Applied Vegetation Science ■■: 1–11, 2009

Three centuries of fire in montane pine-oak stands on a temperate forest landscape

Aldrich, Serena R.[1*]; Lafon, Charles W.[1,2]; Grissino-Mayer, Henri D.[3]; DeWeese, Georgina G.[4] & Hoss, Jennifer A.[5]

[1]*Department of Geography, Texas A&M University, College Station, TX 77843, USA;*
[2]*E-mail clafon@geog.tamu.edu;*
[3]*Department of Geography, University of Tennessee, Knoxville, TN 37996, USA; E-mail grissino@utk.edu;*
[4]*Department of Geosciences, University of West Georgia, Carrollton, GA 30118, USA; E-mail gdeweese@westga.edu;*
[5]*6112 Moose Ct, El Paso, TX 79924, USA; E-mail ja.hoss@gmail.com;*
**Corresponding author; Fax +1 9798624487; E-mail serena@neo.tamu.edu*

Abstract

Question: What was the role of fire in montane pine-oak (*Pinus-Quercus*) stands under changing human land uses on a temperate forest landscape in eastern North America?

Location: Mill Mountain in the central Appalachian Mountains, Virginia, US.

Methods: A dendroecological reconstruction of fire history was generated for four stands dominated by xerophytic pine and oak species. The fire chronology began under presettlement conditions following aboriginal depopulation. Subsequent land uses included European settlement, iron mining, logging, and US Forest Service acquisition and fire protection.

Results: Fires occurred approximately every 5 years until 1930 without any evidence of a temporal trend in fire frequency. Burning ceased after 1930. Area-wide fires affecting multiple pine stands were common, occurring at intervals of approximately 16 years. Most living pines became established during the late 1800s and early 1900s. Dead pines indicated that an older cohort established ca. 1730. Most hardwoods were established between the 1920s and 1940s.

Conclusions: Except for fire protection, changes in land use had no discernible influence on fire frequency. Lightning ignitions and/or large fire extent may have been important for maintaining frequent burning in the 1700s, while fuel recovery may have constrained fire frequency during later periods. The disturbance regime appears to be characterized by frequent surface fires and occasional severe fires, insect outbreaks or other disturbances followed by pine recruitment episodes. Industrial disturbances appear to have had little influence on the pine stands. The greatest impact of industrial society is fire exclusion, which permitted hardwood establishment.

Keywords: Appalachian Mountains; Dendroecology; Disturbance; Fire history; *Pinus pungens*; Table Mountain pine; Tree ring.

Nomenclature: Kartesz & Kartesz (1980).

Abbreviations: LEI = lower exceedance level; MFI = mean fire interval; UEI = upper exceedance level; WMI = Weibull median interval.

Introduction

Understanding disturbance history is important for explaining contemporary vegetation properties and guiding ecosystem restoration (Foster 2000). Disturbances such as prescribed fires are often incorporated into ecosystem management, particularly where fire protection, landscape fragmentation, or other changes in land use have diminished the historic role of fire (White 1987; Brose et al. 2001; Nowacki & Abrams 2008). Fire history research provides a context for such applications by revealing the historical variability in the incidence of fire and indicating the extent to which shifts in human land use have influenced fire regimes (Frost 1998). Human land use is thought to have exerted a strong control on the fire history of temperate forests. Pyne (1982) argued that the frequency of fire was high in European forests under extensive land uses such as agricultural expansion, but declined with shifts to intensive sedentary agriculture and industrial forestry. Such shifts in land use occurred more rapidly, and more recently, in North America than in the Old World (Pyne 1982), hence more evidence about historic fire regimes is still available (Frost 1998).

Burning has apparently contributed to vegetation development in many temperate forest ecosystems of eastern North America (Abrams 1992; Harrod et al. 2000). However, site-specific evidence needed for evaluating hypotheses about past fire regimes is sparse because decay and human manipulation have obliterated many old fire-scarred trees (but see Mann et al. 1994; Shumway et al. 2001; Guyette et al. 2002). We took advantage of an opportunity to study the fire history of an apparently unlogged forest within a larger landscape in the central Appalachian Mountains that has been subjected to multiple, contrasting land use episodes. The forest contained pines (*Pinus*) with a fire-scar record extending from before European settlement to the present. Typically, in the central Appalachian Mountains, pine stands occupy dry ridgetops and west-facing mountain slopes (Stephenson et al. 1993), oak (*Quercus*)-dominated stands comprise the matrix cover type, and mesophytic stands grow along narrow valleys, high elevations and other moist sites. Some fire history work has been conducted for oak forests (Shumway et al. 2001; McEwan et al. 2007b), but pine trees preserve fire scars better than oaks and appear to offer a more reliable record of fire history (McEwan et al. 2007a).

The Appalachian pine stands are considered to have developed in association with fire (Frost 1998; Williams 1998; Brose & Waldrop 2006). More shade-tolerant hardwoods occupy many of the stands, and it is widely thought that the stands are undergoing succession toward hardwood dominance because of fire exclusion.

Dendroecological fire chronologies have been created for a number of temperate forest sites in eastern North America (e.g. Mann et al. 1994; Shumway et al. 2001; Hoss et al. 2008), particularly on the Ozark Plateau (e.g. Guyette et al. 2002). However, many of the chronologies (e.g. Harmon 1982; Schuler & McClain 2003; McEwan et al. 2007b) are restricted to the mid- or late-nineteenth to twentieth centuries. They demonstrate low fire frequency over recent decades. The chronologies also reveal that fires occurred at approximately 2-17 year intervals during the late 1800s and early 1900s, when capital-intensive logging generated abundant dead woody fuel and ignition sources. Consequently, many existing forests originated during or in the aftermath of frequent burning (McEwan et al. 2007b).

The role of fire prior to the great logging episode is less certain in most of the temperate forest region, but is of considerable academic and applied interest. Resource managers in North America commonly use presettlement conditions as a restoration target and have less interest in perpetuating disturbance regimes that emerged because of recent industrial activities. It is thought by many that fires ignited by humans and possibly lightning were widespread and frequent across eastern North America before European settlement (e.g. Abrams 1992; Frost 1998; Brose et al. 2001), and that frequent burning continued as settlers adopted aboriginal burning practices (Pyne 1982). However, it is not clear whether fires were restricted primarily to areas near Native American and, later, European settlements along river valleys (Russell 1983; Vale 1998; Williams 1998), or if they also were common across the larger forested landscapes.

