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Drivers and ecological impacts of a wildfire outbreak in the southern Appalachian Mountains after decades of fire exclusion

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ABSTRACT

During one of the warmest and driest droughts of the last century, the southern Appalachian Mountains experienced a regional outbreak of over a dozen large wildfires in late fall of 2016. We provide a synthesis of long-term forest changes leading up to the 2016 wildfires, examine the climatic setting and patterns of burn severity in relationship to topography, and discuss the ecological and management implications of these and future fires. During the pre- and post-European settlement periods, frequent low- and mixed-severity wildfires interacted with complex topographic gradients and maintained heterogenous landscapes dominated by several species of oak (*Quercus* spp.), pine (*Pinus* spp.), and the American chestnut (*Castanea dentata*). Land-use changes associated with European settlement, loss of the American chestnut, and 20th century fire exclusion resulted in large scale shifts towards mesic, fire-intolerant species (i.e. mesophication). Wildfire activity began increasing in the early 1980s, but most fires in the region are small (<1,000 ha). In Fall of 2016, deciduous tree leaf fall occurred concurrently with a period of anomalously dry and warm weather, creating ideal conditions for fire ignition and spread. Thousands of ignitions across the region strained suppression resources and eight fires grew to greater than 5,000 ha. The 2016 fires were larger and burned more area than in the previous three decades combined. In one unique landscape setting, the Chimney Tops 2 Fire, a synoptic wind event drove extreme fire behavior and burned large, high-severity patches resulting in devastating effects in the wildland urban interface. However, immediate post-fire burn severity mosaics for other fires were composed primarily of low- (73 %) and moderate-severity (21 %) fire effects. High-severity fire comprised only 6 % of the area burned, and occurred mostly on steep upper slopes and ridges on south-facing aspects, reflecting the importance of bottom-up topographic drivers in this region. Although the fires will likely enhance biodiversity by restoring fire-dependent species and creating early seral habitat, invasions of non-native plant species, delayed mortality of mature pines and oaks, and rapid re-sprouting of pyrophyllic shrubs pose significant management challenges. Although similar large fire outbreaks may become more common under future climatic conditions, they are unlikely to reverse the effects of mesophication and significantly alter forest dynamics at broad spatial scales. The 2016 fires exposed the vulnerability of the region to wildfire during acute fall drought and demonstrate the potential ecological effects of future wildfires in mixed pine-hardwood landscapes of the southern Appalachians.

1. Introduction

Despite having one of the highest historic fire frequencies in North America (Guyette et al. 2012), forests of the southern Appalachian Mountains have experienced relatively little recent area burned by wildfires. Prior to the fall of 2016, wildfire activity in the mixed-pine hardwood forests of the southern Appalachian Mountains of North Carolina, Georgia, South Carolina, and Tennessee was limited to relatively small (<2,500 ha) wildfires with the rare occurrence of wildfires exceeding 5,000 ha (Fig. 1). A moderate climate characterized by warm summers with frequent lightning, a long history of human occupation, and occasional drought provide an environment conducive to fire. However, high humidity and fuel moisture often inhibit the spread of fire under moderate burning conditions while an extensive road network facilitates rapid response. Burning by Native Americans and European colonizers created a cultural landscape that was largely

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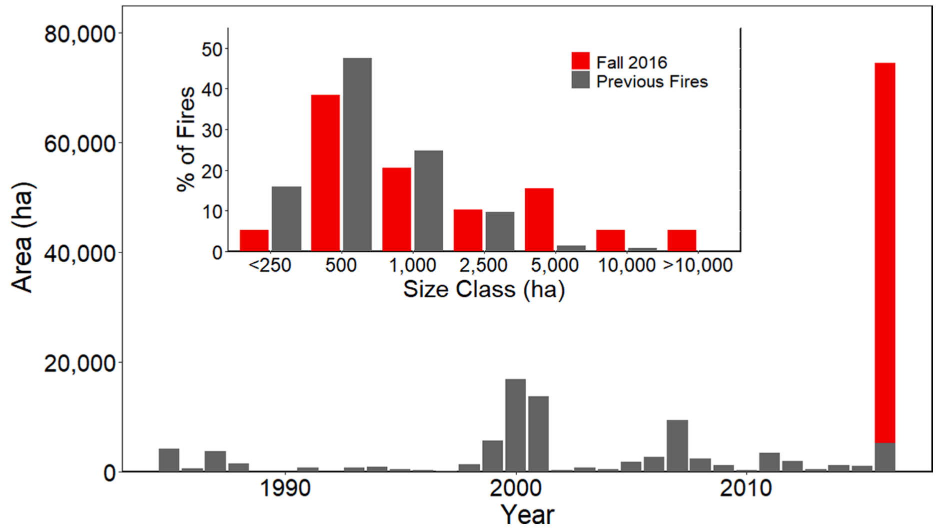

Fig. 1. Trends in area burned and cumulative size class distribution of wildfires (inset) in the southern Appalachian Mountains from 1985 to 2016. Data from the Monitoring Trends in Burn Severity project (www.mtbs.gov).

