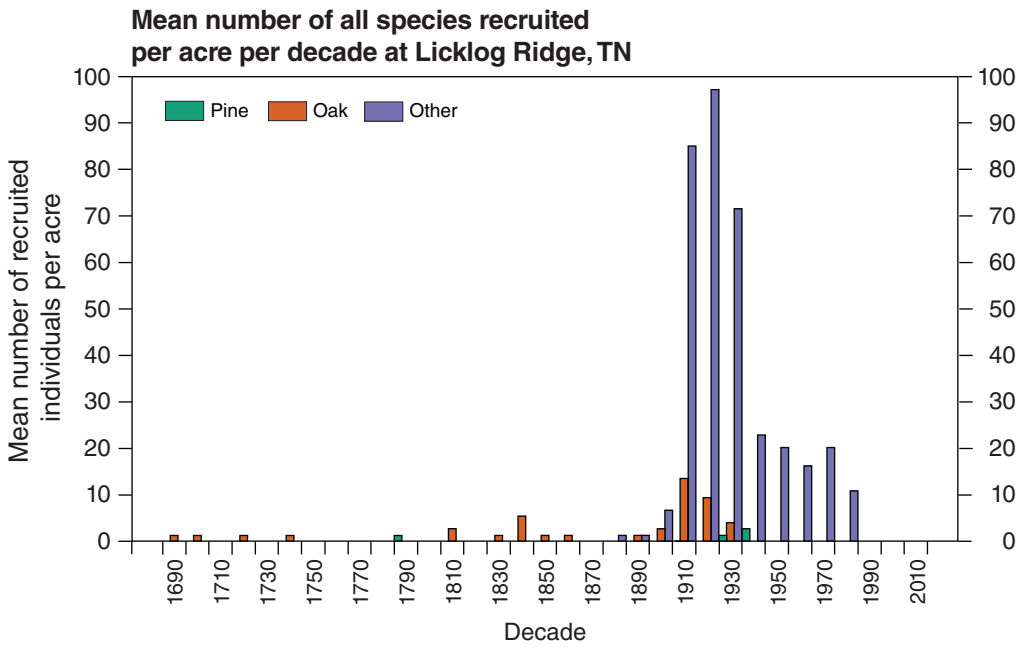


Figure 5.03—The mean number of all tree species recruited per acre per decade in the chestnut oak stands at the Licklog Ridge site in Tennessee (based on data from Flatley and others 2013). The "other" species include various species aside from oaks and pines. The oaks were established regularly under the regime of frequent burning, whereas the other tree species were primarily recruited during the fire exclusion period (after c. 1910–1930).

When summarized in this manner, the establishment dates for yellow pine stands indicate relatively abundant recruitment of yellow pines during the pre-exclusion era (i.e., decades designated by negative numbers in fig. 5.04A). They also show that a pulse of yellow pine establishment coincided with the cessation of frequent burning (decades 0–3). This establishment pulse likely reflects favorable tree recruitment opportunities in the open conditions that had been maintained in the forest understories by frequent burning in the past. Once fire was excluded and no longer threatening the pine seedlings, they recruited in great abundance (cf. Brose and Waldrop 2006). This recruitment declined after a few decades, however, as the stands grew more crowded. Yellow pines are also present in oak-dominated stands (fig. 5.04B) in low numbers.

Oak trees maintained populations within both pine- and oak-dominated stands during the pre-exclusion period (fig. 5.04C, D). Small oaks were probably top-killed repeatedly by fires but would have persisted by resprouting after each fire, developing large roots, and then eventually bolting to take advantage of an anomalously long fire interval (Brose and others 2014). By the time of the next fire, some of these stems would have attained a large enough size to survive the fire and continue growing.

Oak sprouts flourished at the beginning of the fire exclusion era. With fire absent, a large cohort of sprouts became established immediately in decades 0–1, producing coppice-like growths of chestnut oak that can be observed in many stands today. This pulse of oak establishment must have rapidly depleted the oak sprouts, leaving few oaks to recruit in subsequent decades. The paucity of oaks originating after decade 3 suggests that the stands have become too dense and shaded for oak seedlings or sprouts to survive.

Other tree species, which include a wide range of species from hickories (*Carya* spp.) to eastern hemlock (*Tsuga canadensis*), are not well represented among the trees established before fire exclusion (figs. 5.04E, F). A few trees of pre-exclusion origin are present, but the age-structure histograms drop off sharply back in time. This drop-off suggests that "other" species sometimes were established under the regime of frequent burning but survived only a few decades before being winnowed out by the relentless fires. Fire exclusion brought a momentous shift, however. This shift is manifested as a strong peak in the age-structure histogram at decade 0, which is followed by a moderate level of establishment for the next several decades. The absence of fire has enabled this suite of species to thrive.

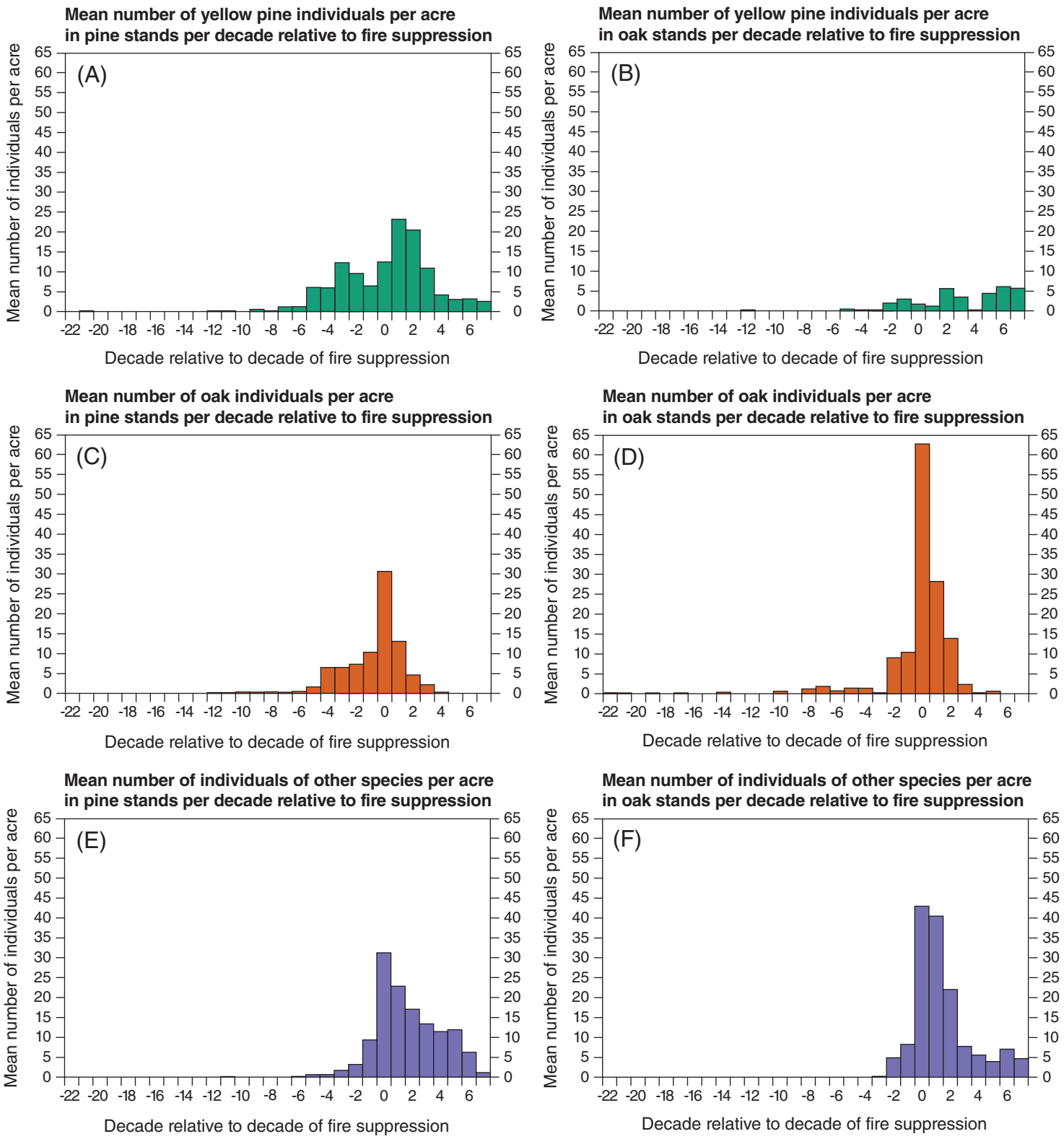


Figure 5.04—(A) The mean number of yellow pines recruited per acre per decade relative to the beginning of fire exclusion in yellow pine-dominated stands in all reviewed studies. Decade "0" refers to the decade in which the last major fire occurred. Decades with negative values represent decades prior to fire exclusion, and those with positive values represent decades after fire exclusion began. (B) The mean number of yellow pines recruited per acre per decade relative to the beginning of fire exclusion in oak-dominated stands in all reviewed studies. (C) The mean number of oaks recruited per acre per decade relative to the beginning of fire exclusion in yellow pine-dominated stands in all reviewed studies. (D) The mean number of oaks recruited per acre per decade relative to the beginning of fire exclusion in oak-dominated stands in all reviewed studies. (E) The mean number of individuals of other species recruited per acre per decade relative to the beginning of fire exclusion in yellow pine-dominated stands in all reviewed studies. (F) The mean number of individuals of other species recruited per acre per decade relative to the decade of fire exclusion in oak-dominated stands in all reviewed studies. In general, pine and oak species had established under frequent burning, showed a pulse of establishment in the first few decades of fire exclusion, and failed to establish thereafter. The other species, in contrast, mostly were established during the era of fire exclusion.

Given the diverse ecological requirements of the "other" species, their age structure histograms likely reflect multiple recruitment modes and fire effects. Under frequent burning, relatively fire-tolerant hardwoods such as hickories and blackgum probably maintained a small presence through repeated sprouting, similar to the oaks. Others, such as red maple and white pine, probably cast their seeds continually into the pine and oak stands without avail. They could not establish there as long as fires recurred every few years. When this pressure was relaxed, however, seedlings of many species became established, and stand composition began shifting toward a more diverse tree assemblage. Today, most of the stands remain dominated by yellow pines and oaks, but their understories are thick with other species that are emerging into the overstory and replacing the dominant trees as they die.

Frequent surface burning, therefore, would have played a filtering role in species composition (McEwan and others 2014). Even though many tree species must have dispersed seeds onto the mountain slopes, few of their seedlings could endure the rigors of frequent fire. Most were filtered out, leaving oaks and yellow pines—and also probably chestnut, which unfortunately is absent from the age-structure graphs—to dominate the fire-prone mountainsides. The less fire-resistant species were relegated to parts of the landscape that were sheltered from fire. These sheltered locations would likely have included moist coves and ravines that housed diverse assemblages of mesophytic tree species. They also probably included rock outcrops and talus slopes where the sparseness and discontinuity of fine fuels inhibited fire and created refugia for such fire-sensitive tree species as Carolina hemlock (*Tsuga caroliniana*) and white pine (fig. 5.05). From such refugia, these fire-sensitive species could have expanded onto other sites after fires were excluded.

The unlogged watershed of Licklog Branch in the Great Smoky Mountains elucidates how fires filtered tree establishment and structured vegetation patterns across complex Appalachian terrain (Flatley and others 2015). As seen above (fig. 5.03), the chestnut oak stands at this site were dominated by an uneven-aged overstory of oaks that were recruited through the era of frequent burning. A pulse of oak establishment followed the last major fire in 1916, but it was the "other" species category that mostly benefitted from the altered fire regime (fig. 5.03).

Figure 5.05—White pine trees growing on talus with discontinuous fuel bed of pine needles. (photo by Steven Q. Croy)

To place the dynamics of these oak stands into their broader landscape context, Flatley and others (2015) established plots along a topographic gradient spanning the entire southeast-facing slope from ridgetop to valley (fig. 5.06). The plots were situated in stands of yellow pine, chestnut oak, white pine–oak, and cove forest. The first three stand types covered most of the slope, and in these stands, xerophytic species prevailed among the trees that were established before fire exclusion (fig. 5.07, top panel). These xerophytes included pines, oaks, and a few other hardwoods. Xerophytic trees generally show greater resistance to fire than do mesophytic trees, apparently as an adaptation to dry sites where fires are common (Huston 1994), and therefore their prevalence on the slopes of Licklog Ridge was expected.

More surprising, however, was that xerophytic species composed about one-third of the pre-exclusion trees in the cove plots (fig. 5.07, top panel). These plots were located along Licklog Branch near the base of the slope (plots labeled "W" in fig. 5.06) in a mesic environment where xerophytic trees generally do not thrive because of competition with taller or more shade-tolerant species (cf. Huston 1994). The presence of xerophytic species in the cove stands apparently reflects the occasional spread of fires from the southeast-facing slope down to the valley, where the fires maintained sufficiently open conditions for oaks and other xerophytic hardwoods to establish. Evidence of fire in the valley exists in the form of fire-scarred hemlocks and other trees along the edge of the stream (Flatley and others 2015).

A different picture emerges just across the branch, however, where the cove forest is sandwiched between the stream on its west and a northwest-facing slope to its east (plots labeled "E" in fig. 5.06). This "east cove" forest apparently was sheltered from frequent fire by the stream, which formed a barrier to fires spreading from the west, and by the steep northwest-facing slope, which was probably too moist to burn frequently down to the slope base. As a consequence, the sheltered east cove stands developed a contrasting composition in which nearly all the old, pre-exclusion trees are of mesophytic species (fig. 5.07, top panel).