Past fire frequency in hilly or mountainous terrain is elusive because topographic barriers can limit fire size and frequency (Frost 1998; Guyette et al. 2002), yet fire-associated vegetation is common in areas such as the Appalachian Mountains (Brose et al. 2001). Fire frequency in mountainous landscapes should be sensitive to changes in human activity because in a fire regime dominated by small fires, a change in anthropogenic ignition density would alter the frequency of fire (Guyette et al. 2002). Fire-scar data have revealed such patterns on the rugged Ozark Plateau (Guyette et al. 2002) of the central US, but not in the northern (Mann et al. 1994) or central (Shumway et al. 2001) Appalachian region.

A conceptual model of *Pinus pungens*-*Pinus rigida* history (Williams 1998) proposes that fire regimes and pine extent varied with land-use history on Appalachian landscapes. Specifically, the model suggests that fire was infrequent before European settlement and that pines were largely restricted to self-replacing stands on sites too dry for hardwoods. After settlement, the frequency of fire increased gradually. Pines expanded to less extreme sites, particularly during logging from the 1890s to 1920s, before declining in the twentieth century. Under this scenario many existing stands may be artifacts of industrial disturbances. In contrast, others (e.g. Frost 1998; Brose et al. 2001) have suggested a long history of moderate to high fire frequency. Frost (1998) proposed that montane pine stands were maintained on presettlement landscapes under "polycyclic" fire regimes characterized by a short cycle (about 5-7 years) of understory fires combined with a long cycle (about 75 years) of stand-replacing fires.

The objective of this study was to develop a lengthy fire chronology for a forest within a mountainous, relatively isolated landscape to assess the influence of land-use history on fire regimes of montane pine stands. Was burning primarily a consequence of industrial logging, or was there a longer history of fire? Our specific questions are: (1) How frequently did fires occur historically? (2) Did the frequency of fire rise as the extent of human land use increased from presettlement to early European settlement to widespread extractive industrial activities (iron mining/smelting and logging)? (3) Did the frequency of fire decline in association with fire protection during the twentieth century? (4) Were fires of sufficient extent to encompass multiple pine stands? (5) Do the pine stands date to presettlement times or did they originate in concert with industrial disturbances? Answering these questions will expand knowledge about the fire history of temperate forests and will provide details relevant to managing specific vegetation associations.

Methods

Study area

The study site is on the northwest side of Mill Mountain in Bath County, Virginia (Fig. 1). Small streams dissect the mountainside, with alternating drainages and spurs aligned southeast to northwest. Mill Mountain is in the Ridge and Valley physiographic province and is within the George Washington National Forest (GWNF). Annual

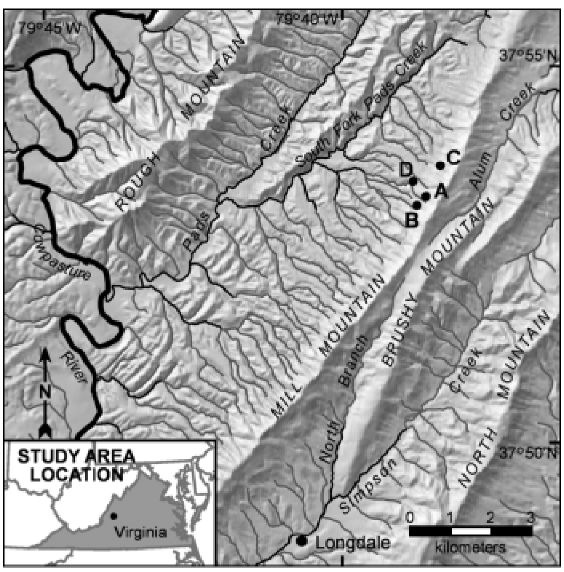

Fig. 1. The study area showing the location of stands **a-d**. The black lines represent perennial streams, and the gray lines represent intermittent streams.

precipitation averages 1090 mm at Hot Springs, Virginia, 20 km to the northwest at 680 m elevation (NCDC 2002). Mean monthly temperatures are between $-1°C$ and $22°C$. The vegetation cover is representative of central Appalachian landscapes, with the typical oak-dominated forest matrix covering most of the landscape, the mesophytic tree species confined to valleys and lower slopes, and the xerophytic pine-oak stands situated on narrow ridgetops and west-facing slopes. These xerophytic stands are dominated by yellow pines, particularly the Appalachian endemic *P. pungens*, along with *P. rigida*, *Quercus montana*, and *Quercus coccinea* (Williams 1998). These trees are relatively shade-intolerant and have fire adaptations such as thick bark and, in *P. pungens*, serotinous cones. A dense hardwood understory is dominated by *Nyssa sylvatica* and *Acer rubrum*.

The study site was chosen for the following reasons (1) It is in a large, forested landscape with typical ridge and valley terrain and vegetation. (2) Its remoteness from large settlements and agriculture should ensure that its fire history is representative of the larger forested landscape (Kou & Baker 2006). (3) Because of nearby mining and logging, fire scars may record industrial impacts on the fire regime. (4) Old pines with a long fire-scar record were present because the middle and upper slopes likely were not logged (SAMAB 1996). (5) It was accessible by a road that facilitated collection of fire-scarred specimens.

Native Americans lived along the Cowpasture River (Fig. 1) and other rivers in Bath County, but the area was apparently a hinterland without large permanent populations or well-developed agriculture (Geier & Boyer 1982). The sites were abandoned by the 1600s, concurrent with depopulation throughout western Virginia a century or more in advance of European settlement (Egloff & Woodward 2006), but hunting, trading and raiding parties continued to travel through western Virginia in the 1700s. European settlement began along the Cowpasture River southwest of the study site ca. 1745 (Morton 1917).

Mill Mountain is within a rugged area occupied by few humans in the past (Morton 1917) or today. Land records (GWNF headquarters) indicate that original land grants on Mill Mountain were made ca. 1795-1825. Scattered settlement may have occurred during that period. Of potential importance for fire history is that iron furnaces operated near Longdale, 9 km from the study site (Fig. 1), from 1827 to 1925, consuming hardwood timber to produce charcoal until conversion to coke in 1874 (Russ et al. 1995). By the 1870s-1880s, furnaces and associated settlements extended along Simpson Creek (Fig. 1) to within about 4 km of the study site, but the settlements were abandoned after iron production ceased (Russ et al. 1995). A railroad was constructed along Pads Creek (Fig. 1) in 1857 (Morton 1917) and continues operation. Logging occurred along South Fork Pads Creek (Fig. 1) in 1927-1928. In 1937, the US Forest Service purchased a 10 526 ha area containing Mill Mountain. The land records mention repeated burning in the past and describe a specific fire that burned much of Mill Mountain in 1930. Fire records for 1970 to present contain no wildfires for the study site since 1970 (USDA Forest Service 1998). A prescribed fire conducted on 27.03.2001 affected part of the study area (stand D in Fig. 1; Steve Smestad, GWNF, personal communication). It was a mild burn that consumed fine fuels and top-killed some understory plants, but appeared to have little influence on larger saplings or overstory trees.