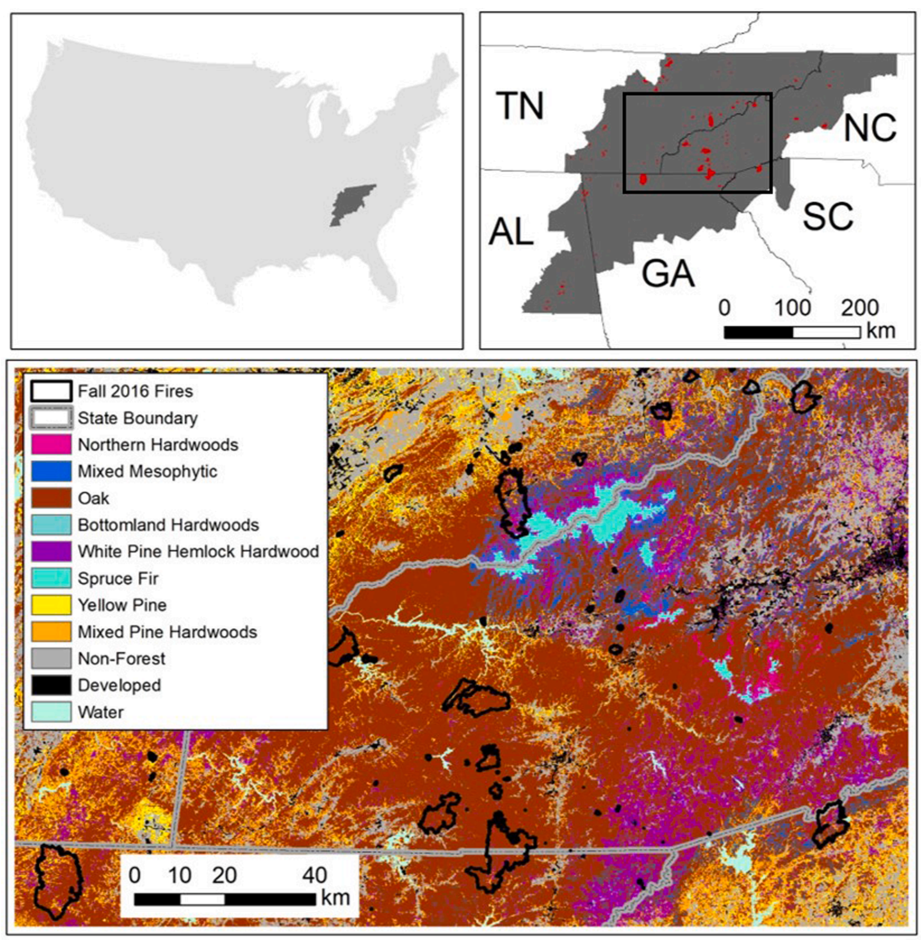

Fig. 2. Study area and common forest types. Map on top left shows location of the study area within the United States. Map on top right shows extent of fall 2016 fires within the southern Appalachian region. Map on the bottom shows a zoomed in view from the map on the top right with fire perimeters and forest types from the Southern Appalachian Man and Biosphere program (SAMAB; http://www.samab.org/wp-content/uploads/2011/06/SAMAB_SAA_terrestrial_report.pdf).

shaped by fire for millennia (Fowler and Konopik, 2007) until 20th century policy shifts related to fire prevention and suppression virtually eliminated fire, with the exception of relatively small, prescribed fires (Arthur et al., 2021).

The 2016 southern Appalachian wildfires represent a profound reintroduction of wildfire to the mixed-pine hardwood forests of this region. Following an anomalously dry and hot fall (Williams et al., 2017), ignitions across the region strained fire suppression efforts and ultimately resulted in more than thirty large fires burning simultaneously. The fires of fall 2016 were larger and burned more area than in the previous three decades combined (Fig. 1). More than 10,000 starts were extinguished before getting larger than a few hectares, but eight of the fires reached more than 5,000 ha, including two fires that reached more than 10,000 ha. These two fires, the Rough Ridge and Rock Mountain Fires occurred in remote wilderness areas in the Chattahoochee and Nantahala National Forests. The Chimney Tops 2 Fire exhibited extreme fire behavior during a rare wind event and devastated the wildland urban interface with tragic loss of life in Gatlinburg, Tennessee immediately outside Great Smoky Mountains National Park.

Projections for future climate change suggest an increasing role of wildfire in southern Appalachian landscapes (Liu et al., 2012, Vose and Elliott, 2016), yet knowledge of recent wildfires is limited to a few case studies of relatively small fires and there is a need for a broad assessment of the ecological implications and management considerations of the 2016 fires. We provide a brief review of the forest vegetation of the region, along with a synthesis of fire history and the role of European colonizers on forest change over the last two centuries. We then examine the climatic conditions that led to the 2016 wildfire outbreak during the months of October and November 2016. Finally, we assess patterns and topographic drivers of burn severity and discuss the ecological implications of the regional fire episode in the context of current management objectives and concerns.