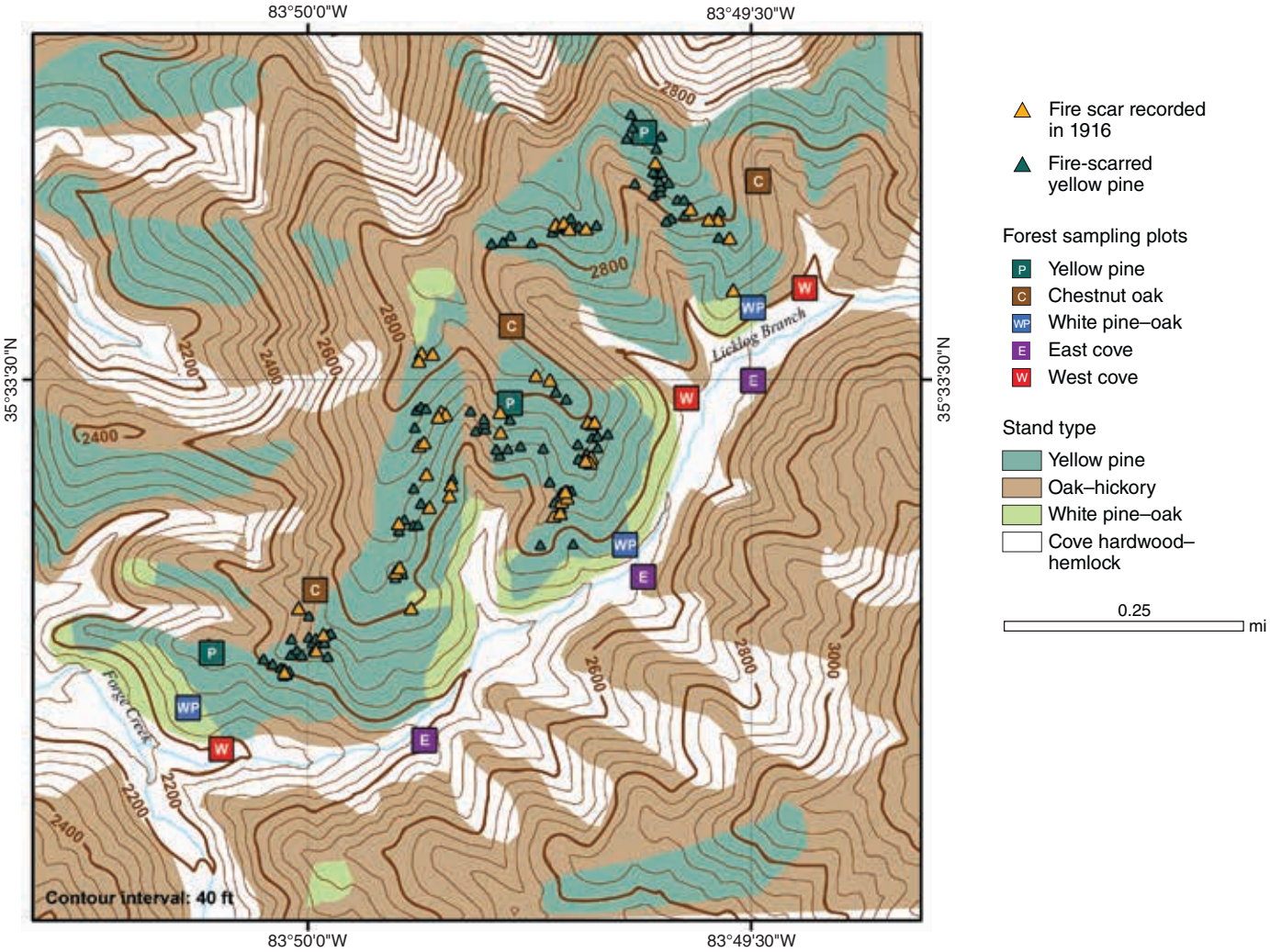


Figure 5.06—Forest stands and sampling sites at the Licklog site that was studied by Flatley and others (2015). Plot locations are indicated by labeled squares, and fire-scarred trees are indicated by triangles. Locational data for plots, fire-scarred trees, and stands were obtained from Flatley and others (2015) and plotted on a topographic map obtained from the U.S. Geological Survey.

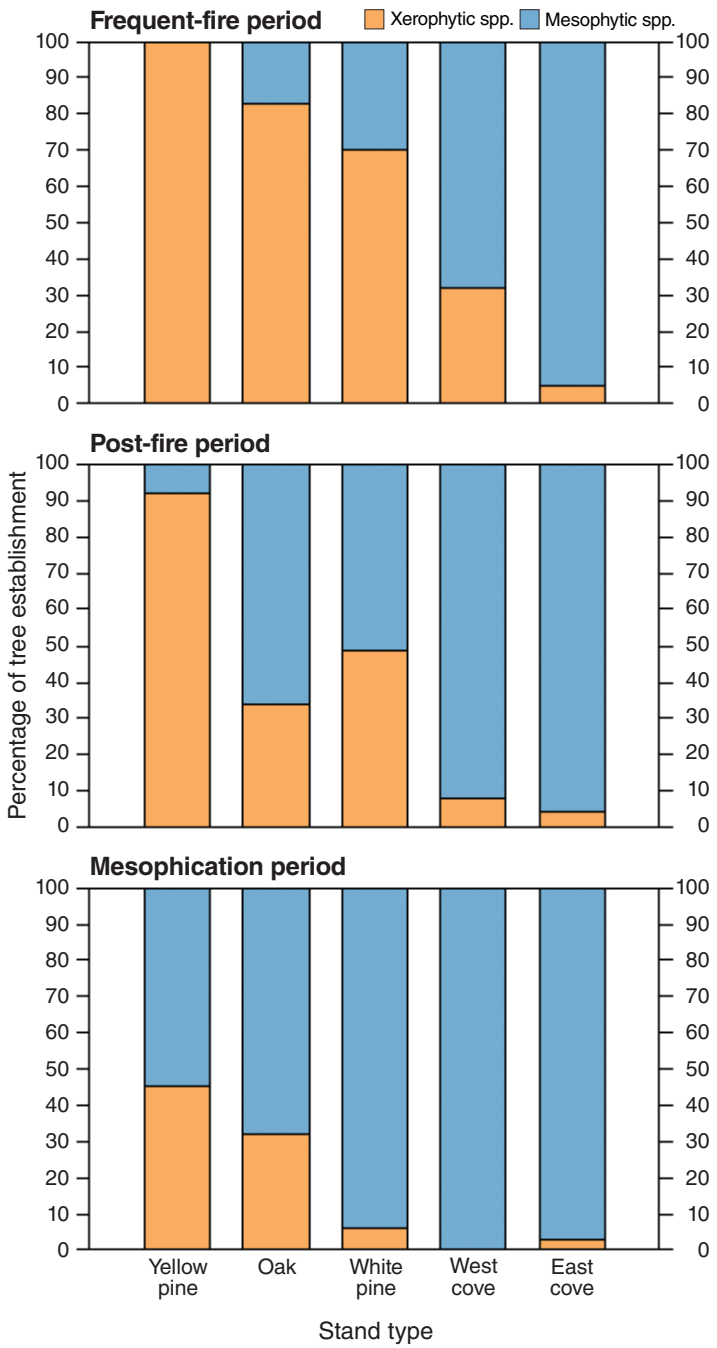


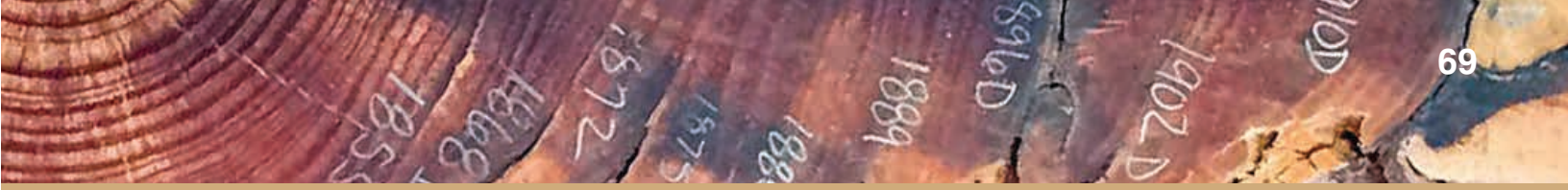
Figure 5.07—Percentage of tree establishment composed of xerophytic and mesophytic trees in each stand type by disturbance period at the Licklog site studied by Flatley and others (2015) across a topographic gradient. The frequent-fire period includes the decades before the decade of the last fire (i.e., before the decade 1910–1919); the post-fire period includes the decades from 1910 to 1949 in the immediate post-fire environment; and the mesophication period includes the decades after 1949, when stand closure and mesophication were occurring. This graph is based on data obtained from Flatley and others (2015) and resembles a figure in that publication. In general, the frequent-fire period favored the establishment of xerophytic species such as pine and oak across dry ridges, open slopes, and even moist cove sites that were exposed to fires spreading from the adjacent ridge. The establishment of mesophytic species was confined to sheltered sites near streams. Under the mesophication that has accompanied fire exclusion, mesophytic species have spread over the entire topographic gradient.

Tree establishment patterns changed across the entire southeast-facing slope of Licklog watershed under fire exclusion. Mesophytic species encroached into all the stands to dominate the young trees across the whole topographic gradient (fig. 5.07, middle and bottom panels). These changes support three important conclusions. First, frequent burning had filtered tree establishment in the past to favor oak and pine. This statement is supported by the fact that mesophytic species have found suitable habitat across the entire ridge in the absence of fire. Second, fire exclusion has favored the establishment of mesophytic species, as proposed in the mesophication hypothesis (Nowacki and Abrams 2008). These mesophytic trees are poised to assume dominance of the stands as overstory pine and oak trees disappear, a successional replacement that is well underway in Licklog Branch and throughout much of the Appalachian region. Third, frequent burning helped shape the spatial patterns of vegetation across a landscape. At Licklog, it was not simply the well-known topographic moisture gradient that arranged tree species across a slope. It was, rather, the interaction of fire with this gradient that maintained the heterogeneous vegetation, with xerophytic pine and oak on the ridge and mesophytic species in moist, sheltered locations. Excluding fire has not merely altered the vegetation of individual stands. It has also changed the spatial arrangement of vegetation across a landscape.

CONCLUSIONS AND IMPLICATIONS

Data on tree age structure augment the fire-scar record by clarifying the severity of past fires as well as the influence of fires (and fire exclusion) on vegetation dynamics. Most fires recorded by fire-scarred trees were of low or moderate severity, and the fires would have maintained open stands dominated by pine, oak, and other fire-favored taxa. Fires appear to have flared occasionally into tree crowns in some of the Table Mountain pine–pitch pine stands that dominate south- or west-facing slopes at middle elevations. These crown fires killed a substantial portion of the overstory pines and made way for the establishment of new pine cohorts. These cohorts may also reflect other severe disturbances, such as ice storms and insect outbreaks. Severe disturbances may have been uncommon in low-elevation pine stands containing shortleaf or Virginia pines mixed with hardwoods. They were probably uncommon in oak-dominated stands, as well.

The frequent passage of fires through pine- and oak-dominated stands played a filtering role in tree establishment and thereby controlled stand composition. Frequent burning created a rigorous environment that few tree seedlings could endure. Even the fire-adapted pines and oaks were recruited in fairly low numbers before fire exclusion. The occasional long fire interval was probably important for enabling oak sprouts to bolt to a fire-resistant height before the next fire occurred. Less fire-resistant seedlings of red maple, hemlock, and other mesophytic tree species were largely prevented from establishing on the mountain slopes during the regime of frequent fire. These species were relegated to riparian areas and other sites that were sheltered from frequent fire. However, they rapidly encroached upslope onto the drier ridges once fires were excluded. As stands became more crowded, pine and oak recruitment diminished, with the result that stands currently dominated by old pine and oak trees harbor an understory containing mesophytic species. These mesophytic trees are poised to assume dominance as the overstory pines and oaks disappear over time. This ongoing mesophication is altering the topographic patterning of forest vegetation across entire landscapes.



Chapter 6. Appalachian Fire History as Reconstructed from Charcoal

INTRODUCTION

Although fire-scarred trees provide direct evidence of fire at local scales with annual or even seasonal resolution, the longest such records from the Appalachian region extend only about 400 years into the past. It would be useful to know about fire history under changing vegetation, climates, and land uses much deeper into the past. For example, was fire present throughout the roughly 9,000 years that Native Americans inhabited the present-day Eastern United States before European contact?

Some information about the long-term history of fire can be obtained by analyzing charcoal fragments in soils and sediments (e.g., Ballard and others 2016, Clark 1988a, Fesenmyer and Christensen 2010, Hart and others 2008, Higuera and others 2007, Horn and Underwood 2014, Patterson and others 1987, Whitlock and Larsen 2001). These charcoal fragments, which can be hundreds or thousands of years old, also provide direct evidence of fire occurrence, though not usually at the high temporal and spatial resolution of fire-scarred trees. The analysis of charcoal preserved in soils or in lake and wetland sediments can document how long fire has been present on a landscape or in a region. In cores of sediment extracted from lakes and wetlands, charcoal concentrations and accumulation rates often show temporal variations that suggest waxing and waning of fire activity over time. These inferred variations in fire activity can sometimes be linked to changes in vegetation, climate, or human land use documented by other materials preserved along with charcoal in sediment profiles, such as pollen grains, diatoms, and stable isotope signatures, or documented by other paleoenvironmental or archaeological research.

Charcoal forms from the incomplete combustion of organic material, generally plants, by fire at temperatures > 518 ºF (> 270 °C) (Orvis and others 2005, Scott 2010). Fires produce charcoal fragments of various sizes that are incorporated into soils of the burn site, or are washed or blown away, sometimes to lakes or wetlands, where fragments may be preserved in accumulating sediments. Researchers distinguish charcoal fragments from other dark organic particles in soils and sediments by their black sheen under reflected light, by their generally angular shape, and by the way larger pieces fracture under pressure (Horn and Underwood 2014, Whitlock and Larsen 2001). Wood charcoal is inert, recalcitrant, and can persist in soils for millennia (Fesenmyer and Christensen 2010, Hart and others 2008, Horn and Underwood 2014, Nelle and others 2013). Its potential to resist decay is enhanced by higher burning temperatures (Scott 2010). Charcoal produced from non-woody plant parts, such as leaves and herbaceous stems, may be less resistant to decay in soils, based on its rarity in comparison to wood charcoal in soil charcoal samples; however, charcoal from non-woody plant tissues is preserved along with wood charcoal in lake and wetland sediments.

Analyses of charcoal in sediment cores to reconstruct fire history include studies of microscopic charcoal on slides prepared for pollen analysis (also called pollen-slide charcoal), and of larger, macroscopic charcoal fragments that are concentrated by sieving sediment samples (Whitlock and Larsen 2001) or examined on thin sections (Clark and Royall 1996). Whitlock and Larsen (2001) defined microscopic charcoal as particles < 0.0039 inch (100 µm or 0.1 mm) in size, although some larger particles may be present on pollen slides depending on the mesh size of the sieves used for pollen preparation (Horn and Underwood 2014). Studies of macroscopic charcoal in sediment cores make use of sieves with mesh sizes ≥ 0.0039 inch (100 µm), and often ≥ 0.0049 inch (125 µm) or ≥ 0.0098 inch (250 µm). Studies of charcoal in soils focus almost exclusively on macroscopic charcoal, generally of still greater size—often ≥ 0.039 inch (1 mm) or ≥ 0.079 inch (2 mm) (Horn and Underwood 2014).