Data collection and analysis

During 2003-2004, full or partial cross-sections were cut from living and dead *P. pungens* and *P. rigida* trees with basal fire scars in four stands (labeled A-D on Fig. 1) on spurs at ca. 785 m elevation. The stands are within a 0.8 km $\times$ 1.2 km area (ca. 1 km^2). In a 20 m $\times$ 50 m quadrat in stands A, B and D, two cores were extracted from opposite sides at the base of each living tree with stem diameter at breast height (DBH, measured at 1.37 m) $\geq$ 5 cm and the species and DBH recorded. Saplings (height $\geq$ 50 cm, DBH $<$ 5 cm) were identified and counted, but not cored. However, branch nodes were counted to estimate the age of pine saplings (Pfeffer 2005). Seedlings (height $<$ 50 cm) of all tree species in a 10 m $\times$ 20 m subplot in each quadrat were inventoried.

Cross-sections and increment cores were surfaced with a belt sander to reveal tree rings and fire scars. Tree rings were cross-dated visually (Stokes & Smiley 1968), and then measured with a Velmex measuring stage accurate to 0.001 mm and cross-dated statistically using the COFECHA program (Holmes 1986). Fire scars were dated to the year of formation. Seasonality was designated according to scar position within the annual ring (Grissino-Mayer 2001): (1) dormant – between rings, assigned the date of the following ring; (2) earlywood; (3) latewood; and (4) undetermined.

The FHX2 program (Grissino-Mayer 2001) was used to archive the fire scar data, summarize scar seasonality, and analyse fire return intervals. A Weibull distribution was fitted to the intervals. We report the Weibull Median Interval (WMI) and the widely used Mean Fire Interval (MFI) to characterize central tendency in the fire return intervals. Lower and Upper Exceedance Intervals (LEI and UEI) were calculated to characterize the range of historical variability within the Weibull-modeled distribution. Specifically, 75% of the fire intervals are expected to fall between the LEI and UEI.

In consideration of uncertainties inherent in fire-scar analyses (Baker & Ehle 2001; Van Horne & Fulé 2006) five different estimates of WMI, MFI, LEI and UEI were obtained, each of which has advantages and disadvantages. (1) The point fire interval was calculated from the fire intervals recorded by individual samples and is an estimate of fire frequency at any point on the landscape. In its calculation, FHX2 analyses only the intervals covered by "recorder" years (i.e. years following the initial scar on a tree) (Grissino-Mayer 2001). The initial wound makes the tree more susceptible to subsequent scarring. Also, tree rings formed after a tree has healed completely over a wound, or during a period in which some of the scars may be obscured by decay or removal by subsequent fires, are not considered recorder rings (Grissino-Mayer 2001). The designation of recorder years is a standard and necessary practice (Grissino-Mayer et al. 2004) to ensure that MFI and other calculations are based on periods when data are available. Limiting the analysis to intervals covered by recorder years prevents the bias that could result from including intervals that appear to have been fire-free for a long time simply because the scars were removed or the tree was not susceptible to scarring. Nonetheless, the point fire interval likely overestimates fire interval length because trees are imperfect recorders of all the fires that burn them even if they are functioning as recorders. (2) The stand-level composite fire interval was calculated using all fires recorded by all trees in a stand. Generally, non-recording intervals of one tree are covered by recording intervals of other trees, therefore FHX2 uses all the composite fire intervals to estimate fire frequency (i.e. no fire scar on any tree is excluded from analysis). Compositing the fire records from multiple trees reduces the likelihood of missing a fire. However, some fires might be missed because of the limited number (13-19) of fire-scarred trees in each stand, causing the fire interval to be overestimated. (3) The combined-stand composite fire interval was based on all fires recorded by all trees in all stands. This is a standard analysis conducted to minimize the likelihood of missing a fire, but it could underestimate fire interval if some of the fires did not burn the entire study area. It provided the most complete record of fire activity in the study area and was useful for investigating temporal trends in burning. We used correlation analysis (Zar 1999) to assess whether the number of fires recorded per decade changed over time. (4) The filtered composite fire interval for all stands combined was based only on "major" fires recorded by at least two trees and $\geq 25\%$ of all recorder trees; such fires may have been more extensive or severe than others. By disregarding potentially small-extent fires, filtering offers a more conservative and possibly more reliable estimate of fire frequency. (5) The area-wide fire interval (Fisher et al. 1987) was based solely on widespread fires recorded in all four stands, if the year of the fire was a recorder year in all stands. For fire years that were recorder years in only two or three stands, an area-wide fire was one that scarred trees in all of those stands. We did not consider fires that occurred when only one stand had recorder years.

Tree age was graphed to portray stand age structure. For cores that did not intersect the pith, tree age was estimated from the width and curvature of the innermost rings (Applequist 1958). Because the age structure histograms were created using 10-years age classes, 16 trees with >10 years added were excluded. Also, "moderate releases" and "major releases" (Lorimer & Frelich 1989) were identified in the ring-width measurements from all the pine and hardwood cores to detect growth increases that could signal major fires or other canopy-thinning disturbances that may have promoted tree establishment. A moderate release was an abrupt ring-width increase ($\geq 50\%$ increase in a year, relative to the mean for the previous 10 years) that was sustained for a decade (i.e. the mean ring width for the decade following the increase was $\geq 50\%$ more than that of the previous decade). A major release had a threshold of 100% increase in ring width relative to the previous decade.

Results

For the period 1704-2003, 209 scars on 63 trees recorded 42 fire dates (Fig. 2a). For scarred trees that could be aged (i.e., had an intact pith), mean age at initial scarring was 19.7 years (range 7-70 years) at the height of the cross-section. Mean diameter (excluding bark) at initial scarring was 7.4 cm (range 0.6-21.5 cm). Fires occurred regularly from 1704 until 1930 (Fig. 2b); correlation analysis indicated that the number of fires per decade did not change during this time ($r = 0.003$, $t = 0.014$, $df = 22$, $P > 0.50$). Only one post-1930 scar was observed: a dormant-season scar caused by the prescribed burn of 2001. The 1930-2001 interval was excluded from the correlation and fire interval analyses because of our interest in the pre-suppression fire regime. For the period beginning in the first year with two or more scarred trees (Grissino-Mayer et al. 2004) and ending in 1930, the various analyses yielded MFI and WMI estimates of 5.1-17.3 years (Table 1). Seasonality was determined for 66% of the fire scars. Most (89.6%) of the scars were in the dormant position, while 9.7% were in the earlywood and 0.7% were in the latewood.