2. An exceptionally diverse region with a long history of frequent fire and an extensive anthropogenic footprint

2.1. Forests of the southern Appalachians

Forests cover approximately 6.8 million ha of the southern Appalachian Mountains (Fig. 2) in western North Carolina, eastern Tennessee, north Georgia, northwestern South Carolina, and northeast Alabama. The region is renowned for its biological diversity, which is partially due to complex underlying environmental gradients that structure landscape patterns of vegetation composition (Whittaker, 1956). Multiple species of oak are present including scarlet oak (*Quercus coccine*a), northern red (*Q. rubra*), white oak (*Q. alba*), and chestnut oak (*Q. prinus*). The American chestnut (*Castanea dentata*) was a dominant species historically but was decimated by the chestnut blight during the 20th century. Several species of pine are common on dry ridges and slopes, including pitch pine (*P. rigida*) and the endemic Table Mountain pine (*P. pungens*), both of which have serotinous cones. In more mesic coves and ravines where soils are acidic, eastern white pine (*Pinus strobus*) and eastern hemlock (*Tsuga canadensis*) dominate, but eastern hemlock, has suffered extensive mortality from the non-native pathogen, hemlock woolly adelgid (*Adelges tsugae*; Vose et al., 2013). On richer cove sites, a diverse assemblage of hardwood species including tulip poplar (*Liriodendron tulipifera*), magnolias (*Magnolia* spp.), ash (*Fraxinus* spp), and sugar maple (*Acer saccharum*) dominate the canopy. A dense layer of shrubs is often present and dominated by mountain laurel (*Kalmia latifolia*) on dry sites and rhododendron (*Rhododendron* spp.*)* on cooler, moister sites. High elevations include forests dominated by red spruce (*Picea rubens)* and the endemic Fraser fir (*Abies fraseri*) are the least fire prone. The region is also known for its exceptionally diverse understory plant communities which include several species of long-lived perennials, many of which are spring ephemerals (e.g. *Trillium* spp.) that emerge and flower prior to leaf out of deciduous trees. Most of the region has been impacted by livestock grazing and logging during the 19th and 20th centuries. Great Smoky Mountains National Park harbors the majority of the region's unlogged forests with the exception of scattered isolated remnants, mostly on National Forest or state lands (Davis, 1996).

2.2. Historical fire regimes and land-use legacies

Paleoecological studies provide evidence of fire activity in the southern Appalachian Mountains for at least the last 10,000 years during the Holocene (Delcourt and Delcourt, 1997). Due to the relative scarcity of natural lakes and ponds, our knowledge of fire activity during this period is limited to a few locations across the region (Lafon et al., 2017). Dominance of oak, chestnut, and pine were related to increased burning approximately 3,000 and 1,000 years ago that corresponded with a shift in prehistoric indigenous lifestyles away from hunting and gathering to a more sedentary agricultural lifestyle (Delcourt and Delcourt, 1998). Climate and lightning also played a role in fire activity, particularly in the drier eastern and western escarpments of the Blue Ridge, but anthropogenic burning was likely the primary driver of fire activity in this region and much of the eastern United States (Abrams and Nowaki, 2019). The effects of burning were likely greatest in close proximity to villages where indigenous tribes burned pastures and woodlands to encourage seed mast, though the extent and impact of indigenous burning remains an issue of debate across the eastern US (Matlack, 2013, Stambaugh et al., 2015).

Fire history studies from cross sections of fire-scarred trees provide much of our knowledge base regarding the historical role of fire in the southern Appalachian Mountains following European settlement. These studies include pine-dominated sites in Great Smoky Mountains National Park in eastern Tennessee and Linville Gorge on the Pisgah National Forest of North Carolina, though research in the central Appalachians of Virginia and West Virginia provide similar findings (Lafon et al., 2017). These studies document a fire regime dominated by dormant season fires with mean fire return intervals <15 years between the early 1700s to the early 20th century (Harmon, 1982, Flatley et al., 2013, Lafon et al., 2017). However, there is little known about historical fire sizes (Lafon et al., 2017) or landscape patterns of burn severity, particularly for mesic forests of the Southern Appalachian landscape. There are no existing fire scar studies from higher elevation studies of the region, but fire return intervals from these forests are thought to be much longer (Guyette et al., 2012).

Both the charcoal and fire scar records indicate that the early 20th century was a period characterized by some of the most widespread burning in the region over the last several centuries (Lafon et al., 2017). Much of the early 20th century fire was related to logging and burning activity associated with European colonizers. There is little to no documentation on fire sizes or perimeters during the early 20th century but reports from the early 20th century suggest that fires were considerably more extensive than at present (Ayres and Ashe, 1905). Ayres and Ashe (1905) provide numerous first-hand accounts of high-severity fire on dry sites, and even-aged stands of the serotinous Table Mountain pine suggest that this period was also characterized by stand-replacing fires (Williams 1998). The lower elevation pine and oak forests have now recovered from high-severity wildfires of the early 20th century, but some higher elevation landscapes dominated by spruce-fir forests are still recovering where fires were particularly severe (Korstian 1937). Many populations of serotinous pines that established following fires during this period are now declining (Williams and Johnson, 1992, Williams, 1998, Brose and Waldrop, 2006).

2.3. 20th century forest change

Wildfire suppression and prevention policies nearly eliminated fire across most of the region except where prescribed fire has been reintroduced (Arthur et al., 2021). The effects of fire exclusion include regional scale shifts in structure and composition of mixed pine and