Records of microscopic and macroscopic charcoal in sediment cores and soils provide evidence of fire activity at different spatial resolution. Microscopic charcoal particles are small enough to have been blown to a lake or wetland from outside the drainage basin (Clark and Patterson 1997, Hart and Buchanan 2012, Horn and Underwood 2014, Ohlson and Tryterud 2000, Scott 2010), and they may indicate regional fires. However, local fires may also deposit small charcoal in lakes and wetlands, or larger pieces may be broken up during transport and incorporation into sediments or during pollen sampling and processing.

In contrast to microscopic charcoal, which may reflect fires both near and distant from the depositional site, macroscopic charcoal particles in sediments and soils provide evidence of local fires. In lake and wetland sediments, they usually indicate fires within the watershed or close by, with charcoal transported relatively short distances by wind and water (Clark and Patterson 1997, Higuera and others 2007, Whitlock and Larsen 2001). In soils, the large macroscopic charcoal fragments that researchers study are interpreted to reflect charcoal left in place following fires at the sampling site or moved only tens of feet by gravity or water (Gavin and others 2003, Ohlson and Tryterud 2000).

The nature and amount of charcoal produced by a fire depends on many factors, such as its size and intensity, and the type of fuel it burns. For example, crown-fire regimes often produce wood particles from the charred trees, whereas fire regimes with frequent and efficient burning of fine surface fuels may produce relatively little charcoal (Whitlock and Larsen 2001). Charcoal accumulation depends on terrain, vegetation, and other landscape features. A large watershed with steep slopes draining into a small lake, for example, will amplify charcoal accumulation in the lake sediments compared to a smaller, less-steep watershed draining into a large lake (Whitlock and Larsen 2001). A fringe of riparian vegetation will trap some of the charcoal and prevent its deposition in the lake.

SEDIMENT CHARCOAL ANALYSIS

To sample the amount of charcoal in lake or wetland sediments, researchers collect cores of sediment using piston corers operated on lakes from anchored floating platforms made from inflatable rafts, canoes, or inner tubes (fig. 6.01). Cores are generally collected in successive 3.28-feet (1-m) sections (fig. 6.02) from positions near the centers of lakes. Each core provides a history of charcoal deposition, with younger sediment and charcoal at the top of the core and older material at the bottom. After the cores are transported to the laboratory, core sections are sliced lengthwise and sediment samples are removed from the cut faces for analysis.

In microscopic charcoal analysis, samples of 0.015–0.061 cubic inch (0.25–1.0 cm^3) are removed at intervals along the core (often ≥ 3.15 inches, or 8 cm) and placed in small test tubes for chemical processing to dissolve and remove minerals and extraneous organic matter. The resulting "pollen residues" are mounted on microscope slides and examined at 400× magnification using compound microscopes to reconstruct vegetation history (from pollen) together with fire history from microscopic charcoal. Charcoal abundance is determined by counting particles or estimating charcoal particle area; in some

Figure 6.01—Collecting sediment from the bottom of Crystal Lake in eastern Tennessee by using a raft as a platform from which to operate the corer. Here researchers are recovering a mud-water interface core that is offset from the rest of the core sections, which are collected from the hole in the center of the raft.

Figure 6.02—Extruding a sediment core section from a piston corer.

studies, graminoid charcoal produced by grasses or sedges is counted separately (Robinson and others 2005). Various charcoal indices are reported in studies of microscopic charcoal, including concentration (charcoal fragments or area by volume or mass, e.g., particles per cubic inch, or particles cm^{-3}); influx (charcoal fragments or area by core site area by year, e.g., square inches of charcoal per square inch per year, or mm^2 charcoal cm^{-2} yr^{-1}); or charcoal-to-pollen ratios (fragment counts or area per pollen grain in the samples (Ballard and others 2016).

Because pollen is sampled at intervals in sediment cores, microscopic charcoal records developed from pollen slides will not capture all fire events that may be recorded in the lake or wetland sediments: gaps between samples can include missed fire events. This sampling method, together with the uncertain source area for the microscopic charcoal particles (Whitlock and Larsen 2001), results in records of fire that are temporally and spatially coarse. However, the ability to directly tie the evidence for fire with pollen evidence for shifts in vegetation from the same slides makes microscopic charcoal records valuable for understanding relationships between fire and vegetation over long time periods (Ballard and others 2016). Also, the sediments at some core sites may contain insufficient macroscopic charcoal for analysis, but ample microscopic charcoal. The presence of relatively high amounts of microscopic charcoal but low amounts of macroscopic charcoal may reflect processes of charcoal production and transport within watersheds and depositional basins as well as local fire history.

Macroscopic charcoal analysis differs from microscopic charcoal analysis in that samples are taken at close or continuous intervals, minimizing or eliminating the chance of missed fire events, and are processed without extensive chemical treatment. We focus here on macroscopic charcoal analysis based on sieving; see Clark (1988b) for the thin section technique. Although some researchers sieve sediment samples with a volume of 0.061 cubic inch (1 cm^3), larger sample volumes of 0.122–0.244 cubic inch (2–4 cm^3) may be necessary to achieve replicable counts in some settings (Carcaillet and others 2001, Schlachter and Horn 2010). The highest resolution fire history records developed from unlaminated sediment cores are based on sampling charcoal at continuous 0.394-inch (1-cm) intervals, with samples cut from core section faces using knives or rectangular samplers that allow removal of contiguous samples (Schlachter and Horn 2010). Some researchers have sampled sediment cores at finer intervals, but doing so may not improve the resolution of the charcoal record owing to blurring of the record by bioturbation (Whitlock and Larsen 2001).

Samples are first disaggregated by using hot distilled water or chemical solutions [often sodium hexametaphosphate, potassium or sodium hydroxide, hydrogen peroxide, or sodium hypochlorite (bleach)] and then sieved to concentrate charcoal of a particular size class or classes. Mesh sizes commonly used for sieving macroscopic charcoal samples include 0.005, 0.007, 0.010, and 0.020 inch (125, 180, 250, and 500 µm) (League and Horn 2000, Lynch and Clark 2002, Whitlock and Larsen 2001). Charcoal is examined wet on sieves, or after transferring to Petri dishes (wet or dry), to determine particle counts and in some cases particle area "by eye" using a dissecting scope or using image analysis. Researchers studying macroscopic charcoal in a sediment core might also investigate pollen evidence of vegetation change, but this requires separate processing of samples for microscopic analysis. Macroscopic charcoal abundance in sediment cores is typically presented as charcoal concentration (charcoal particle numbers, area, or mass by volume or mass) or as influx (charcoal particle numbers, area, or mass per square inch per year, or cm^2 per year), which is also referred to as charcoal accumulation rate, or CHAR, in some studies (Whitlock and Larsen 2001).

To develop a chronology for the sediment core, the researcher collects charcoal or other organic fragments from different levels in the core and sends them to a laboratory for radiocarbon dating using accelerator mass spectrometry (AMS), which can provide dates for organic materials up to approximately 45,000 years old (Horn and Underwood 2014). In addition, lead-210 dating is often used to provide higher-resolution dating for lake sediments deposited during approximately the last 200 years (Appleby 2008, Whitlock and Larsen 2001).

Computer software programs (e.g., CALIB; Stuiver and Reimer 1993) linked to calibration datasets (Reimer and others 2013) allow researchers to convert the radiocarbon age of each dated sample to calendar years before "present" (defined as the year 1950), usually expressed as "cal yr BP." The calibrated age is presented as a range such that there is a 95-percent probability that the true age of the sample falls somewhere in this range. The radiocarbon age represents the time since carbon was removed from the atmosphere and incorporated in the wood, and not the age of the fire that produced the charcoal (Gavin 2001, Gavin and others 2003, Sanford and others 1985). This "inbuilt" age of the charcoal must also be taken into account in estimating the timing of past fires. Fesenmyer and Christensen (2010) estimated the inbuilt age of charcoal in the southern Appalachian region to be on the order of 50–100 years. This inbuilt age must be added to the calibrated age range of a sample. For example, a sample with

a calibrated age of 650–480 cal yr BP has an estimated age of 650–380 cal yr BP when the inbuilt age is added to the age range (Horn and Underwood 2014).

In cores of sediment from lakes and wetlands, radiocarbon dates on charcoal or other organic particles provide ages for the levels in the core from which they were obtained. The ages for intervening levels of the core can be estimated through linear interpolation or other methods of age modeling. Sufficient radiocarbon dates must be obtained for sediment cores to allow researchers to recognize dates that are outliers representing the intrusion or incorporation of material younger or older than surrounding material; these dates should not be used in the development of chronologies. Because charcoal can persist for long periods on the landscape and in soils, charcoal is more likely than unburned organic material to yield dates that are older than expected at a particular depth in a core. In these cases, the age of the charcoal predates the age of surrounding core material and should be excluded from the age model. However, old charcoal pieces that are outliers in age models still contribute to understanding fire history by documenting the timing of earlier fires. Their occurrence in sediment profiles may have additional paleoenvironmental significance, potentially signaling major erosive events in watersheds (Kennedy and others 2006).

Despite the constraints imposed by uncertainty in calibrated ages and age models, and the possibility of unrecognized outliers, researchers studying charcoal in sediment cores have been able to interpret temporal variations in charcoal accumulation to understand how fire regimes have changed over time within watersheds and regions. For some macroscopic charcoal records of watershed fires, researchers have estimated mean fire interval (MFI). These estimates require the researcher to decompose the charcoal time series into two components, a low-frequency "background component" and a high-frequency "peaks component" (Whitlock and Larsen 2001). The background charcoal deposition can represent multiple sources, including "secondary" charcoal that is stored in the watershed and delivered to the lake for years or even decades following a fire, and possible fallout from regional fires outside the watershed, although macroscopic charcoal is generally interpreted to reflect fires within watersheds or nearby, rather than regional fires. Observed trends in background charcoal have also been interpreted to result from long-term changes in vegetation that alter fuel loads in watersheds (Millspaugh and others 2000). Charcoal peaks, on the other hand, represent the charcoal from a fire event in the watershed. A fire event is not necessarily a single fire, however, because it could result from multiple fires within the period spanned by the charcoal peak. Therefore, the peak may represent an episode of frequent burning. Using charcoal peaks to estimate MFI indicates the frequency of fire events and not necessarily of individual fires.

Whether a charcoal time series is suitable for estimating MFI depends on the temporal resolution of the charcoal record compared to the MFI. The resolution of a charcoal record reflects the sedimentation rate in the lake or wetland and the spacing of samples in the core. Rapid sedimentation permits high-resolution reconstructions because each centimeter of the core represents sediment deposited over only a few years. For lakes in temperate North America, Whitlock and Larsen (2001) suggested that 0.394 inch (1 cm) of sediment typically represents 5–20 years of deposition (e.g., sedimentation rates of 0.020–0.079 inch per year, or 0.05–0.2 cm yr^{-1}). Thus, it is not possible to resolve whether the charcoal in that 1-cm segment of core originated from one fire or from several.

Studies of charcoal in sediment cores from lakes and wetlands in the Appalachian region have revealed sedimentation rates of < 0.001 inch per year to 0.142 inch per year, or 0.002–0.36 cm yr^{-1} (Lynch and Clark 2002), i.e., significantly lower for some time periods at some sites than for the typical eastern lakes in the example above. The intervals of very low apparent sediment accumulation may reflect intervals of missing sediment, perhaps associated with droughts. The consequence for reconstructing past fires is that 0.394 inch (1 cm) of sediment that accumulated at the slow end of the range shown by Appalachian lakes would represent as many as 500 years, resulting in a fire record of very low temporal resolution, even if sampled at contiguous 0.394-inch (1-cm) intervals. Even at sites with the highest sedimentation rates, where 0.394 inch (1 cm) of sediment could represent less than 3 years for some core sections, it will be impossible to distinguish individual fires if they recurred at intervals of only a few years, as we have found in fire-scar analyses at our sites in the Appalachians (see chapter 3). Whitlock and Larsen (2001) recommended that to estimate MFI from a sediment charcoal series, sample resolution should be approximately one-eighth the MFI (Whitlock and Larsen 2001), meaning that a 5-year resolution would permit MFI estimates

for a fire regime with MFI ≥ 40 years. Thus, sediment charcoal analysis in the Appalachian region is ill suited for reconstructing MFI estimates for past intervals in which fire regimes were characterized by the high fire frequencies we have reconstructed for recent centuries. However, charcoal analysis is nevertheless valuable in providing evidence of watershed and regional fires prior to the last few hundred years, and of changes over time in relative fire activity resulting from changes in human activity, climate, and vegetation going back as far as the late glacial period.

Although charcoal records from most lakes in the Appalachian region or worldwide cannot provide the annual resolution of tree-ring-based fire records, a rare type of lake sediment offers the possibility of annually resolved charcoal records. Varved lake sediments with annual laminations are found in some lakes with anoxic deepwater (Zolitschka 2007), including two at the northern edge of the Appalachian region, where Clark and Royall (1996) reconstructed high-resolution fire histories by using thin-section analyses of varved sediments.

SOIL CHARCOAL ANALYSIS

Following fires, some charcoal stays within the burn area, where it is incorporated into the soil profile and provides site-specific evidence of past fires. In the Appalachian region, where few lakes or wetlands exist, this soil charcoal may be the best source of long-term fire history data. Horn and Underwood (2014) recommended a procedure for soil charcoal collection and analysis, and here we summarize their procedure.

Although charcoal can be recovered from the walls of excavated soil pits, most researchers collect samples by using a soil corer (fig. 6.03), which saves time, reduces environmental impact, and can be accomplished in the rain. A popular coring device for collecting samples for soil charcoal analysis is the "single root auger" manufactured by Eijkelkamp, which despite its name has a cylindrical, rather than helical, cutting head (Horn and others 1994, Horn and Underwood 2014). These augers collect soil cores of 3.15 inches (8 cm) in diameter and up to 39.37 inches (100 cm) in length, in increments of 1.97 or 3.94 inches (5 or 10 cm). A pressure plate in the device facilitates extrusion of each core increment into a labeled plastic bag for return to the laboratory (figs. 6.04, 6.05).