Pine establishment dates peaked during the 1900s-1920s for stands A and B, but in the 1870s-1880s for stand D (Fig. 3a). Cross-sections reveal earlier pine establishment, especially in the 1730s (Fig. 3d). (Note that only fire-scarred cross-sections were collected from stand C; no plot was established). *Pinus pungens* was the most abundant species, with 10.9 $m^2\,ha^{-1}$ of the 27.1 $m^2\,ha^{-1}$ mean stand basal area (BA). *Pinus rigida* and *Pinus virginiana* had mean BA of 2.0 $m^2\,ha^{-1}$ and 0.4 $m^2\,ha^{-1}$. Yellow pines comprised 33 saplings ha^{-1} and 67 seedlings ha^{-1}, all of which were *P. pungens*.

Most hardwood trees were established during the 1920s-1940s (Fig. 3b and c), but some *Quercus montana* and *Quercus coccinea* were older. These two species were the most abundant hardwoods (mean BA = 7.8 $m^2\,ha^{-1}$ and 3.1 $m^2\,ha^{-1}$, respectively). Others had a combined mean BA of 2.8 $m^2\,ha^{-1}$. These included *N. sylvatica*, *Quercus velutina*, *Quercus rubra*, *A. rubrum*, and *Carya glabra*. Hardwood tree species comprised 247 saplings ha^{-1} and 4317 seedlings ha^{-1}, with *A. rubrum* the most abundant species in both size classes. The peak decades for radial growth releases (in pine and hardwood cores combined) were the 1890s, 1960s, and 1980s (Fig. 4).

Discussion

Our analyses of fire frequency (question 1) indicates a regime of frequent fires at Mill Mountain in the past. The composite fire interval was shorter than the 7-10 year intervals estimated in previous work on Appalachian pine stands (Harmon 1982; Sutherland et al. 1995; Armbrister 2002). However, those studies had small sample sizes, hence they likely missed fires recorded by only a few trees. Some fire chronologies for oak forests in the Appalachian

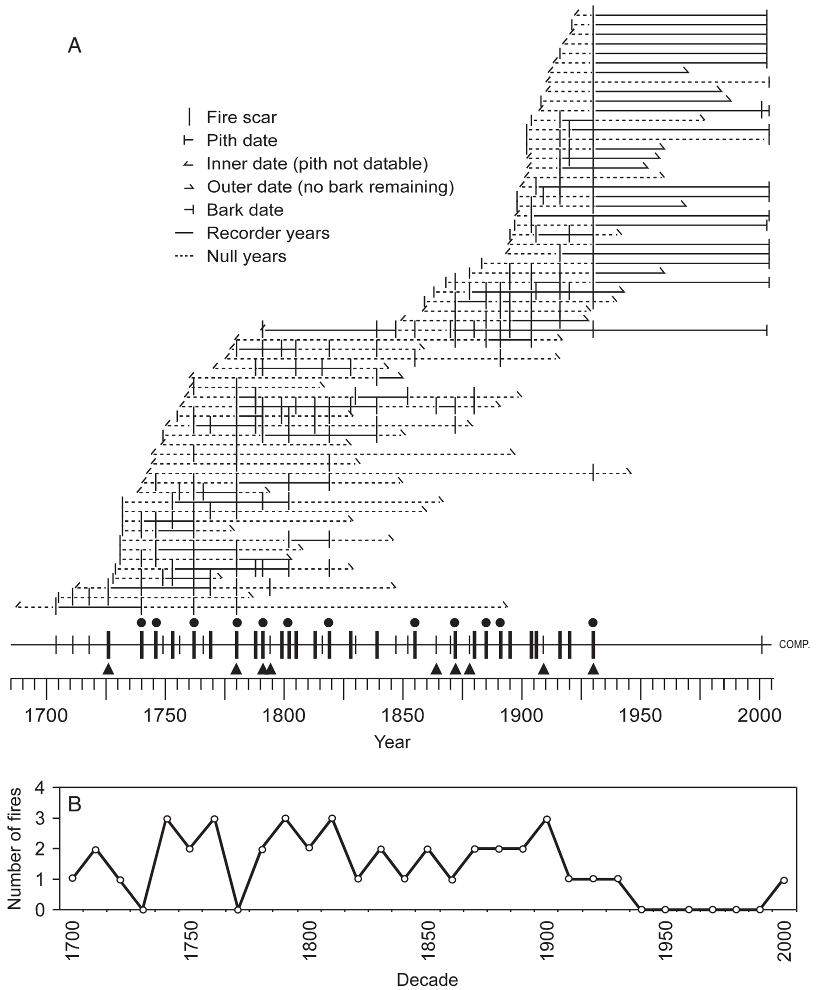

Fig. 2. Fire chronology for Mill Mountain: (**a**) Record of fire scars for each tree, 1704-2003. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars. For the composite fire axis (labeled "Comp.") at the bottom, the long, heavy vertical lines depict major fires recorded by $\geq 25\%$ of trees. Short, thin vertical lines indicate less extensive fires. Closed circles above the composite axis mark the area-wide fires, and closed triangles beneath the composite axis point to fires for which at least one tree recorded a growing-season fire. (**b**) Number of fires recorded each decade.

Table 1. Fire interval calculations for Mill Mountain. Abbreviations: MFI = mean fire interval; WMI = Weibull median interval; SD = standard deviation; LEI = lower exceedance level; UEI = upper exceedance level.