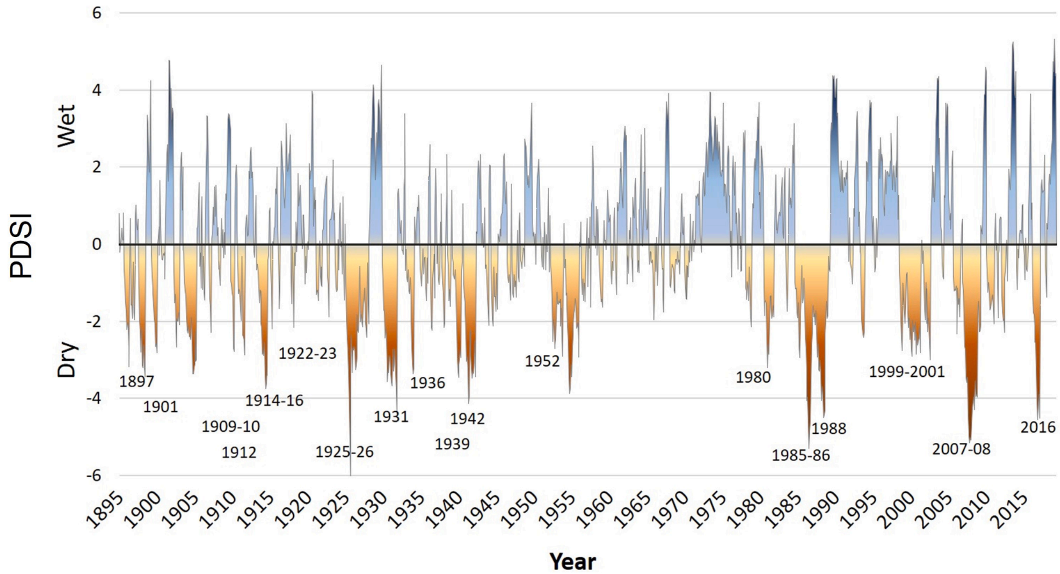

Fig. 3. Palmer Drought Severity Index (PDSI) from 1895 to 2016 in the southern Appalachians from NOAA Climate Divisional data (available at https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00005) with notable fire years recorded in the Library of Congress's U.S. Newspaper Directory, newspaper.com, and early state and federal reports (S. Norman unpublished data).

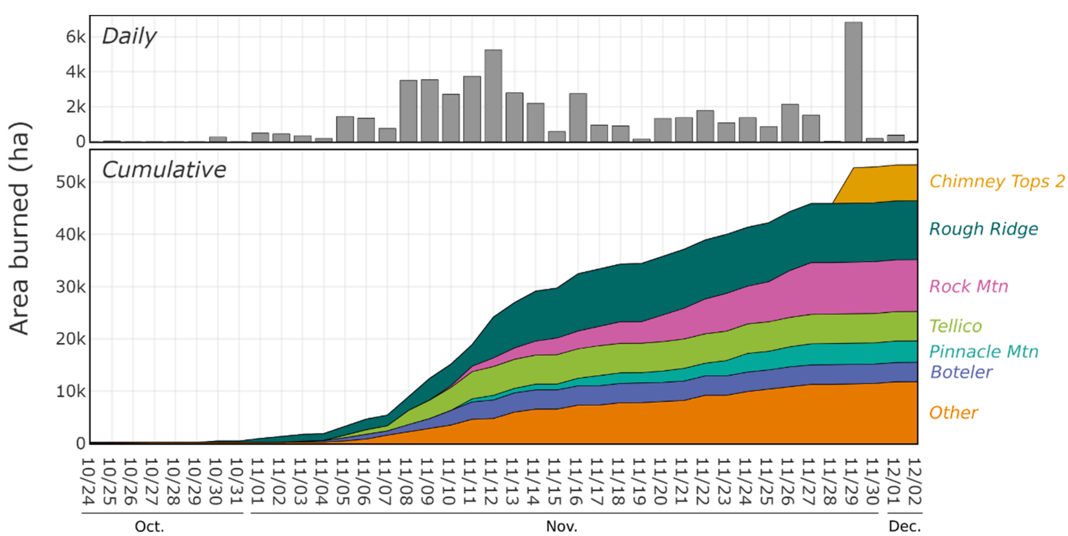

Fig. 4. Cumulative area burned in the Southern Appalachian Mountains from October 24th to December 2nd, 2016. Daily progression data were not available for all fires, thus the total hectares do not add up to those in Fig. 1.

hardwood forests, collectively referred to as "mesophication" (Nowacki and Abrams, 2008). Increases in fire sensitive mesophytic species such as red maple and blackgum also altered litter and fuel composition and structure, effectively reducing flammability across the region (Kreye et al., 2013; Dickinson et al., 2016). In addition to regional-scale effects of mesophication, industrial logging removed what little remained of the large mature oaks and old-growth forests and an invasive pathogen devastated the American chestnut, one of the most dominant and abundant trees in the region (Elliott and Vose, 2011). This species provided valuable seed mast for both wildlife and human consumption. The thin, papery leaves of the American chestnut also provided fuels to facilitate late fall fires (Kane et al., 2019) and were allelopathic to some fire-sensitive species including red maple and mountain laurel (Vandermast et al., 2002). Fire exclusion likely had less of an effect in more mesic and higher elevation forests, but these forests have also declined from novel stressors in addition to hemlock woolly adelgid. High elevation spruce-fir forests were also impacted by invasive pathogens and acid rain in the last century (Pauley et al., 1996). The loss of dominant species combined with the effects of fire exclusion altered the successional pathways of these forests into a no-analogue ecosystem state (Williams and Jackson, 2007).

3. Climate and weather conditions leading up to and during the 2016 fires

Climatic conditions during the late fall in 2016 were characterized as the fourth most extreme drought the southern Appalachians experienced since at least 1895, though drought magnitude varied across the region (Williams et al., 2017). Droughts of similar magnitude also coincided with notable wildfire activity including 1914, 1925, 1942, and 2007 (Fig. 3). By September, much of northeast Georgia, western North Carolina, and east Tennessee had received <50 % of normal precipitation.