Figure 6.03—Using a single root auger to collect soil charcoal.

Figure 6.04—Extrusion of a 3.94-inch (10-cm) soil core into a labeled plastic bag.

Figure 6.05—Close-up view of a soil core in which charcoal fragments are visible.

In the laboratory, researchers separate charcoal fragments from the soil by first soaking the samples in water overnight. Following disaggregation by water, samples are wet-sieved using an 8-inch diameter sieve with a 0.079-inch (2-mm) mesh. The material retained on the sieve is examined, either on the sieve or after transfer to a large plate or dish, under a dissecting scope. Charcoal fragments are picked using forceps and washed with distilled water. From there, charcoal fragments are placed in glass vials and dried in a laboratory oven at 194 °F (90 °C).

After the charcoal fragments are dried, researchers weigh the fragments to determine the charcoal mass in the soil core increment (usually reported as ounces of charcoal per cubic inch, or g charcoal cm^{-3}) and then select fragments for taxonomic identification and radiocarbon dating. In soils of the Appalachian region, the depth at which charcoal fragments are found is generally not a reliable indicator of their relative age, i.e., deeper fragments are not necessarily older (Fesenmyer and Christensen 2010), because physical and biological factors mix the soil. Hence, random selection of individual fragments for dating may have advantages over selecting samples based on depth in the soil core (Hammond and others 2007), as would be done in the analysis of a lake sediment core. Following radiocarbon determination, radiocarbon dates are converted to calendar-year ages, as described above for sediment charcoal, taking into account possible inbuilt age. Taxonomic identification must be done prior to radiocarbon dating because samples are destroyed in the dating process. Charcoal fragments can be identified to species (e.g., *Acer rubrum*) or subgenus (e.g., *Pinus*, diploxylon group) based on distinctive wood anatomy (fig. 6.06); this identification provides key information on the plants present at the burn site at the time of the fire.

The lack of a depth-age relationship for charcoal in soils is disadvantageous for reconstructing fire history from soil charcoal. Unlike studies of charcoal in sediment cores, for which a chronology can be developed based on a relatively small number of radiocarbon dates and used to infer the ages of charcoal particles in samples between dated horizons, the age of a soil charcoal fragment cannot be estimated from radiocarbon dates that bracket it in the soil profile. Therefore, researchers must date numerous pieces of charcoal to obtain a record of fire activity. This is an expensive undertaking, given the standard cost for AMS radiocarbon dates of about $500–600 per date.

Soil charcoal offers some compensating advantages, however. The first is that evidence is site specific. Soil charcoal indicates that a fire occurred at or very near the location where the charcoal was found. In contrast, charcoal in lake or wetland sediments reflects fires within the drainage basin, at best, and possibly from the broader region. A second advantage of soil charcoal is the ability to identify the tree or shrub taxon from the charcoal, providing information about vegetation history at a specific site with collocated fire history information. Finally, the method is applicable over wide areas, facilitating the collection of fire history information from the specific site of interest. Soil charcoal analysis is not restricted to the rare natural lakes and wetlands of the Appalachian region or to forest stands with trees that scar in fires.

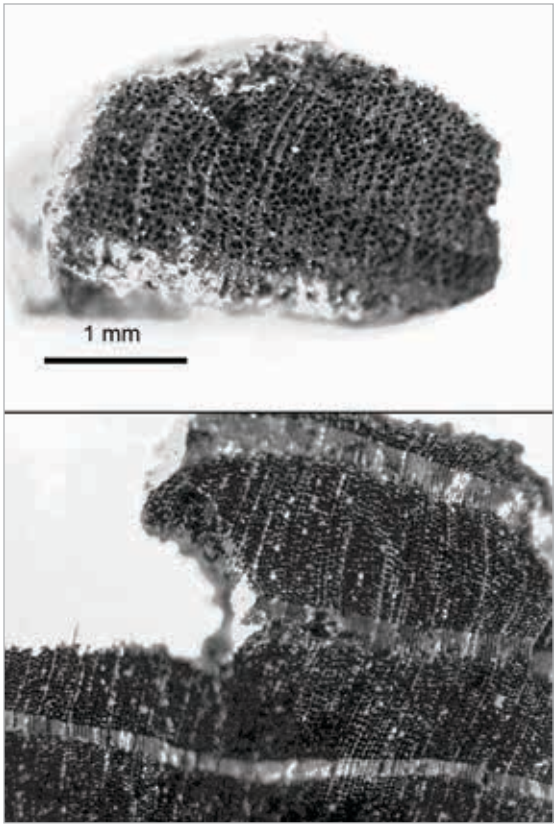


Figure 6.06—Macroscopic charcoal from study sites in Great Smoky Mountains National Park. The upper photograph shows charcoal from red maple (*Acer rubrum* L.). Anatomical features that allow identification of red maple are narrow rays that are approximately the same width as the widest pores, absence of tyloses, and diffuse-porous wood. The lower photograph shows charcoal from a southern yellow pine (*Pinus*, diploxylon group). Anatomical features that allow identification of southern yellow pine are tracheids, resin canals, and pronounced earlywood to latewood transition at ring boundaries. The wood anatomy of the diploxylon pines that grow in the southern Appalachian Mountains is too similar to allow differentiation of charcoal specimens to species. The scale bar is approximate and is for both photographs. (photos by Christopher A. Underwood)

CHARCOAL-BASED FIRE HISTORY RESEARCH IN THE APPALACHIAN REGION

Here we present, and seek to compare and synthesize, charcoal-based reconstructions of past fire at selected study sites across the Appalachian region (fig. 6.07). To do this, we have prepared a series of charcoal graphs using a standard graph format that facilitates comparison. We must state at the outset, however, that comparison is complicated by a number of factors. The sites we include in our review were sampled by several researchers using different techniques. One major difference is whether the researchers studied charcoal in sediment or soil, but there are also variations in the manner of collecting and analyzing the charcoal. Additionally, the lake and wetland sites investigated for sediment charcoal analyses differ in size, type (lake or pond versus bog), and topographic situation. However, despite the constraints, our review of selected records provides a long-term perspective without which the shorter records of fire from scarred trees and other sources would be unmoored from their historical context.

We used charcoal values provided in tables or that we estimated from diagrams in the original studies to generate graphs depicting changes over time in charcoal accumulation or relative abundance. Although the graph format was standardized, the y-axis scales are based on the range of charcoal values in the study and so they differ between graphs. Some difference also exists in the charcoal measures, or indices, plotted, as these also differ between the original studies. We added shading to show the Archaic (9,500–2,800 BP), Woodland (2,800–1,000 BP), and Mississippian (1,000–300 BP) Archaeological Periods and the Historic Period (300 BP to present), based on Delcourt and others (1986). Where available, we also added pollen data from the sites.

We present the graphs in four groups according to their temporal resolution and charcoal source (sediment or soil):

(1) High-resolution sediment charcoal records with annual to decadal resolution. We used the graphs in each study to estimate the charcoal value for each decade and then plotted the decade-to-decade variations on our graphs.

(2) Sediment charcoal records from sites with moderate to high sedimentation rates that appear to resolve the general trend in fire activity at each site across the past millennium. For each of these sites, we have summarized charcoal level by century, so the graphs furnish a view of century-to-century variation in charcoal accumulation.

(3) Long sediment charcoal records that show variations over many millennia. We have summarized these data for 500-year intervals to portray the broad changes and to accommodate charcoal records that have modest resolution because of low sedimentation rate or sampling procedure (i.e., sampling at intervals along a core instead of continuously at 1-cm intervals).

(4) Soil charcoal records summarized at a 500-year resolution and yielding multimillennial records.

High-Resolution Charcoal Records

Three sites in the Appalachian region have yielded high-resolution records of fire covering 1,000 to > 8,000 years (figs. 6.08–6.10). The charcoal record from Trout Pond (fig. 6.08A) is the record of highest temporal resolution in a series of sediment charcoal records developed by Lynch and Clark (2002) using macroscopic charcoal (≥ 0.0071 inch, or 180 µm) from sites in the Blue Ridge Mountains and the Ridge and Valley province in North Carolina, Virginia, West Virginia, and Maryland. Trout Pond is a small natural lake that fills a sinkhole formed by dissolution of limestone bedrock in the Ridge and Valley province of eastern West Virginia.[3] The pond is fed by streams draining the slopes of a nearby mountain. The fire history record developed from the sediments of this lake, and supported by three radiocarbon dates together with lead-210 analyses, extends back nearly a millennium. The record shows fairly consistent background charcoal deposition (about 0.05–0.02 square inch per square inch per year, or 0.5–2.0 $mm^2\ cm^{-2}\ yr^{-1}$), which may indicate frequent surface fires, superimposed by charcoal peaks of varying magnitude. These peaks could represent crown or mixed-severity fires that affected parts of the drainage basin. The Trout Pond charcoal record seems consistent with tree-ring studies, which indicate a regime of frequent, low-severity fires that, at least in pine stands, were punctuated occasionally by mixed- or high-severity fires that facilitated tree establishment (chapters 4 and 5). These consistencies suggest that the fire regime of the last few centuries (as indicated by fire scars) is similar to that which prevailed over the whole millennium.

The Ely Lake (fig. 6.08B) and Devil's Bathtub (fig. 6.08C) sites in Pennsylvania and New York yielded longer records of burning that extend back about 2,300 years and 10,500 years, respectively. These lakes were sampled as part of a study comprising seven sites across the Northeastern United States and Great Lakes (Clark and others 1996, Clark and Royall 1996), but these two are the only sites that fall within the Appalachian Mountains. At both lakes, sediments are characterized by varves

[3] Personal communication. April 27, 2016. Steven Q. Croy, Ecologist/Fire Planner, George Washington and Jefferson National Forests, U.S. Forest Service. 5162 Valleypointe Parkway, Roanoke, VA 24019.

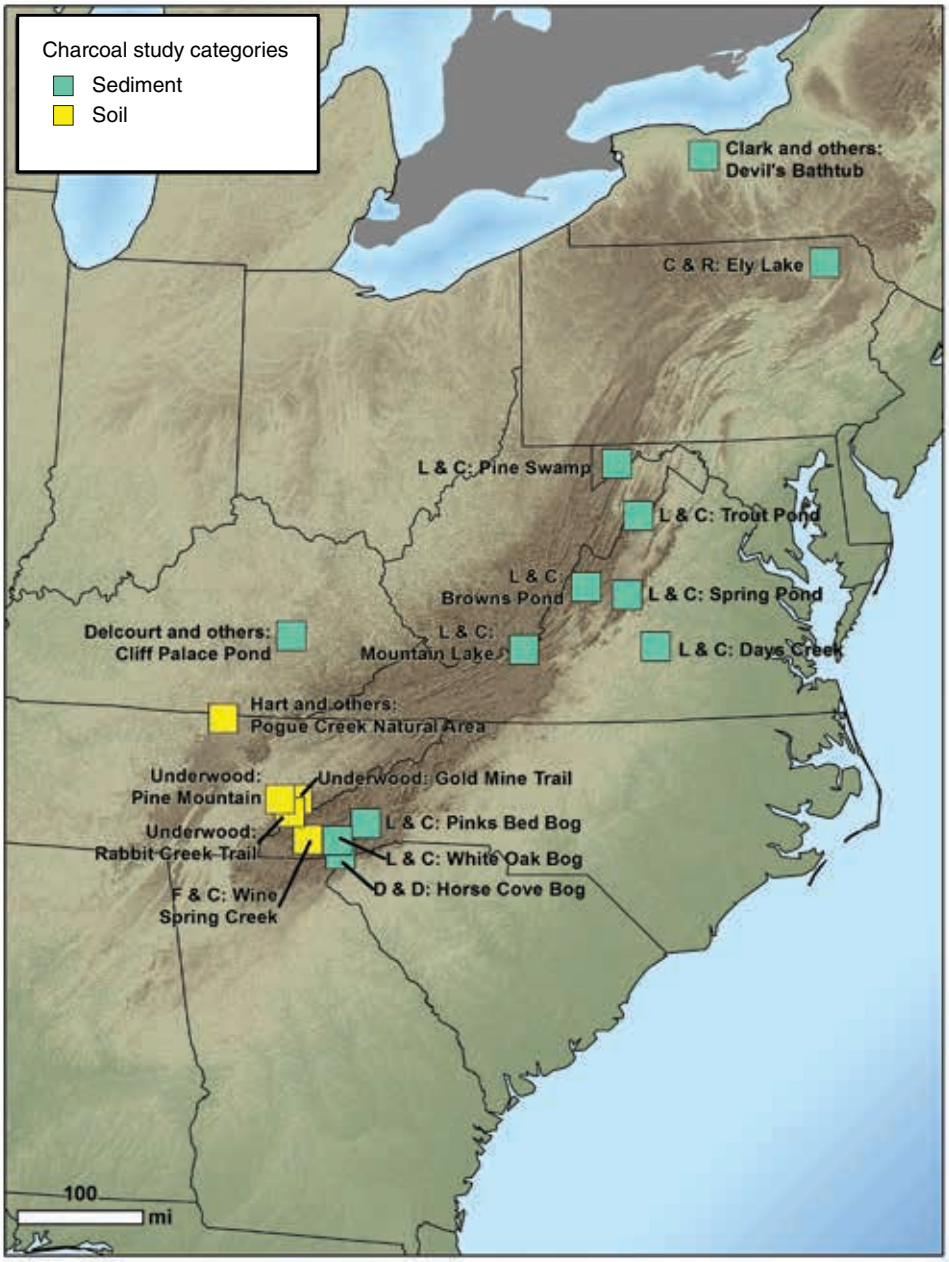


Figure 6.07—Locations of sediment and soil charcoal sites examined in this report. Site labels indicate the authors of the studies and the site names. C&R = Clark and Royall (1996), Delcourt and others = Delcourt and others (1998), D&D = Delcourt and Delcourt (1998), F&C = Fesenmyer and Christensen (2010), Hart and others = Hart and others (2008), L&C = Lynch and Clark (2002), Underwood = Underwood (2013).