	MFI	WMI	SD	LEI	UEI	Range	Number of intervals	Years covered
Point fire interval	11.1	10.2	6.7	4.1	18.8	2–48	82	1726–1930
Stand-level composite fire interval								
Stand A (1.7 ha)	7.3	6.6	5.0	2.4	12.9	2–26	26	1740–1930
Stand B (2.7 ha)	11.9	10.0	9.7	3.0	22.0	3–39	16	1740–1930
Stand C (0.9 ha)	15.9	11.7	19.4	2.5	32.4	4–59	7	1819–1930
Stand D (1.5 ha)	8.3	8.1	3.9	4.2	12.6	4–16	7	1872–1930
Combined-stand composite fire interval	5.4	5.1	2.9	2.2	8.8	2–14	38	1726–1930
Filtered composite fire interval	7.8	7.5	3.9	3.6	12.4	2–17	26	1726–1930
Area-wide fire interval	17.3	16.0	10.9	6.4	29.4	6–39	11	1740–1930

region with larger sample sizes had fire intervals nearer, or shorter than, those reported here (Shumway et al. 2001; McEwan et al. 2007b; Hoss et al. 2008). Another potential factor is that these oak forests were in locations that likely were exposed to more anthropogenic fire than Mill Mountain.

Differing sample sizes may obscure between-site differences in fire interval. Comparing point fire in-

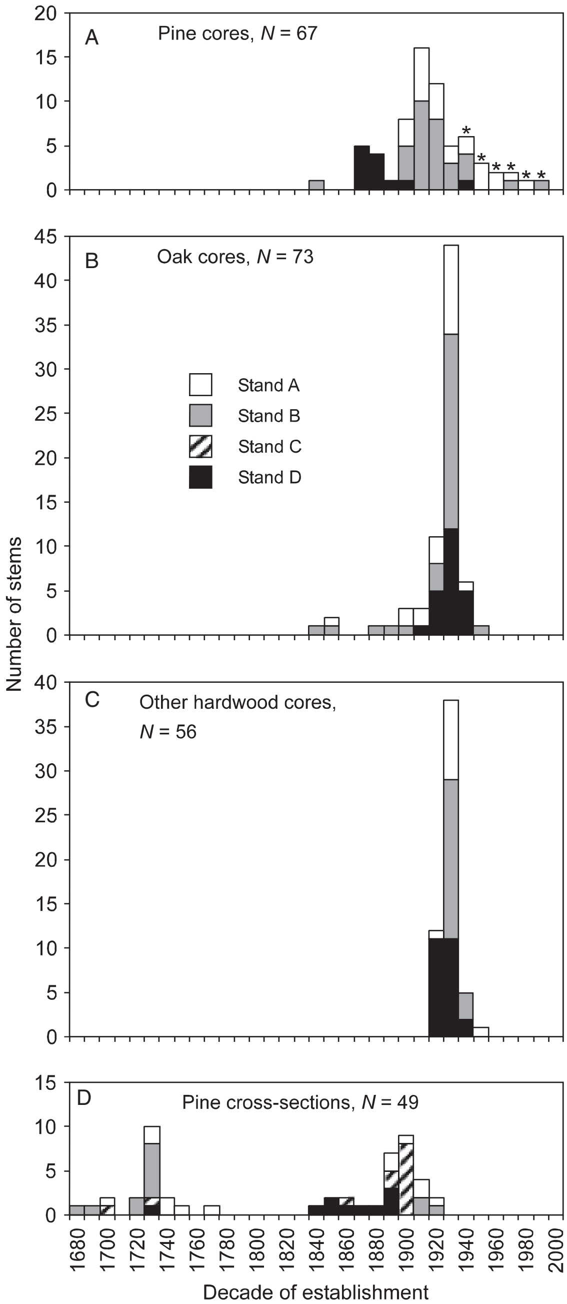

Fig. 3. Tree establishment dates for (**a-c**) trees cored in the plots and (**d**) fire-scarred pines with intact pith. Asterisks indicate that one or more stems was a sapling aged by node-counting.

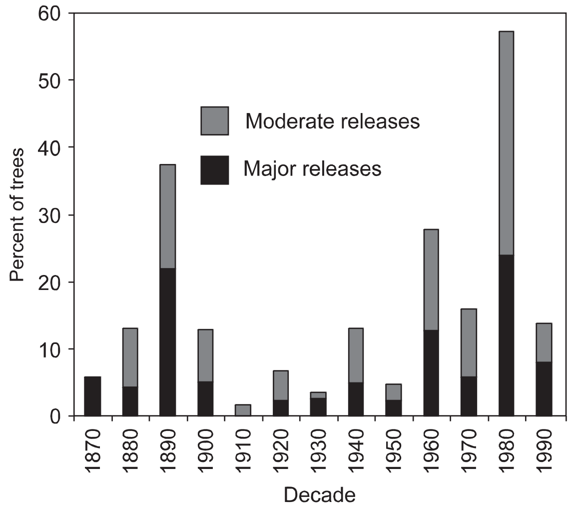

Fig. 4. Percentage of all trees (including pines and hardwoods) showing moderate and major release patterns each decade, 1870s-1990s, the period with $\geq$ 10 trees available to analyse.

tervals can help alleviate this problem (Hoss et al. 2008). Point fire intervals for montane pine stands in eastern Tennessee (MFI = 12.7 years; Harmon 1982) and an oak forest in southwestern Virginia (MFI = 18.4 years and WMI = 16.7 years; Hoss et al. 2008) suggest that despite its remote location Mill Mountain had as much fire activity as some other sites in the Appalachian region and therefore its fire history is applicable to understanding and managing forest dynamics in the region. Further standardized, comparative studies of fire regimes clearly is required for eastern North America (Hoss et al. 2008).

Question 2 concerns temporal variations in the frequency of fire under different land uses. The high frequency of fire at Mill Mountain during the 1700s was unexpected given the apparently negligible human presence. Lightning ignitions may help explain this finding. Anthropogenic fires dominate many temperate fire regimes (Guyette et al. 2002) but recent work (Cohen et al. 2007; Lafon & Grissino-Mayer 2007) suggests that lightning is an important ignition source in the Appalachian Mountains. Terrain-forced convection can generate thunderstorms under high pressure conditions with dry fuels (Lafon & Grissino-Mayer 2007), a circumstance that appears to be less common in the lower terrain of the central US (O'Neal 1996). Gradients in lightning climatology may help explain why other Appalachian fire chronologies (Mann et al. 1994; Shumway et al. 2001) also show that burning was common before settlement, while some from the central US do not (e.g. Guyette et al. 2002), at least after aboriginal depopulation.

Widespread human land use from the middle of the 1800s to the early 1900s did not increase the frequency of fire at these sites. Fuel recovery rate may have limited fire frequency during this time by imposing a minimum fire-free interval during which fine fuels recovered sufficiently to carry a fire regardless of ignition density, as identified for the Ozark Plateau (Guyette et al. 2002). The humid climate of Mill Mountain may also have constrained the frequency of fire by limiting widespread burning mostly to dry years (cf. Lafon et al. 2005), although anthropogenic ignitions apparently were so abundant in some temperate forest landscapes as to overcome such climatic constraints (McEwan et al. 2007b).