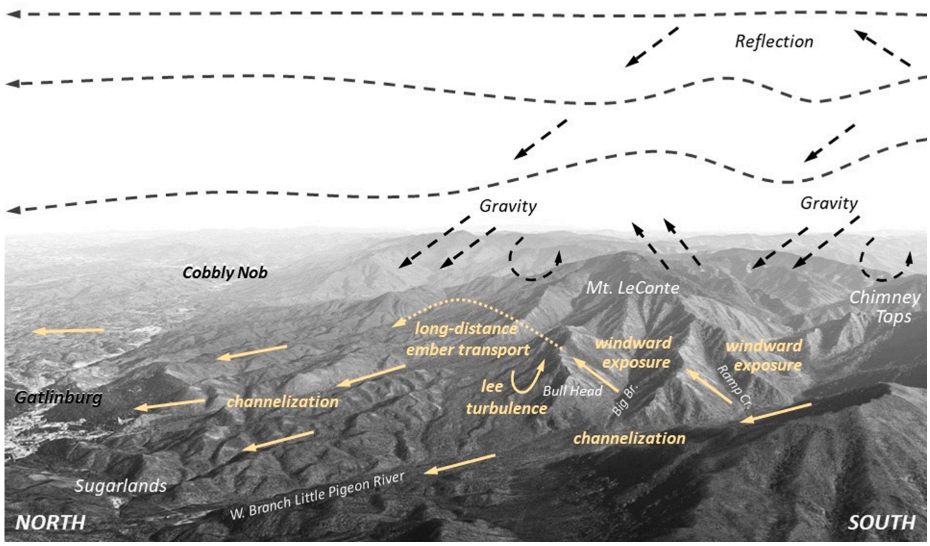

Fig. 5. Schematic representation of mountain wave and surface wind behavior in the Great Smoky Mountains National Park and mountain wave associated on November 28, 2016.

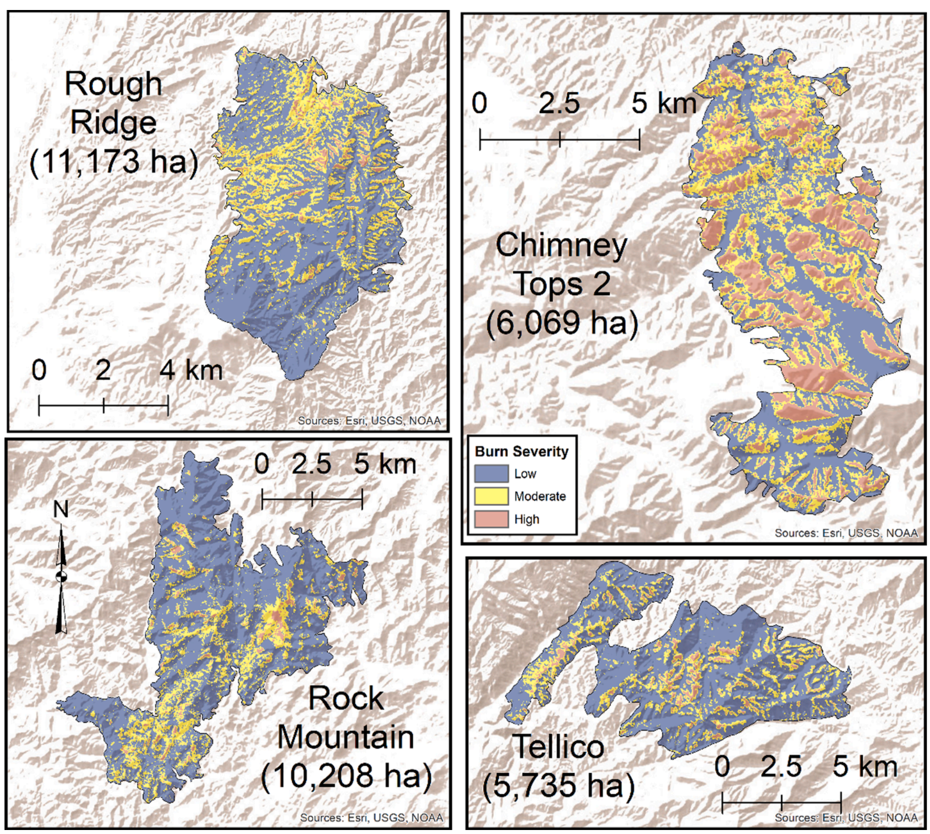

Fig. 6. Post-fire landscape burn severity mosaics for four of the largest wildfires. Burn severity maps are based on the relativized change in the relativized change in the normalized burn index (Appendix 1).

This trend continued into October and November. The Fall of 2016 was unique not only because of the duration of rain-free days compared to other drought years, but also in that the drought overlapped with leaf fall. Precipitation patterns and leaf fall resulted in airy, dry deciduous leaf litter that experienced little to no rain since summer.

3.1. Simultaneous ignitions and fire growth

All but two of the fires that reached more than 3,000 ha (Boteler and Rock Mountain) were reportedly anthropogenic ignitions that occurred over the period of October to November. There were also thousands of smaller fires scattered throughout the region that were contained and suppressed. During a three-week period before Thanksgiving in November, the number of large fires increased from five to thirty-five.