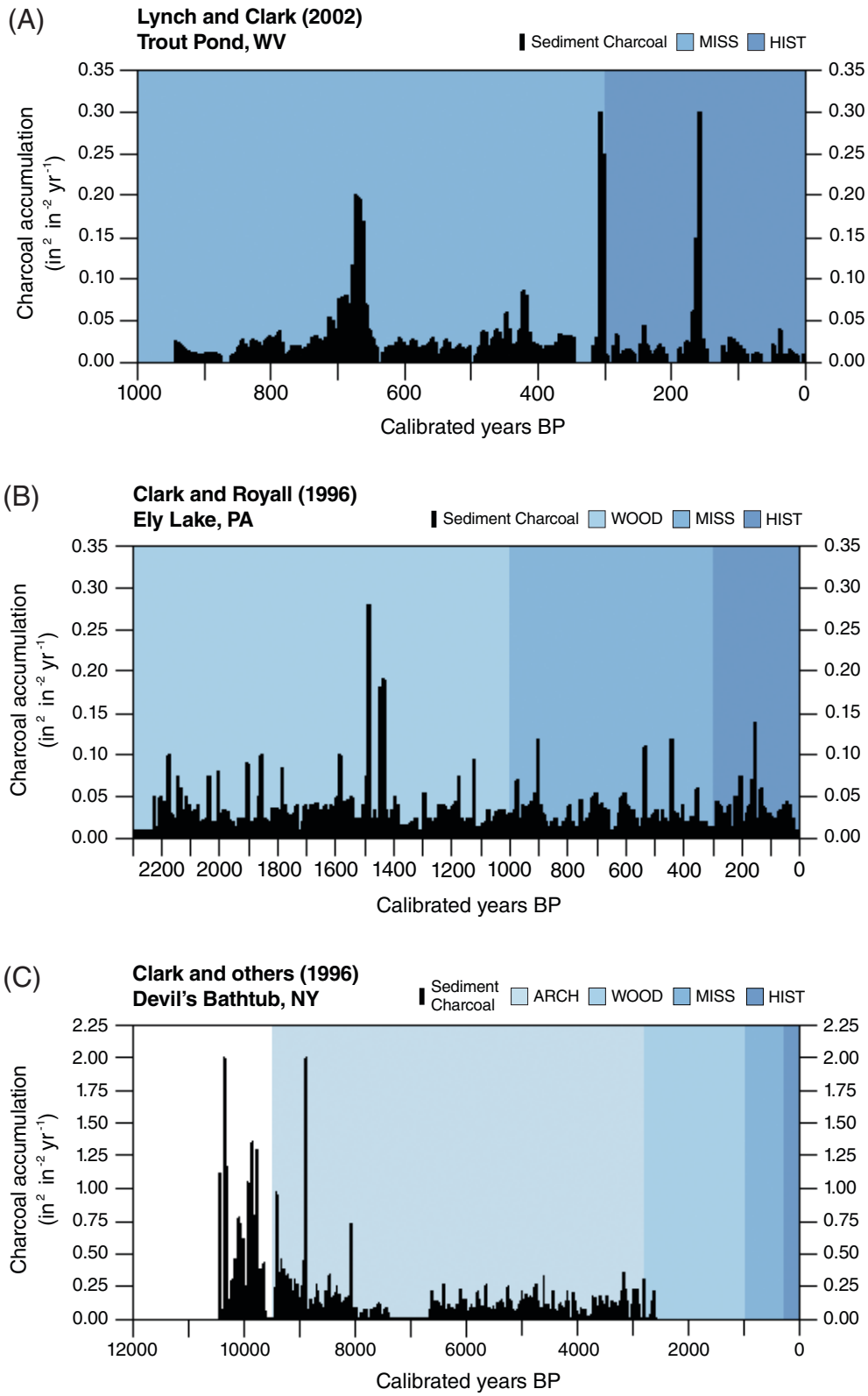


Figure 6.08—High-resolution (decadal) estimates of charcoal levels for (A) Trout Pond, (B) Ely Lake, and (C) Devil's Bathtub. Background shading indicates the Archaic (ARCH; 9,500–2,800 BP), Woodland (WOOD; 2,800–1,000 BP), and Mississippian (MISS; 1,000–300 BP) archaeological periods and the Historic Period (HIST; 300 BP–present). Fairly consistent deposition of charcoal particles at Trout Pond and Ely Lake throughout the record suggests frequent surface fires. At Devil's Bathtub, the transition from high rates of charcoal deposition to lower rates of deposition was related to a shift from jack pine to white pine and probably a concurrent trend from crown fires to surface fires.

or annual laminations, which in combination with radiocarbon dating and the identification of cultural horizons in pollen data provided high-resolution chronologies for the charcoal records. The near-surface sediments of Devil's Bathtub were not varved, however, so the researchers did not analyze the last 2,300 years of charcoal deposition at this site. For both sites, charcoal was examined on thin sections prepared from the lake sediments, a method that makes it possible to count charcoal particles in varve couplets corresponding to single years. The researchers counted charcoal fragments ≥ 0.0024 inch, or 60 µm, in size.

Ely Lake is located within a hardwood–hemlock forest on a rolling section of the Appalachian Plateau. It had a low sedimentation rate, and charcoal accumulation suggested a relatively consistent level of fire activity over the entire record. Clark and Royall (1996) had expected to see a rise in charcoal accumulation associated with the inception of maize agriculture among the Iroquois during the past millennium, but no such change is evident, a finding interpreted by Clark and Royall to mean that Iroquois burning was probably confined to the vicinity of settlements and did not affect more remote locations around Ely Lake.

Devil's Bathtub is on the till plain about 12 miles north of the Appalachian Plateau in an area primarily covered with northern hardwoods forest under the current climate but with other hardwoods and conifers also present. For this site, Clark and others (1996) also analyzed pollen to reconstruct vegetation changes; they found that fire history corresponded with vegetation changes over the Holocene. Early in the record, when jack pine was an important constituent of the forest, crown fires were more common, as indicated by large charcoal peaks. The diminution of these peaks about 8,000–9,000 years ago may indicate a change from crown fires to surface fires with the transition to white pine. Later, fire frequency declined with the expansion of hardwoods about 8,000 years ago.

Century-to-Century Charcoal Variations Over the Past Millennium

In this subsection, we explore patterns of fire activity over the last millennium in the records of multiple sites with charcoal time series of moderate to high resolution, summarized at intervals of one century for this common period. The past 1,000 years spans the Mississippian Archaeological Period (1,000–300 BP) and the Historic Period (300 BP–present).

The six sites for which we present charcoal diagrams (fig. 6.09) are located mainly within the southern Blue Ridge Mountains and the Ridge and Valley province, with one site on the Piedmont and one on the Appalachian Plateau. This plateau site (Ely Lake) and one Ridge and Valley site (Trout Pond) were discussed in the previous subsection, but here we have aggregated the charcoal records to the century scale to compare with the remaining, lower-resolution records.

At two sites (Trout Pond and Ely Lake; fig. 6.09A and B), fire appears to have been present over the last millennium but to have varied from century to century, especially at Trout Pond. The relatively low values for the most recent century probably correspond to fire exclusion. At White Oak Bog in the southern Blue Ridge Mountains (fig. 6.09C), fire activity increased during the late Mississippian Period, possibly reflecting agricultural intensification and/or expanding human population. Fire activity peaked during the Historic Period.

The records for the three remaining sites are distinct in some respects from all others. The Days Creek record (fig. 6.09D) exhibits high charcoal accumulation in the most recent century, a pattern that may reflect heavy soil erosion and hence accelerated charcoal delivery from this Piedmont landscape. Charcoal accumulation during the prehistoric period is consistent with a rise in fire activity during the middle to late Mississippian Period. The Mountain Lake record (fig. 6.09E) from a high-elevation site in the Ridge and Valley province shows little or no charcoal accumulation until European settlement, likely a consequence of the remoteness of the site and the incombustible nature of the northern hardwoods–hemlock forest on the surrounding landscape. A most unusual pattern is evident at Pink Beds Bog (fig. 6.09F) in the southern Blue Ridge Mountains, where fire activity apparently declined in the middle Mississippian Period and then remained low.

On the basis of these six study sites, it seems reasonable to conclude that fire activity was relatively high during the middle and late Mississippian Period, and in general that it remained high during the Historic Period. Nonetheless, the dating of these charcoal records is somewhat imprecise, as is the translation between charcoal accumulation and fire activity. Additionally, the data for five of the six study sites come from an unpublished study (Lynch and Clark 2002). Although we chose the records in which we had more confidence to include in this discussion, all of them have low numbers of radiocarbon dates and some were characterized by slow sedimentation. One site, Mountain Lake, has a dynamic geomorphic setting characterized by periodic disruption of sedimentation (e.g., Cawley and others 2001).

Given these limitations, we attempted to distill the most basic patterns across the six sites by using a ranking method. Specifically, for each study site we ranked the 10 centuries of the millennium by charcoal accumulation, assigning a rank of 10 to the century with the highest value and a rank of 1 to the century with the lowest value. For centuries with tied values (including zeroes), we assigned the average rank for all the centuries with tied values. We then averaged the ranks for each century across all six sites (fig. 6.10). Thus synthesized, the charcoal records suggest a moderate to high level of burning through the Mississippian Period, with slightly higher ranks between 900 and 400 cal yr BP than for the rest of the period. They also indicate that frequent burning continued into the early Historic Period and peaked during the 19th century.