The only pronounced temporal change in fire frequency at Mill Mountain was the cessation of fire during the twentieth century (question 3). This shift coincided with acquisition by the US Forest Service, the advent of effective fire control and depopulation of the Longdale area (cf. Russ et al. 1995). The ability to make such a fundamental alteration in the disturbance regime sets apart the fire-protection strategies and technologies of the twentieth century from all human activities of the previous 230 years. The lack of burning after 1930 is consistent with other fire chronologies from eastern North America (Shumway et al. 2001; McEwan et al. 2007b) and with the success of fire control efforts (Brose et al. 2001). More broadly, it matches the expected pattern of declining frequency of fire as temperate forest landscapes transitioned from extensive to intensive land uses, such as industrial forestry (Pyne 1982). However, the Mill Mountain fire history is notable for the abruptness and absolute success of fire protection. The abrupt change may indicate that most of the past fires were ignited elsewhere and spread to the stands, in which case reducing fire frequency would be largely a matter of suppressing small fires before they spread (cf. Pyne 1982; Ward et al. 2001).

The scenario of relatively large-extent fires that spread from elsewhere into the sampled stands is consistent with our finding related to question 4, that area-wide fires were frequent. Fires commonly spread between pine stands, despite the rugged terrain. The occurrence of large fires may be explained by the hypothesis of Harrod et al. (2000): frequent burning maintained open stands with contiguous fine fuels, which would have diminished the importance of topographic barriers to the spread of fire, particularly in drought years or during seasonal dry periods (e.g. autumn, early spring) (cf. Lafon et al. 2005). It would be instructive to collect fire scars from sites spread across Mill Mountain to determine the full extent of past fires. Nonetheless this study yields important new insights about the extent of past fires on a rugged Appalachian landscape and provides a foundation for future research.

Question 5 concerns the history of tree establishment with respect to disturbance history. Williams' (1998) conceptual model of Appalachian pine forest history suggests that on presettlement landscapes fires occurred infrequently. In this scenario pines were restricted to self-replacing stands on sites too extreme for hardwood survival, and generally did not establish on more moderate sites until industrial logging. However, at Mill Mountain fire was common before European settlement and the study sites showed a successional trend toward hardwoods in the absence of fire. The presence of dead fire-scarred pines in all four stands indicates that pines have existed since at least the late 1600s or early 1700s in association with frequent burning that predated European activity. Moreover, the ages of living pines do not suggest that the trees established in association with industrial disturbances. Most were established 30-50 years after conversion of iron furnaces to coke (i.e. after extensive fuelwood cutting ceased), but before the 1927-1928 timbering, which, in any case, apparently did not affect the stands (SAMAB 1996). However, pine recruitment in stand D in the 1870s and 1880s could have been associated with iron furnaces. Undoubtedly logging and associated fires promoted pine recruitment in many Appalachian forests, as suggested by Williams (1998). Nonetheless, this fact does not obscure the longer history of fire and pine establishment (see also Sutherland et al. 1995; Lafon & Kutac 2003; Brose & Waldrop 2006) and should not hamper the use of fire to restore montane pine-dominated stands.

Our results are consistent with the proposal (Frost 1998) that montane pine stands of the Appalachian Mountains were maintained since presettlement times under a polycyclic regime of frequent surface fires and relatively infrequent fires of greater severity. The frequent burning that is evident from this study would have restricted woody fuel accumulation; hence most fires probably were of low or moderate severity, as implied by the survival of small pines after initial scarring. Frequent burning would have favored the fire-resistant pines by top-killing hardwood competitors and maintaining open stands. That these fires were punctuated occasionally by more severe fires is suggested by the existence of distinct, if broad, age cohorts of pine (Williams & Johnson 1990; Lafon & Kutac 2003). These cohorts may reflect establishment pulses following overstory mortality from infrequent severe fires that were associated with periodic droughts or build-ups of heavy dead fuels from insect outbreaks or storm damage (White 1987).

The pattern of fire seasonality may have contributed to the polycyclic regime. In particular, the less frequent growing-season fires may have been more severe than dormant-season fires because of plant susceptibility to mortality during the growing season (Sutherland et al. 1995; Whelan 1995). A growing-season burn in 1726 potentially contributed to tree mortality and to the 1730s pine recruitment. Similarly, recruitment in stand D during the 1870s and 1880s followed growing-season fires in 1864, 1872 and 1878; under frequent burning an individual cohort may have been influenced by multiple fires. The relative infrequency of growing-season fires is consistent with the contemporary Appalachian fire regime in which most fires occur during autumn or early spring while trees are dormant and the weather is often favorable for fire (Lafon et al. 2005). Except during occasional drought years, the growing season is unfavorable for extensive burning because of high humidity, low wind speed and high plant moisture content.

Pines dating to the early 1900s in stands A and B offer more direct evidence of establishment following a major disturbance. The disturbance is implied by radial growth releases in the 1890s. Also, although sapwood decay obscures their death dates, some of the trees in Fig. 2a that were dead prior to 1900 may have been killed by the 1890s disturbance event. The disturbance may have been a severe fire, but other disturbances in Appalachian pine stands include insect outbreaks and storms (White 1987; Williams 1998; Brose & Waldrop 2006; Waldron et al. 2007). An extensive outbreak of insects, probably southern pine beetles (*Dendroctonus frontalis* Zimmermann), is reported to have occurred in Bath County ca. 1895-1900 (Morton 1917). Stand development likely reflects the combined influence of multiple interacting disturbances, but fire appears to be the critical disturbance agent (Lafon & Kutac 2003). Without fire, insect outbreaks or storms will not necessarily perpetuate the historic vegetation composition. At Mill Mountain the understory was occupied rapidly by hardwood trees concurrent with the decline of fire. Under these conditions a canopy-opening disturbance such as an insect outbreak likely would not promote pine recruitment because of hardwood competition, supported by the fact that the disturbances of the 1960s and 1980s (implied by growth releases) were not followed by pine recruitment pulses. This suggests that in the continued absence of fire the overstory pines eventually will be depleted and replaced at low levels, if at all, by younger pines.