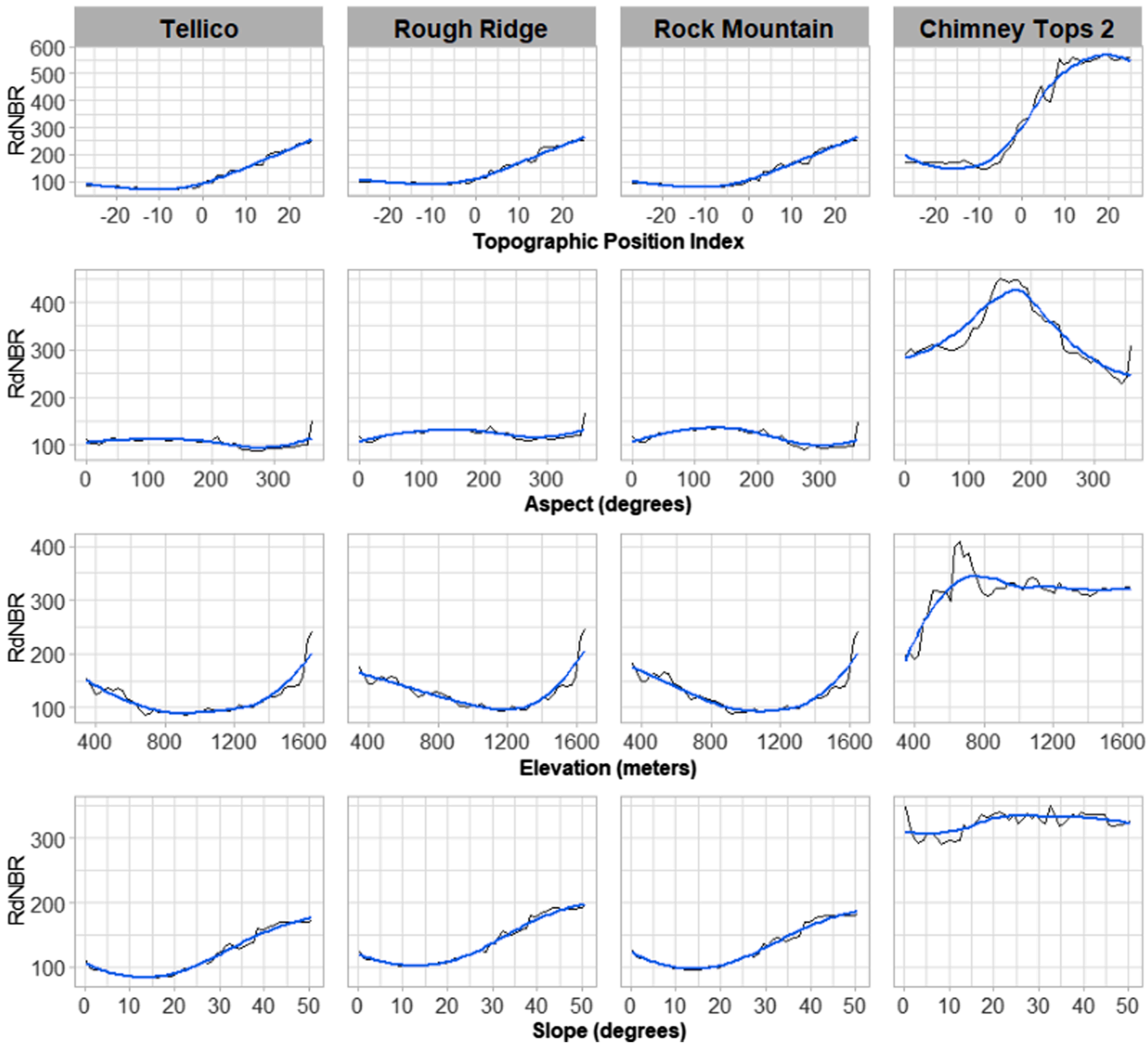

Fig. 7. Partial dependence plots from a random forest model predicting burn severity as measured by the relativized change in the normalized burn index (RdNBR) in the four largest southern Appalachian fires. Low topographic position index valleys correspond with sheltered ravines and low slopes while higher values correspond with upper slopes and ridges.

During a single week, four fires approached or exceeded the size of any fire in the region experienced since at least the 1950 s (Fig. 4). Although many of these fires were initially contained, subsequent ignitions nearly doubled the number of fires in the following week. The simultaneous occurrence of so many ignitions spread local suppression resources thin, prompting an escalation of suppression coordination. Furthermore, steep topography and ongoing leaf fall hampered suppression efforts and initial attack across the rugged terrain, particularly in remote areas. The recently fallen leaves had not yet received rain, and provided a deep, airy, continuous fuel bed across the deciduously dominated landscapes. Winds created dynamic fuel situations and redistributed light, dry leaves across fire lines and into areas that previously burned. Fuels normally not available for combustion due to high moisture that would normally inhibit fire spread (e.g. stream sides and cove vegetation) burned actively. After burning for almost a month, most of the fires appeared to be largely contained by the end of November after extensive rainfall.

3.2. *The Chimney Tops 2 Fire*

On November 23rd, the human-ignited Chimney Tops 2 was reported burning in steep terrain off a popular hiking trail in Great Smoky Mountains National Park (GSMNP) approximately-eight miles east of Gatlinburg, Tennessee. Rugged terrain and cliffs around the area of ignition hindered initial attack. The area had heath vegetation and associated deep histosols that were smoldering, and the fire remained confined to a small area. After five days, the fire remained at <200 ha, but on the afternoon of November 28th, a mountain wave wind event from the eastern slope of the mountains reached gusts of over 120 km per hour, driving rapid fire spread and extreme fire behavior. Mountain waves are characteristic of the southern Appalachian Mountains (Gaffin, 2009). These winds are similar to foehn winds of other regions (e.g. Santa Ana, Chinook) and often occur on the leeward slopes of large mountain ranges. Mountain waves are associated with cold fronts and

Fig. 8. Flowering *Trillium grandiflorum* in a mixed mesophytic forest of the Nantahala Gorge in western North Carolina the first spring after the Tellico Fire (photo credit Steve Norman).