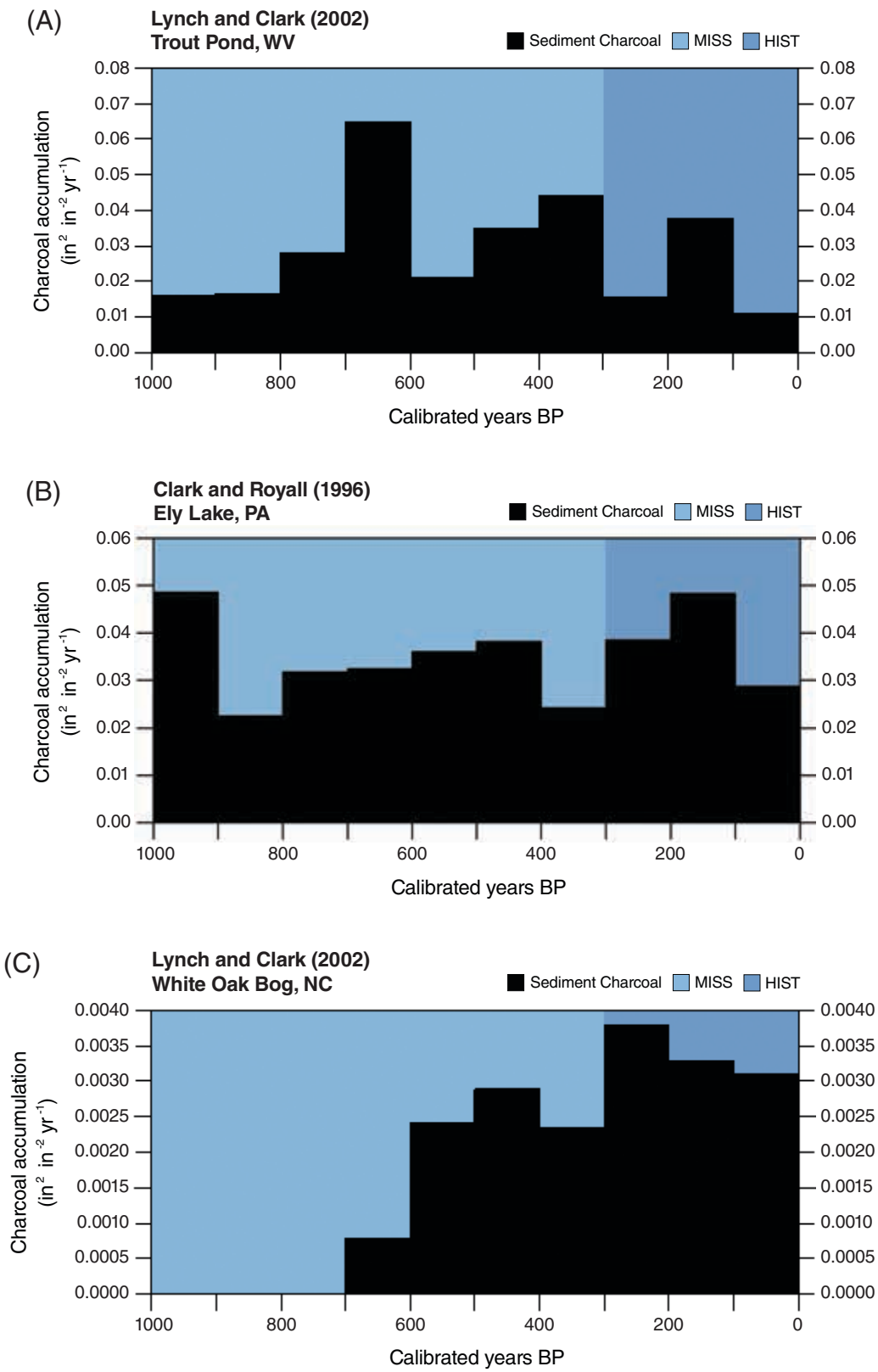


Figure 6.09—Estimates of charcoal level for each century over the past millennium for (A) Trout Pond, (B) Ely Lake, (C) White Oak Bog, (D) Days Creek, (E) Mountain Lake, and (F) Pink Beds Bog. Background shading as in figure 6.08. MISS = Mississippian Period, HIST = Historic Period. The charcoal levels indicate century-scale variations in fire activity and suggest that fire was relatively common at most sites during the MISS and HIST periods.
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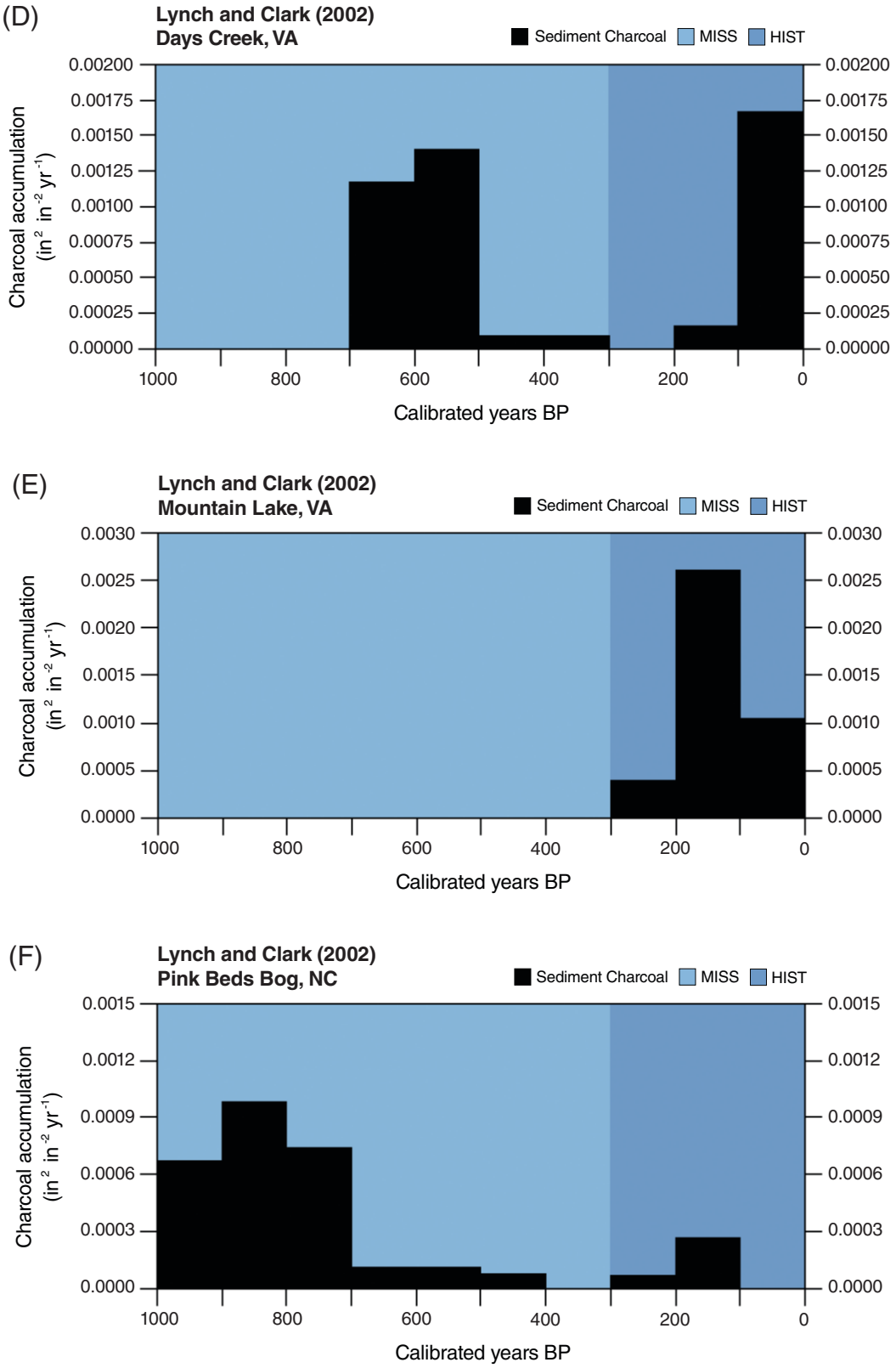


Figure 6.09 *(continued)*—Estimates of charcoal level for each century over the past millennium for (D) Days Creek, (E) Mountain Lake, and (F) Pink Beds Bog. Background shading as in figure 6.08. MISS = Mississippian Period, HIST = Historic Period. The charcoal levels indicate century-scale variations in fire activity and suggest that fire was relatively common at most sites during the MISS and HIST periods.

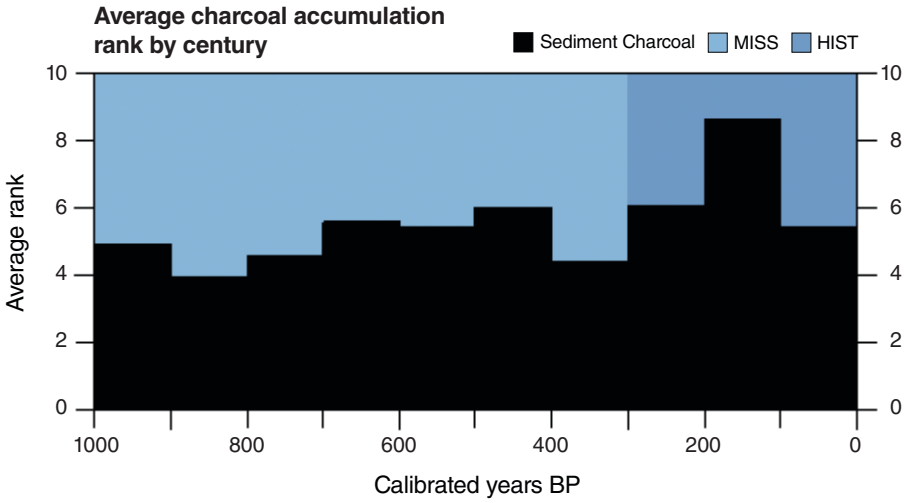


Figure 6.10—Average rank of charcoal level for each century of the past millennium among the six study sites portrayed in figure 6.09. Centuries with higher mean ranks (maximum possible rank = 10) are represented, on average, by higher levels of charcoal at the six study sites than are centuries with lower mean ranks (minimum possible rank = 1). MISS = Mississippian Period, HIST = Historic Period.

A Multimillennial View of Fire History at Coarse Resolution from Sediment Charcoal

To place the most recent millennium of fire history into the broadest possible temporal context, we now enlarge our perspective by using longer (multimillennial) records from seven sediment charcoal sites distributed across the Appalachian region (fig. 6.11). Low sedimentation rates limit the resolution of some of these records, so we have aggregated the data to 500-year intervals. For several of the sites, pollen data were presented in addition to charcoal, allowing us to summarize pollen percentages for tree genera that commonly benefit from fire (pine, oak, chestnut, and hickory).

The longest records (fig. 6.11A–D) are from four of Lynch and Clark's (2002) sites and span most or all of the Holocene Epoch. None of the four records has the same charcoal pattern, but each shows that fire was present through the Holocene. Fire activity does not seem to have responded strongly to changes in human activity except at Pine Swamp (fig. 6.11A) on the Appalachian Plateau in Maryland, where charcoal peaked sharply during the last 500 years, consistent with intensification of indigenous agriculture and with European settlement. The Pink Beds Bog site (fig. 6.11B) in the southern Blue Ridge Mountains of North Carolina indicates an opposing pattern in which burning was more pronounced during the Archaic Period than later; whether this apparent shift reflects changes in anthropogenic burning or Holocene shifts in climate and vegetation is not known. The coincidence between the decline in charcoal accumulation and the decline in chestnut pollen percentages between 5,000 and 3,000 BP led Lynch and Clark (2002) to suggest that fire has played an important role in shaping Appalachian chestnut forests.

The two remaining sites in Virginia, Browns Pond (fig. 6.11C) and Spring Pond (fig. 6.11D), display no obvious long-term temporal trends, although they indicate considerable variability between successive 500-year intervals. Pollen records from the two Virginia sites suggest that after the shift from boreal to temperate forest in the early Holocene, oak dominance was favored for much of the Holocene.

Two additional sites have yielded records spanning much of the Holocene—Devil's Bathtub and Cliff Palace Pond. As discussed above, at Devil's Bathtub (fig. 6.11E), charcoal accumulation declined in the early Holocene and then leveled off. At the Cliff Palace Pond site (fig. 6.11F) on the Appalachian Plateau of Kentucky, Delcourt and others (1998) retrieved a sediment core from a pond near rock shelters that had been used by aboriginal people since the early Archaic Period or before. They analyzed microscopic charcoal fragments on pollen slides, including fragments with mean diameters as small as 0.0004 inch (9 µm). Fire activity appears to have been relatively high during the early and middle Archaic Period and to have declined dramatically in the late Archaic. The area became an important center for plant husbandry and domestication during the late Archaic and early Woodland Periods, and as human use of the landscape intensified, fire activity increased. These fires are thought to have contributed to the increase in oak, pine, and chestnut (Delcourt and others 1998).

Similarly, Delcourt and Delcourt (1997) found charcoal evidence of fire through the past 4,000 years at Horse Cove Bog (fig. 6.11G) near the Blue Ridge escarpment of western North Carolina, based on microscopic charcoal on pollen slides

(> 0.0004 inch, or 9 µm). They attributed the prehistoric fires to aboriginal burning because several important archaeological sites dot the landscape and because the extremely wet climate along the escarpment does not favor lightning ignitions, at least currently. These fires appear to have maintained oak, chestnut, and pine on this landscape, where in the absence of fire the moist environment would favor shade-tolerant mesophytic tree species. The recent charcoal spike at this site was ascribed to European settlement and to an increase in erosion (and hence charcoal delivery) following widespread land clearance (Delcourt and Delcourt 1997).

Any overall conclusions based on the patterns observed at the seven sites with charcoal records spanning many millennia must be made with caution because of the uncertainties that arise from low rates of sedimentation and low numbers of radiocarbon or other dates at several of the sites. Questions also exist concerning how to compare the evidence from charcoal with the more highly resolved records of fire history derived from the study of fire-scarred trees in the Appalachian region. Much of the research on reconstructing long-term fire history from charcoal, especially in terms of separating background charcoal and charcoal peaks to estimate MFIs, has been carried out in areas of North America where the fire regime is characterized by catastrophic crown fires that occur at long intervals. In these situations, a decline in charcoal influx and in the frequency of charcoal peaks indicates reduced fire frequency and increased MFIs. However, reductions in overall charcoal influx and increased spacing between charcoal peaks could also result from a shift toward a fire regime of increased surface fires. These surface fires may burn more frequently but result in lower production and transport of charcoal particles to sedimentary basins than more severe, convective-driven crown fires (Whitlock and Larsen 2001).

Another important question is what is indicated if a site yields extremely small amounts of charcoal, as at Spring Pond. Lynch and Clark (2002) interpreted the Spring Pond record to indicate that fires were rare or absent over the past 20,000 years. This interpretation is at odds with the frequent burning during the last three centuries documented by the analysis of fire-scarred trees growing on the slopes of Kelley Mountain, approximately five miles away within the Blue Ridge Mountains (see chapter 4) (Aldrich and others 2014). Spring Pond is one of several ponds dotting a debris fan complex along the base of Kelley Mountain and associated ridges. The streams that drain the ridges flow onto the fans through channels incised into the fan surface, presumably transporting charcoal from the ridges onto the fans. But little sediment from the mountain slopes appears to be delivered to Spring Pond because it is a spring-fed pond that occupies an interfluvial position on a fan, hence the low sedimentation rate and the disconnection between charcoal and tree-ring records of fire history on the nearby mountain slopes. Such disconnections commonly appear where a lake or bog is not well positioned to receive charcoal (Whitlock and Larsen 2001), and they need to be taken into account when interpreting records. The low charcoal levels for Spring Pond should not be interpreted to indicate that fire has been rare. In fact, fires probably swept frequently across the debris fans. The fans make up a relatively flat area adjacent to the floor of the Shenandoah Valley, where frequent fires likely maintained open woodlands and areas of savanna (Mitchell 1972). Fine, grass fuels may have also extended onto the fans. The combustion of these fuels would not have produced abundant macroscopic charcoal fragments of the size analyzed by Lynch and Clark (≥ 0.0071 inch, or 180 µm); hence their absence from the Spring Pond sediment core does not provide evidence for the rarity or absence of fire.

In the ideal situation for studies of sedimentary charcoal, the history of recent fires in the watershed is known from historic records or tree-ring analyses, making it possible to compare and calibrate the recent portion of the sediment charcoal record against the historic record of fires. If lake sediment charcoal cannot be calibrated against fire-scar or other records, Whitlock and Larsen (2001) advise that another site should be chosen for charcoal analysis. Several situations conspire against this ideal and recommendation in the Appalachian region. First, information is sparse or lacking on historic fires within watersheds with lakes or wetlands suitable for charcoal analyses. Second, lakes and wetlands suitable for charcoal analysis are few. And third, as noted by Whitlock and Larsen (2001), the technique of macroscopic charcoal analysis is heavily biased toward the detection of catastrophic crown fires, a type of fire that is limited in frequency and spatial extent in most Appalachian ecosystems today and may have been for many millennia. The surface fires that we reconstruct in tree-ring analyses, which produce less charcoal and smaller convective plumes than more severe crown fires, may not leave distinct peaks of charcoal in lake sediments. Instead, frequent surface fires may primarily contribute to background charcoal. Thus, even the availability of fire-scar studies within lake watersheds may not provide the calibration suggested by Whitlock and Larsen (2001). However, this possibility needs to be tested through paired studies of fire-scarred trees and lake sediments in Appalachian watersheds, a type of study that to our knowledge has not yet been undertaken, likely owing to the very few sites that might be amenable to such a study.

Bearing such uncertainties in mind, we can conclude at a minimum that fire has been present on Appalachian landscapes through the Holocene. Some of the graphs in fig. 6.11 show considerable temporal variations, but the fire histories examined are unique. Hart and Buchanan (2012) examined an overlapping set of sediment charcoal records from the Appalachian region and also found a lack of clear, ubiquitous patterns. Because most of the sediment charcoal records summarized here were based on the analysis of macroscopic charcoal, a signal of local fires, the absence of strong correlations between records is not surprising. We can expect that the history of burning over time in the Appalachian region was spatially variable, and the sediment charcoal records confirm this to be true.