Prescribed burning and other restoration efforts are being implemented to curtail vegetation shifts from pines to hardwoods. Our study provides direct evidence demonstrating the frequency of fire and the sequence of vegetation changes in the context of multiple land-use episodes. The pre-industrial origin of the pine stands at Mill Mountain, the history of frequent fire and the alterations wrought by fire exclusion make them an important conservation priority. However, reintroducing fire will not necessarily produce an immediate shift to vegetation conditions similar to those of the past. One potential obstacle to restoration is the dense hardwood understory that developed over decades of fire exclusion. Several studies (Elliott et al. 1999; Waldrop & Brose 1999; Welch et al. 2000) of post-fire regeneration after single prescribed burns in Appalachian pine stands reveal that, while pine seedling density increased, hardwood understory density also increased because of resprouting. Multiple burns conducted over many years at intervals similar to those reported here, perhaps at varying seasonality or intensity and combined with mechanical or chemical treatment, may be necessary to control the hardwood understory and reduce duff accumulations (Elliott et al. 1999; Welch et al. 2000). An urgent need exists to take such actions in the near future while mature seed-producing trees and flammable xerophytic vegetation remain (Nowacki & Abrams 2008).

We consider our findings to be applicable to other parts of the central Appalachian region, where similar terrain and montane pine-oak stands are common (Stephenson et al. 1993), on account of their general agreement with other fire chronologies showing frequent burning at several locations in eastern North America. Nonetheless, more work is needed for sites with a record of fire extending back to presettlement times. The Mill Mountain fire chronology is one of the longest and most thorough from eastern North America. It is consistent with the view that burning occurred frequently in forest ecosystems of eastern North America from presettlement times until the implementation of fire protection.

Acknowledgements. This research was supported by the National Interagency Fire Center's Joint Fire Science Program, project number 01C-3-3-09 through co-operative agreements 03-PA-11080821-040 and 03-PA-11080821-050 with the GW and Jefferson NFs. We are grateful for the cooperation provided by Forest Service personnel, particularly Steve Croy and Elaine Kennedy Sutherland. We thank James Dalton, Alexis Green, Adam Krustchinsky and Michelle Pfeffer for assistance with field data collection and data analyses, Keith Egloff and Laura Galke for access to archaeological reports, and Tim

O'Connor, Marc Abrams and two anonymous reviewers for suggestions that helped improve the manuscript.

References

Abrams, M.D. 1992. Fire and the development of oak forests. *Bioscience* 42: 346–353.

Applequist, M.B. 1958. A simple pith locator for use with off-center increment cores. *Journal of Forestry* 56: 141.

Armbrister, M.R. 2002. Changes in fire regimes and the successional status of Table Mountain pine (Pinus pungens Lamb.) in the southern Appalachians. M.Sc. Thesis, University of Tennessee, Knoxville, TN, USA.

Baker, W.L. & Ehle, D. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. *Canadian Journal of Forest Research* 31: 1205–1226.

Brose, P., Schuler, T., van Lear, D. & Berst, J. 2001. Bringing fire back: the changing regimes of the Appalachian mixed-oak forests. *Journal of Forestry* 99: 30–35.

Brose, P.H. & Waldrop, T.A. 2006. Fire and the origin of Table Mountain pine-pitch pine communities in the southern Appalachian Mountains, USA. *Canadian Journal of Forest Research* 36: 710–718.

Cohen, D., Dellinger, B., Klein, R. & Buchanan, B. 2007. Patterns in lightning-caused fires at Great Smoky Mountains National Park. *Fire Ecology* 3: 68–82.

Egloff, K. & Woodward, D. 2006. *First people: the early Indians of Virginia*. 2nd edn. University of Virginia Press, Charlottesville, VA, US.

Elliott, K.J., Hendrick, R.L., Major, A.E., Vose, J.M. & Swank, W.T. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. *Forest Ecology and Management* 114: 199–213.

Fisher, R.F., Jenkins, M.J. & Fisher, W.F. 1987. Fire and the prairie-forest mosaic of Devils Tower National Monument. *The American Midland Naturalist* 117: 250–257.

Foster, D.R. 2000. From bobolinks to bears: interjecting geographical history into ecological studies, environmental interpretation, and conservation planning. *Journal of Biogeography* 27: 27–30.

Frost, C.C. 1998. Presettlement fire frequency regimes of the United States: a first approximation. In: Pruden, T.L. & Brennan, L.A. (eds.) *Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20*. pp. 70–81. Tall Timbers Research Station, Tallahassee, FL, US.

Geier, C.R. & Boyer, W.P. Jr. 1982. *The Gathright Dam-Lake Moomaw cultural resource investigations: a synthesis of the prehistoric data*. Occasional papers in Anthropology No. 15. James Madison University, Harrisonburg, VA, US.

Grissino-Mayer, H.D. 2001. FHX2 – software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Research* 57: 115–124.

Grissino-Mayer, H.D., Romme, W.H., Floyd, M.L. & Hanna, D.D. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* 85: 1708–1724.

Guyette, R.P., Muzika, R.M. & Dey, D.C. 2002. Dynamics of an anthropogenic fire regime. *Ecosystems* 5: 472–486.

Harmon, M. 1982. Fire history of the westernmost portion of Great Smoky Mountains National Park. *Bulletin of the Torrey Botanical Club* 109: 74–79.

Harrod, J.C., Harmon, M.E. & White, P.S. 2000. Post-fire succession and 20th century reduction in fire frequency on xeric southern Appalachian sites. *Journal of Vegetation Science* 11: 465–472.

Holmes, R.L. 1986. Users manual for program COFECHA. In: Holmes, R.L., Adams, R.K. & Fritts, H.C. (eds.) *Tree-ring chronologies of western North America: California, eastern Oregon, and northern Great Basin. Chronology Series 6*. pp. 41–49. Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, US.

Hoss, J.A., Lafon, C.W., Grissino-Mayer, H.D., Aldrich, S.R. & DeWeese, G.G. 2008. Fire history of a temperate forest with an endemic fire-dependent herb. *Physical Geography* 29: 424–441.

Kartesz, J.T. & Kartesz, R. 1980. *A synonymized checklist of the vascular flora of the United States, Canada, and Greenland*. Vol. 2, University of North Carolina Press, Chapel Hill, NC, US.

Kou, X. & Baker, W.L. 2006. A landscape model quantifies error in reconstructing fire history from scars. *Landscape Ecology* 21: 735–745.

Lafon, C.W. & Grissino-Mayer, H.D. 2007. Spatial patterns of fire occurrence in the central Appalachian Mountains and implications for wildland fire management. *Physical Geography* 28: 1–20.

Lafon, C.W. & Kutac, M.J. 2003. Effects of ice storms, southern pine beetle infestation, and fire on Table Mountain pine forests of southwestern Virginia. *Physical Geography* 24: 502–519.