occur multiple times a year between November and March with winds up to 175 km per hour (Gaffin, 2007). Mountain waves are driven by adiabatic compression of air masses that decrease in relative humidity and increase in temperature as they descend downslope into valleys. The topographic setting directed winds over the high dividing ridge of GSMNP and down the valley of the West Branch of the Pigeon River towards Gatlinburg (Fig. 5). Winds drove air up south-facing slopes where it combined with turbulence on the lee side, increasing the potential for ember transmission with long-distance spotting for kilometers (Fig. 5). The Chimney Tops 2 Fire, in addition to several other fires ignited by downed powerlines, created what could aptly be named a firestorm. The event was the largest wildfire in the Gatlinburg area since the early 20th century and resulted in the loss of 14 lives and 2,545 structures in the surrounding communities (National Park Service, 2017). The frontal passage that drove the Chimney Tops 2 Fire brought rain that ultimately extinguished the regional fire event.

4. Ecological implications

The 2016 fires burned 66,598 ha of primarily low-severity fire (72.7 %) with relatively little moderate (21.1 %) and high-severity fire (6.2 %) based on Landsat imagery taken the year following the fire (see Appendix 1 for methods). The largest fires generally reflected important bottom-up controls associated with topography, but patterns varied among fires (Fig. 6, Fig. 7). A random forest model predicting burn severity as measured by the relativized change in normalized burn index (RdNBR) accounted for 38 % of the variance (Appendix 1). Ridges experienced higher levels of burn severity than other landscape positions in all four of the large fires, and generally increased with slope (Fig. 7). Such fire patterns are consistent with the few existing studies on recent wildfires in the region (Wimberly and Reilly, 2007, Reilly et al., 2014), as well as with those that would be expected given what is known about historical fire regimes (Ayres and Ashe, 1905). The wind driven Chimney Tops 2 Fire was unique among fires and had higher severity as well as a much greater area burned by large patches of high-severity fire (Fig. 6) which occurred on exposed, southern aspects subject to high winds during the mountain wave event.

4.1. Landscape patterns of burn severity

Patterns of landscape burn severity in these four large wildfires (Fig. 6) indicate a wide range of potential ecological outcomes in both the immediate and long-term future. Research on recent prescribed fires and wildfires in the region indicate that low- and moderate-severity fire effects may have many positive ecological outcomes that enhance understory plant diversity and potentially promote regeneration of oak and pine species (Black et al., 2018, Brose et al., 2014) by removing litter and organic soil (duff) as well as competing shrubs. However, single, and even repeated, low-severity fires may have little long-term effect on regeneration as they stimulate resprouting of many shrub and tree species which may eventually increase in density (Elliott et al., 2009, Keyser et al., 2019, Arthur et al., 2021). Moderate- and high- severity effects in prescribed fires (Welch and Waldrop, 2001) and wildfires (Wimberly and Reilly, 2007) also promote Table Mountain pine and pitch pine regeneration in decadent, fire excluded stands that comprise much of the limited distribution of these species (Williams and Johnson, 1990, Williams and Johnson, 1992, Williams, 1998, Brose and Waldrop, 2006). Reilly et al. (2006a) found that wildfire promoted understory richness through immigration of early seral species of forbs, and that perennial spring wildflowers are primarily resistant to fire across a range of burn severities (Fig. 8).

4.2. Early seral habitat

The creation of structurally and compositionally diverse early seral habitats in locations that experienced high-severity fire and significant mortality of overstory trees will contribute to landscape and regional biodiversity. As in other regions of the United States, decreases in early seral conditions are a major conservation concern in recent decades (Greenberg et al., 2011). Early seral conditions following wildfire in the southern Appalachians are associated with increases in understory plant diversity (Reilly et al., 2006a), pollinator visitation (Campbell et al., 2007), and fruit production. Patches of early seral habitat may provide foraging for insects and fruits for many species of wildlife (Greenberg et al., 2007). Several bird species in the region are dependent on early seral habitats (Hunter et al., 2001), many of which respond to high-severity fire at a range of spatial scales (Rose and Simon, 2016). Some species of bats may suffer from negative effects of smoke and immediate loss of roosts (Ford et al., 2016). However, fire is essential for long-term habitat persistence by both reinitiating pine stands and creating large pine snags for roosting the federally endangered Indiana bat (O'Keefe and Loeb, 2017). Other species of bats may also benefit from low-severity fire (Burns et al., 2019) and more open forest structure including small patches of early seral habitat with sparse cover of vegetation which increase foraging efficiency (Loeb and O'Keefe, 2006).

4.3. Management challenges

The effects of the 2016 wildfires will also inevitably challenge forest management in many ways, but particularly in terms of non-native species invasions and fuels management. Princess tree (*Paulownia tomentosa*) is a common invader following fire (Langdon and Johnson, 1994, Kuppinger et al., 2010, Black et al., 2018). This species grows rapidly and matures quickly, often producing copious amounts of wind-dispersed seeds in the first decade following establishment. Chinese silvergrass (*Miscanthus sinensis*), a large perennial non-native grass, is also associated with high-severity fire which can promote invasion of more non-native plant species (Black et al., 2018). Management strategies to address invasion of non-native include monitoring for early detection and rapid response to mitigate the potential for invasion. Identification and eradication of invading populations can help reduce further spread while rehabilitation and restoration of native plant species are also essential parts of integrated management of invasives (Miller et al., 2013).