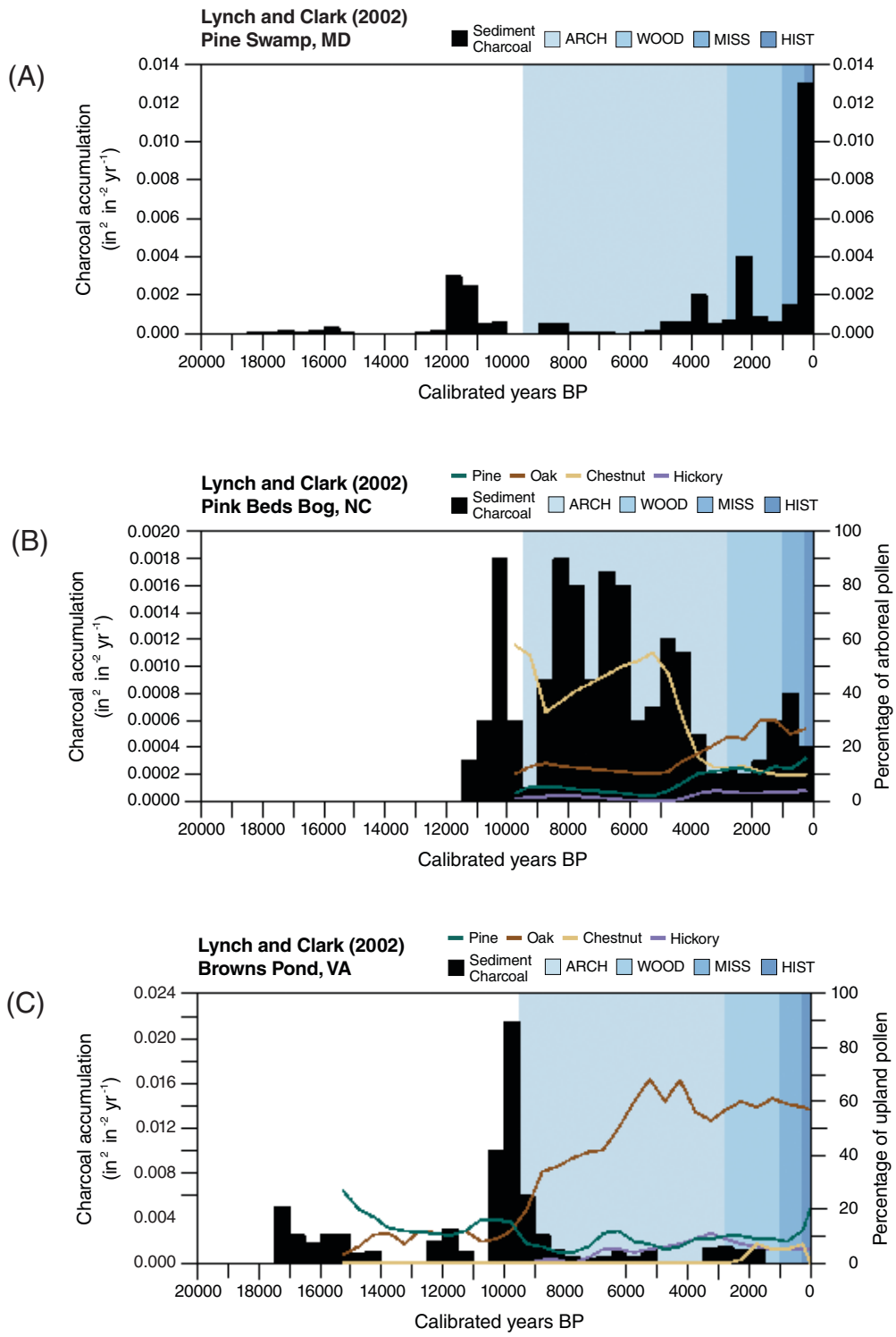


Figure 6.11—Estimates of charcoal levels (black bars) and tree pollen (colored lines) for 500-year intervals at sites with multimillennial records: (A) Pine Swamp, (B) Pink Beds Bog, (C) Browns Pond, (D) Spring Pond, (E) Devil's Bathtub, (F) Cliff Palace Pond, and (G) Horse Cove Bog. Pollen data are from the same study as the charcoal data except for two sites: Browns Pond, with pollen data from Kneller and Peteet (1993), and Spring Pond, with pollen data from Craig (1969). Background shading as in figure 6.08. ARCH = Archaic Period, WOOD = Woodland Period, MISS = Mississippian Period, HIST = Historic Period. *(continued on next page)*

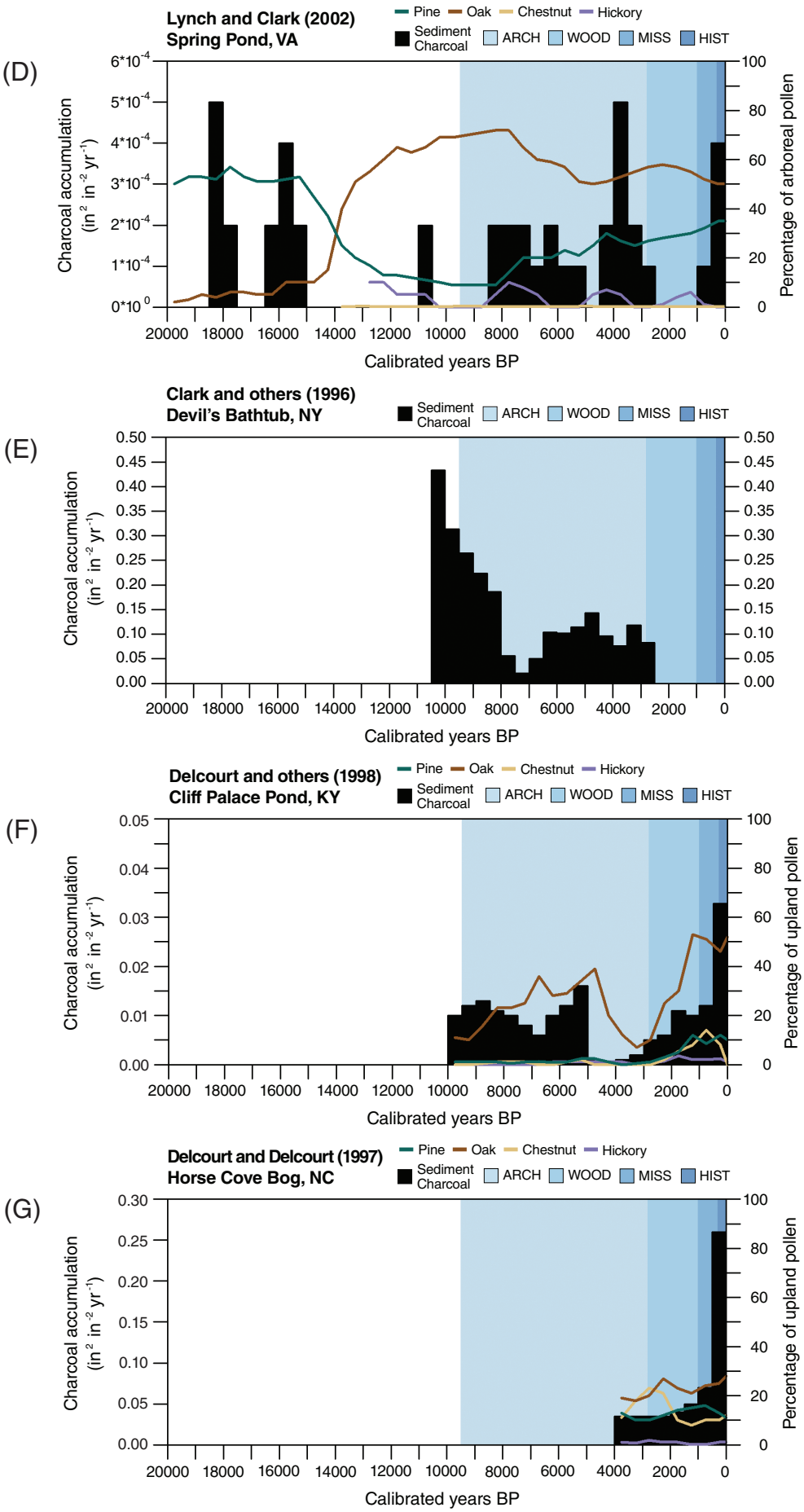


Figure 6.11 *(continued)*—(D) Spring Pond, (E) Devil's Bathtub, (F) Cliff Palace Pond, and (G) Horse Cove Bog. Pollen data are from the same study as the charcoal data except for two sites: Browns Pond, with pollen data from Kneller and Peteet (1993), and Spring Pond, with pollen data from Craig (1969). Background shading as in figure 6.08. ARCH = Archaic Period, WOOD = Woodland Period, MISS = Mississippian Period, HIST = Historic Period.

The spatial and temporal variability in fire in the Appalachian region documented by the sediment charcoal records raises the question of how strongly these variations relate to climate and environmental factors and trends, as compared to prehistoric human activities that purposefully or inadvertently increased or decreased wildland fires. From the records, we can conclude that fire activity increased at some sites because of anthropogenic burning during the Woodland or Mississippian Archaeological Periods. But teasing apart human activity versus climate and environmental change as drivers of past fire requires more research. Specifically, we need a larger number of carefully sampled and analyzed charcoal records, coupled with information on past climate, vegetation, and human activity that is derived from analyses of additional proxies in the sediment cores or other paleoenvironmental archives, and from local archaeological investigations.

A Multimillennial View of Fire History at Coarse Resolution from Soil Charcoal

Soil charcoal analyses that include radiocarbon dating of fragments have been conducted in the Appalachian region only in the last decade, with data available from just five sites: four in the southern Blue Ridge Mountains and one on the Appalachian Plateau in Tennessee (fig. 6.07). At Wine Spring Creek in North Carolina (fig. 6.12A), Fesenmyer and Christensen (2010) dated 83 charcoal fragments from 18 soil cores collected along a topographic gradient (dry ridge to moist cove). At three sites in Great Smoky Mountains National Park (figs. 6.12B–D), Underwood (2013) obtained 133 radiocarbon dates for charcoal fragments in 48 soil cores. These cores were collected from the same sites where LaForest (2012) sampled yellow pines to develop fire-scar records.

The charcoal dates for the Blue Ridge Mountains show a similar temporal distribution across the four study sites (fig. 6.12), with more charcoal from the last millennium than the previous three millennia. The rarity of charcoal fragments with ages > 1,000 BP may in part reflect the gradual breakdown of charcoal fragments over time (Horn and Underwood 2014). Therefore, the graphs should not be interpreted to necessarily indicate a steady or exponential increase in fire activity over time. The records indicate, instead, that fire has burned these particular mountain slopes through much of the Holocene. The site specificity of soil charcoal is one of its main advantages over sediment charcoal. At Wine Spring Creek, it is possible to infer that fires have a history of burning the entire topographic gradient, which today includes mesophytic cove forest as well as xerophytic oak–pine forest on the upper slopes. For the Great Smoky Mountains sites, Underwood (2013) taxonomically identified the charcoal fragments to provide evidence of the vegetation that burned in past fires. He found the most abundant charcoal type in his samples to be charcoal from the yellow pine group, which suggests that the long history of burning has helped maintain yellow pine populations for thousands of years. However, charcoal from oaks, chestnut, American elm (*Ulmus americana*), white pine, and hemlock was also present in the samples. The presence of charcoal from these taxa suggests past intervals of relatively low fire activity that enabled less fire-resistant trees to occupy the slopes, followed by a resurgence of fires that burned these tree taxa.

Some interpretations of broad temporal changes in fire activity may be possible from the soil charcoal studies conducted in the southern Blue Ridge Mountains. Underwood (2013) noted peaks in soil charcoal dates in the late Archaic Period (figs. 6.12B–D) and tentatively linked them to a late Archaic cultural shift from hunting and gathering to cultivation. Similarly, Fesenmyer and Christensen (2010) noted that their charcoal record begins in the late Archaic Period, and their charcoal dates from this interval may indicate an increase in burning associated with the cultural transition. They also interpreted an increase in charcoal dates around 1,000 years ago as a potential reflection of more widespread burning associated with the maize-based agriculture of the Mississippian Period.

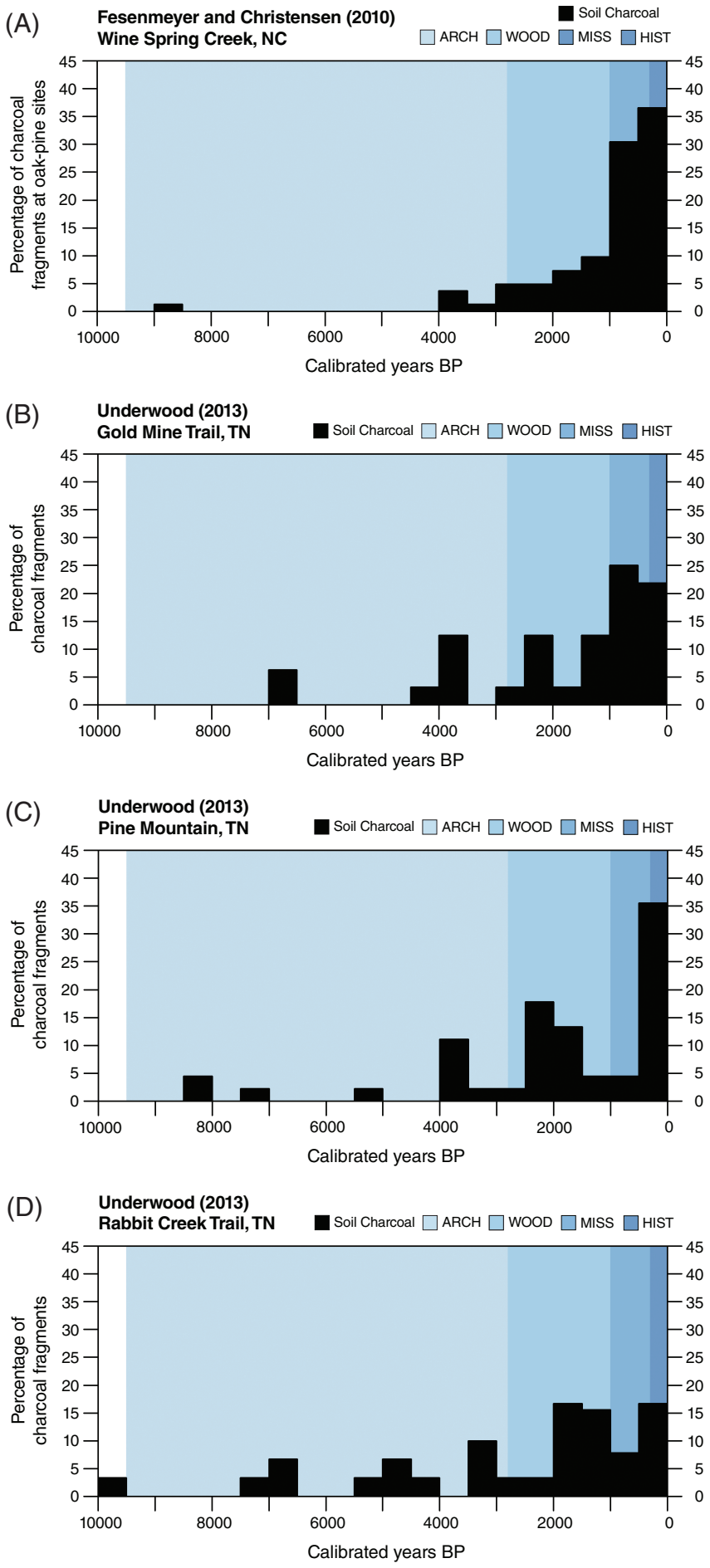


Figure 6.12—Estimates of charcoal levels for 500-year intervals at (A) Wine Spring Creek, (B) Gold Mine Trail, (C) Pine Mountain, and (D) Rabbit Creek Trail. ARCH = Archaic Period, WOOD = Woodland Period, MISS = Mississippian Period, HIST = Historic Period.