Lafon, C.W., Hoss, J.A. & Grissino-Mayer, H.D. 2005. The contemporary fire regime of the central Appalachian Mountains and its relation to climate. *Physical Geography* 26: 126–146.

Lorimer, C.G. & Frelich, L.E. 1989. A methodology for estimating canopy disturbance frequency and intensity in dense temperate forests. *Canadian Journal of Forest Research* 19: 651–663.

Mann, D.H., Engstrom, F.B. & Bubier, J.L. 1994. Fire history and tree recruitment in an uncut New England forest. *Quaternary Research* 42: 206–215.

McEwan, R.W., Hutchinson, T.F., Long, R.P., Ford, R.D. & McCarthy, B.C. 2007a. An experimental evaluation of fire history reconstruction using dendrochronlogy in white oak (*Quercus alba*). *Canadian Journal of Forest Research* 37: 806–816.

McEwan, R.W., Hutchinson, T.F., Long, R.P., Ford, R.D. & McCarthy, B.C. 2007b. Temporal and spatial patterns in fire occurrence during the establishment of mixed-oak forests in eastern North America. *Journal of Vegetation Science* 18: 655–664.

Morton, O.F. 1917. *Annals of Bath County, Virginia*. The McClure Co. Inc., Staunton, VA, US. (Reprinted 1970; C. J. Carrier Company Historical and Genealogical Books, Bridgewater, VA, US).

NCDC (National Climatic Data Center). 2002. *Climatography of the United States*, No. 81. NOAA National Climatic Data Center, Asheville, NC, US.

Nowacki, G.J. & Abrams, M.D. 2008. The demise of fire and 'mesophication' of forests in the eastern United States. *Bioscience* 58: 123–138.

O'Neal, M. 1996. Interactions between land cover and convective cloud cover over Midwestern North America detected from GOES satellite data. *International Journal of Remote Sensing* 17: 1149–1181.

Pfeffer, M.D. 2005. Regression-based age estimates of yellow pine saplings, Jefferson National Forest, Virginia. Honors thesis. University of Tennessee, Knoxville, TN, US.

Pyne, S.J. 1982. *Fire in America: a cultural history of wildland and rural fire*. Princeton University Press, Princeton, NJ, USA.

Russ, K.C., McDaniel, J.M. & Wood, K.T. 1995. *The archaeology of nineteenth-century iron manufacturing in southwestern Virginia: an example from the Longdale Iron Mining Complex (Paper on life)*. Anthropology Laboratory, Washington and Lee University, Lexington, VA, US.

Russell, E.W.B. 1983. Indian-set fires in the forests of the northeastern United States. *Ecology* 64: 78–88.

SAMAB (Southern Appalachian Man and the Biosphere). 1996. The Southern Appalachian Assessment terrestrial technical report. USDA Forest Service, Atlanta, GA, US.

Schuler, T.M. & McClain, W.R. 2003. Fire history of a Ridge and Valley oak forest. Research Paper NE-724. USDA Forest Service, Newtown Square, PA, US.

Shumway, D.L., Abrams, M.D. & Ruffner, C.M. 2001. A 400-year history of fire and oak recruitment in an old-growth forest in western Maryland, USA. *Canadian Journal of Forest Research* 31: 1437–1443.

Stephenson, S.L., Ash, A.N. & Stauffer, D.F. 1993. Appalachian oak forests. In: Martin, W.H., Boyce, S.G. & Echternacht, A.C. (eds) *Biodiversity of the southeastern United States: upland terrestrial communities*. pp. 255–303. John Wiley & Sons Inc, New York, NY, US.

Stokes, M.A. & Smiley, T.L. 1968. *An introduction to tree-ring dating*. University of Chicago Press, Chicago, IL, US.

Sutherland, E.K., Grissino-Mayer, H.D., Woodhouse, C.A., Covington, W.W., Horn, S., Huckaby, L., Kerr, R., Kush, J., Moore, M. & Plumb, T. 1995. Two centuries of fire in a southwestern Virginia *Pinus pungens* community. In: *Inventory and management techniques in the context of catastrophic events: altered states of the forest*. Pennsylvania State University, Center for Statistical Ecology & Environmental Statistics, University Park, PA, US.

USDA Forest Service. 1998. *National Interagency Fire Management Integrated Database (NIFMID): Technical Guide*. USDA Forest Service, Washington, DC, US.

Vale, T.R. 1998. The myth of the humanized landscape: an example from Yosemite National Park. *Natural Areas Journal* 18: 231–236.

Van Horne, M.L. & Fulé, P.Z. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern United States ponderosa pine forest. *Canadian Journal of Forest Research* 36: 855–867.

Waldron, J.D., Lafon, C.W., Coulson, R.N., Cairns, D.M., Tchakerian, M.D., Birt, A. & Klepzig, K.D. 2007. Simulating the impacts of southern pine beetle and fire on the dynamics of xerophytic pine landscapes in the southern Appalachians. *Applied Vegetation Science* 10: 53–64.

Waldrop, T.A. & Brose, P.H. 1999. A comparison of fire intensity levels for stand replacement of table mountain pine (*Pinus pungens* Lamb.). *Forest Ecology and Management* 113: 155–166.

Ward, P.C., Tithecott, A.G. & Wotton, B.M. 2001. Reply – a re-examination of the effects of fire suppression in the boreal forest. *Canadian Journal of Forest Research* 31: 1467–1480.

Welch, N.T., Waldrop, T.A. & Buckner, E.R. 2000. Response of southern Appalachian table mountain pine (*Pinus pungens*) and pitch pine (*P. rigida*) stands to prescribed burning. *Forest Ecology and Management* 136: 185–197.

Whelan, R.J. 1995. *The ecology of fire*. Cambridge University Press, Cambridge, UK.

White, P.S. 1987. Natural disturbance, patch dynamics, and landscape patterns in natural areas. *Natural Areas Journal* 7: 14–22.

Williams, C.E. 1998. History and status of Table Mountain pine-pitch pine forests of the southern Appalachian Mountains (USA). *Natural Areas Journal* 18: 81–90.

Williams, C.E. & Johnson, W.C. 1990. Age structure and maintenance of *Pinus pungens* in pine-oak forest of southwestern Virginia. *American Midland Naturalist* 124: 130–131.

Zar, J.H. 1999. *Biostatistical analysis*. Prentice Hall, Upper Saddle River, NJ, US.

Received 4 November 2008;
Accepted 10 June 2009.
Co-ordinating editor: T. O'Connor