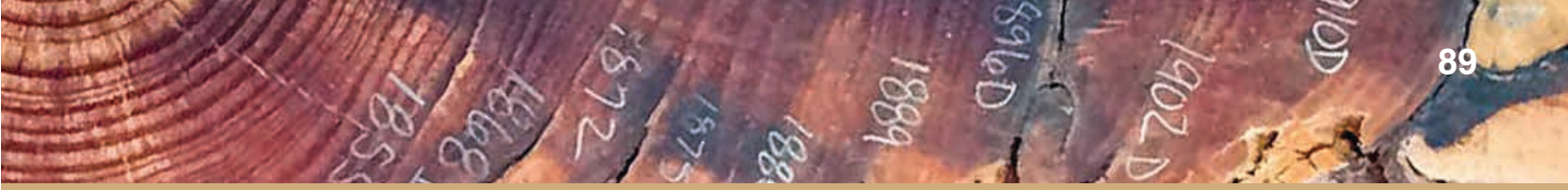
Additional soil charcoal data are available from the work of Hart and others (2008), who examined macroscopic charcoal in 10 soil cores collected in a mixed hardwood forest on the Cumberland Plateau of Tennessee. This project was completed before the studies in the Blue Ridge Mountains, when the importance of dating individual charcoal fragments was not yet recognized. Five samples were submitted for radiocarbon determination, four of which consisted of multiple charcoal fragments from the same depth increment of a particular soil core. Calibrated ages for the samples indicated fires at the site as early as about 7,000 cal yr BP, but this result may underestimate the age of the earliest fire if the charcoal fragments in the oldest sample were a mix of older and younger charcoal particles. The study by Hart and others (2008) was the first to attempt taxonomic identification of charcoal in Appalachian soils. Twelve of the larger charcoal fragments recovered were examined and determined to be from trees with a diffuse porous growth-ring structure, possibly sugar maple, red maple, American beech, or yellow-poplar. These trees are present today, but the site is dominated by mixed oak and hickory species that do not have this growth-ring structure. The representation of diffuse porous taxa in the charcoal assemblages suggested that one or more of these species were present at the time of past fires.

CONCLUSIONS AND IMPLICATIONS

Charcoal-based fire histories help to contextualize the fire-scar studies discussed in chapter 4; they also extend our understanding of Appalachian fire history beyond the temporal limits of tree-ring research. Charcoal in sediment cores from Appalachian lakes and wetlands does not provide the temporal resolution of fire scars and therefore cannot offer guidance to resource managers about appropriate intervals or seasons for controlled burning. In the best cases, however, where macroscopic charcoal is analyzed in cores from basins with rapid sedimentation, results may indicate whether fire history reconstructions from fire scars at nearby sites may pertain to centuries or millennia that precede the tree-ring record. The Trout Pond charcoal record (fig. 6.08A), for example, suggests that the frequent surface burning documented by fire-scar studies from the central Ridge and Valley province (e.g., Aldrich and others 2010, 2014; Hessl and others 2011) was typical for at least the past millennium. Similarly, it seems reasonable to infer from the collocated soil charcoal records (Underwood 2013) that the historic regime of frequent burning established by LaForest (2012) from fire-scar chronologies in the Great Smoky Mountains has characterized the sites for millennia.

Such inferences should be made cautiously, of course, because charcoal sampled in soils and sediments does not offer the annual precision of fire-scarred trees. Most Appalachian charcoal records have only low or modest resolution. Some of this is a consequence of the sedimentation rate in the basin selected, which provides a constraint on the resolution that can be achieved. In other cases, resolution could be improved through additional radiocarbon or lead-210 analyses. A clear need exists to develop additional multimillennial fire chronologies from sediment and soil charcoal studies across the Appalachian region, to extend the high-resolution records that we and others are developing from tree-ring analyses.

In the interim, the charcoal records at hand demonstrate unequivocally that fire has a long history in the Appalachian Mountains. This history extends through most of the Holocene, and it varies over space and time as we would expect given the spatial heterogeneity of the landscape and past changes in human activity and climate. For at least some locations, the amount of burning seems to have risen when human populations increased and intensified their land use. Finally, soil charcoal identification and pollen analyses of sediment profiles provide some evidence that Holocene fires helped maintain fire-favored trees such as oak, chestnut, and yellow pine in the Appalachian region.



Chapter 7. Summary: The Picture That Emerges of Appalachian Fire History

The vegetation of the Appalachian region (fig. 1.01) has been shaped by a history of fire. Evidence of this fire history has been obtained from various sources, and it suggests that the conceptual model of Appalachian fire history outlined by Brose and others (2001) (fig. 1.02) is generally correct. Fires had recurred at short intervals for centuries before they became mostly excluded beginning in the early to middle 20th century. In fact, fire has played an important role in the development of Appalachian vegetation for millennia.

The model of Brose and others (2001) diverges from empirical observations in predicting anomalously high levels of fire activity during the industrial logging episode of the late 19th through early 20th centuries. This period did not actually see more frequent burning than previous centuries, at least in areas covered by oak- and pine-dominated forests of the central and southern Appalachian Mountains. We have therefore suggested a modification of the model that does not include a peak in fire activity during the logging episode (fig. 4.18). Nonetheless, a pattern resembling the original model applies in some places, notably the northern edge of the study region where the northern hardwoods forest did not burn regularly until human land use intensified during the 19th century.

The evidence concerning fire and vegetation history of the Appalachian region is consistent with the fire-oak hypothesis (e.g., Lorimer and others 1994, Nowacki and Abrams 2008), which proposes that frequent surface fires maintained an open canopy and understory that enabled the establishment of oaks (and, historically, American chestnut) and inhibited the recruitment of mesophytic competitors. These mesophytic species lack the thick bark, large hypogeal roots, and other traits that favored the survival of oaks. Young oaks, by growing large roots and sprouting repeatedly after top-kill, would have persisted through multiple cycles of burning until they were able to bolt to a more fire-resistant size during the occasional fire-free interval of abnormal length, i.e., a length on the order of 10–15 years. Burning also favored yellow pines, particularly on relatively dry, infertile sites with sandy, well-drained soils on ridgetops and south- or west-facing slopes. On these sites, post-fire vegetation recovery was slow, and fires often burned with greater severity than elsewhere. Fire essentially operated as a filter on tree establishment within fire-prone sites by destroying the seedlings of fire-sensitive species. These species undoubtedly dispersed seeds onto the flammable mountain slopes, but to little avail. They were relegated to mesic coves, riparian zones, talus slopes, and other sites that were sheltered from frequent burning. In this way, fires contributed to the topographic patterning of vegetation over mountainous terrain.

The legacy of the past fire regime still endures in the form of widespread oak and yellow pine dominance in forests of the Ridge and Valley province, the Blue Ridge Mountains, the Piedmont, and parts of the Appalachian Plateau. In fact, a montane oak–pine vegetation complex covers as much as three-fourths of the total land area in the National forests that sprawl over the Ridge and Valley and the Blue Ridge provinces. This vegetation is by no means a consequence of past fires alone—human land use, climate, soil, and other factors also come into play. With respect to land use, for example, oak and pine recruitment was favored by the sequence of land clearance and subsequent abandonment that unfolded during the one to two centuries that followed European settlement. But fire was an essential factor without which oak- and pine-dominated ecosystems could never have grown to cover such extensive areas. Even before European settlement, oak and pine were the most abundant tree genera in the Ridge and Valley, Blue Ridge, and Piedmont provinces, according to multiple vegetation proxies (figs. 3.02, 5.03, 6.11).

The Appalachian Plateau had less oak and pine. That is not to say these genera were absent, however. Oak was relatively important in witness tree and pollen records from the plateau (figs. 3.02, 6.11). Nonetheless, the Appalachian Plateau was less extensively covered with pyrogenic vegetation, and this regional vegetation gradient appears to have paralleled a regional gradient in past fire frequency. Predictive models of pre-exclusion fire interval (Frost 1998, Guyette and others 2012) indicate that the central

and eastern sections of the Appalachian Plateau saw longer fire intervals than the rest of the Appalachian region (figs. 4.20, 4.21), a geographical pattern that reflects regional gradients in climate, terrain, and vegetation.

This broad pattern of fire frequency is consistent with fire-scar data (figs. 4.22–4.25), suggesting that the predictive model developed by Guyette and others (2012) is useful for estimating and mapping past fire intervals for areas that lack fire-scarred trees or other empirical records. However, comparing observed and predicted fire intervals for specific study sites reveals that the model overestimates the length of fire-free intervals (fig. 4.26). This mismatch indicates that the mean fire interval predicted by the model of Guyette and others (2012) should be viewed as a conservative estimate of pre-exclusion fire activity at a site.

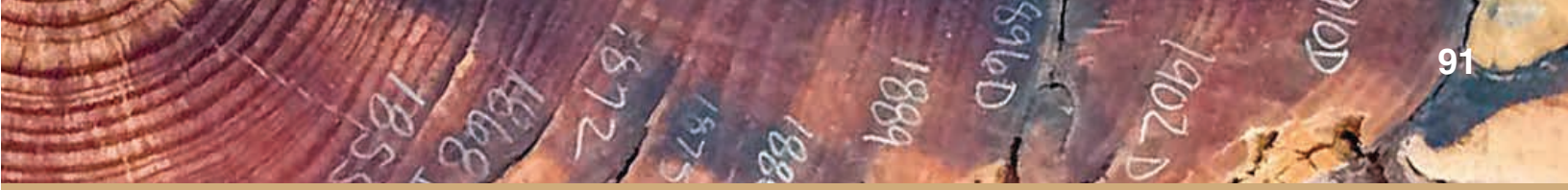
The divergence between observed and predicted fire intervals probably reflects factors that are not readily incorporated into a predictive model. Two such factors seem especially important—spatial contingencies and fire-fuel feedbacks. Spatial contingencies would have emerged because fire is a contagious disturbance that spreads across a landscape (Peterson 2002). Its occurrence at a specific point did not depend solely on the environmental conditions at the point but also on the flammability of the surrounding landscape through which fires were conveyed to that point. Contingencies likely played an important role in the Ridge and Valley province and Blue Ridge Mountains because the relatively cool, moist sites at middle elevations were connected to warmer, drier, more flammable sites at lower elevation. The spread of fire across a landscape ultimately would have conveyed fire to every point on the landscape at a higher frequency than would be expected from site conditions alone.

Fire spread was probably abetted by fire-fuel feedbacks that maintained a flammable vegetation structure. Open forest/woodland canopies with continuous fine fuels comprising grass, small shrubs, and oak and pine litter would have favored rapid drying of fuel and ready ignition by people or lightning. This flammable fuel structure would have enabled fires to spread quickly across a landscape to encompass many stands. Individual fires must have burned much larger acreages than observed at present, thereby maintaining a short fire interval at individual sites through which the fires passed. In turn, this frequent burning would have favored the development of a flammable, self-perpetuating vegetation structure.

Appalachian vegetation has been shifting in structure and composition as a consequence of fire exclusion. In its early phase, fire exclusion allowed a pulse of tree establishment by xerophytic and mesophytic species alike (figs. 5.03–5.04). As mesophication progressed, however, the establishment of oak and yellow pine diminished. The formerly open, flammable woodlands have transitioned toward dense forest stands with canopy dominants that were recruited under one fire regime but with an understory of shrubs and mesophytic trees that emerged under a new fire regime. As the overstory dominants die and are replaced by the understory species, former vegetation patterns are disappearing. Forests of fire-intolerant species that can regenerate in shaded, closed-canopy environments are expanding from formerly fire-sheltered refugia onto the broad mountainous landscape that once supported forests and woodlands of oak, chestnut, and yellow pine (fig. 5.07). With these vegetation changes will also come a further reduction in the general flammability of the landscape and a concomitant decline in the frequency of fire.

The departures from past conditions have motivated resource managers to implement prescribed burning and other measures, such as mechanical thinning, to restore pyrogenic vegetation on the National forests, National parks, and State and private conservation lands across the Appalachian region. Our synthesis of fire history underscores the need to continue these restoration projects and to expand them where feasible, possibly by using landscape-level burning where appropriate to mimic the large-extent fires that once occurred, especially in the Ridge and Valley province and the Blue Ridge Mountains. Our synthesis also suggests areas for further research. These research needs include an expansion of fire history studies to cover parts of the Appalachian region that are underrepresented in terms of fire history research; a better characterization of landscape patterns of burning; and more detailed information on such topics as the seasonality of past fires, the weather conditions that favor lightning ignitions, and the history of shrub establishment in forest understories during the era of fire exclusion.

As fire history research is expanded geographically and deepened topically, new findings will no doubt suggest refinements to our portrayal of Appalachian fire history and to the management needs implied by this portrait. However, we do not anticipate any changes to the general picture that emerges from our synthesis of fire history—that before the exclusion era, fires burned frequently and widely across broad swaths of the Appalachian Mountains.



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The importance of fire in shaping Appalachian vegetation has become increasingly apparent over the last 25 years. This period has seen declines in oak (*Quercus*) and pine (*Pinus*) forests and other fire-dependent ecosystems, which in the near-exclusion of fire are being replaced by fire-sensitive mesophytic vegetation. These vegetation changes imply that Appalachian vegetation had developed under a history of burning before the fire-exclusion era, a possibility that has motivated investigations of Appalachian fire history using proxy evidence. Here we synthesize those investigations to obtain an up-to-date portrayal of Appalachian fire history. We organize the report by data type, beginning with studies of high-resolution data on recent fires to provide a context for interpreting the lower-resolution proxy data. Each proxy is addressed in a subsequent chapter, beginning with witness trees and continuing to fire-scarred trees, stand age structure, and soil and sediment charcoal. Taken together, these proxies portray frequent burning in the past. Fires had occurred at short intervals (a few years) for centuries before the fire-exclusion era. Indeed, burning has played an important ecological role for millennia. Fires were especially common and spatially extensive on landscapes with large expanses of oak and pine forest, notably in the Ridge and Valley province and the Blue Ridge Mountains. Burning favored oak and pine at the expense of mesophytic competitors, but fire exclusion has enabled mesophytic plants to expand from fire-sheltered sites onto dry slopes that formerly supported pyrogenic vegetation. These changes underscore the need to restore fire-dependent ecosystems.

Keywords: Age structure, Appalachian Mountains, charcoal, fire history, fire regime, fire scars, witness trees.

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