Given the productivity of the region and resilience of southern Appalachian forests to even severe wildfire (Reilly et al., 2006b), forests burned by the 2016 fires are likely undergoing rapid structural change as forests respond to each fire. Although fire at low- and moderate-severity initially decreases density of pyrogenic shrubs like mountain laurel and midstory trees, resprouting mountain laurel and hardwoods, as well as regenerating pines may exceed pre-fire and immediate post-fire density within less than a decade (Harrod et al., 2000, Elliott et al., 2009, Elliott and Vose, 2010, Hagan et al., 2015, Black et al., 2018). Although there is limited work on reburns in this region, there is some evidence to suggest that burn severity is likely to be higher than in the initial fire (Reilly et al., 2014, Hagan et al., 2015). Post-fire landscapes in the region will likely change rapidly in the coming years and may be especially vulnerable to high-severity reburn where resprouting ericaceous shrubs (i.e. mountain laurel) respond quickly. Managing fuels with repeated prescribed fire where possible may help reduce risk while potentially also reaching longer term restoration goals in unburned forests. Repeated mechanical treatment of resprouting ericaceous shrubs could help reduce risk around homes and other valued infrastructure where prescribed fire is not an option.

A further unanticipated challenge lies in the paradox of higher post-fire mortality in fire-adapted tree species driven by O horizon consumption. The same traits that confer flammability to litter from fire associated tree species such as oaks and pines, along with their mycorrhizal symbionts, also promote the formation of a deep O horizon (duff), more so than the mesic species such as *Acer rubrum* (Carpenter et al., 2021). Over time, fine roots grow into the duff layer. When duff is consumed during a fire, considerable fine root mortality occurs which can initiate a physiological decline that ends in tree death often delayed by several years (Robbins et al., 2022). While this phenomenon is extensively documented in other historically frequent fire forest types in the southeastern United States (Varner et al., 2007, O'Brien et al., 2010), little is known about how southern Appalachian forests will respond. However, Carpenter et al. (2021), observed more post-fire canopy decline for pines and oaks (rather than e.g. maples and poplars) three years after the Rock Mountain Fire where fire severity was initially characterized as low (Fig. 7). This suggests that mesophication could be accelerated by wildfire as higher mortality in oaks and pines will reduce their dominance (Robbins et al., 2022) and alter fuels to a less flammable type (Dickinson et al., 2016). Further work based on longer term trends is needed, but lessons learned when applying prescribed fire in other forest types with deep duff may be useful (e.g. fire excluded longleaf pine; Varner et al., 2007, O'Brien et al., 2010). These include prescriptions that are applied in a manner allowing fire to consume litter but minimizes duff consumption. In general, repeated applications of fire over time can slowly reduce the O horizon by eliminating litter inputs and allowing trees a chance to move roots from O horizon into to A horizon.

5. Conclusions

The 2016 wildfire outbreak demonstrates the potential for large regional fire events in the southern Appalachians and is consistent with expectations for more wildfire from a warming climate and more frequent droughts (Liu et al., 2012, Mitchell et al., 2014, Vose and Elliott, 2016). The 2016 wildfires also highlight a key vulnerability under future climatic conditions – multiple ignitions during late fall drought. As the probability of ignition increases linearly with the number of consecutive dry days (Lafon et al., 2017), more droughts that coincide with fall leaf abscission will increase the likelihood of regional fire outbreaks from anthropogenic ignitions which may increase with a rapidly expanding wildland-urban interface (Vose and Elliott, 2016). If warmer droughts occur at a higher frequency and extend the late fall fire season into early winter, the potential for ignitions to correspond during mountain wave seasons would create a locally important but relatively poorly understood vulnerability. Identifying landscape settings where evidence of similar fire events occurred in the past and mountain waves are mechanistically likely from a topo-atmospheric perspective are important first steps to understanding geographic patterns of vulnerability to events like the fires that devastated Gatlinburg, Tennessee.

The 2016 fires also present a clearer understanding of the drivers of large fires during drought. Patterns of burn severity suggest that even under extreme drought conditions, the effects of fall fires, like spring fires, are likely to be characterized by low- and moderate- burn severity across the vast majority of area burned. Although there is potential for extreme fire behavior in landscapes where mountain waves occur, topography is likely to be a major constraint on the occurrence of high-severity fire effects which are most likely on steep upper slopes and ridges under more moderate fire weather conditions. Topographically driven patterns of burn severity may increase landscape heterogeneity and reinforce underlying environmental gradients that historically maintained landscape patterns of forest vegetation (Reilly et al., 2006b), however single fires are unlikely to restore historical conditions and meet many management objectives at stand and landscape scales (Arthur et al., 2021) and uncertainty remains on the role of delayed mortality following fire.

Invasions of non-native species, rapid regrowth of ericaceous shrubs and resprouting mesophytic species will create additional challenges for managers charged with restoring fire dependent communities and preserving biodiversity across the region. While the future likely holds more large wildfire events, the vast majority of the landscape remains unburned for almost a century and even relatively large, infrequent wildfires are unlikely to alter the trajectory of mesophication at meaningful scales. Future fires may potentially accelerate mesophication through the differential formation and subsequent wildfire driven consumption of an O horizon (Carpenter et al., 2021), as well as by shifting species dominance due to resprouting mesic species and delayed mortality of oaks (Robbins et al., 2022). In future, historical-like pine-oak may exist only on harsh inherently resilient sites like dry rocky slopes where fire is less critical and where there are concerted management efforts to restore. Judicious use of prescribed fire in strategic locations that experienced fire in 2016 may provide opportunities to leverage wildfires and restore historical fire regimes at larger scales. Additionally, prescribed fire is the best means for preventing the formation of duff in areas still dominated by oaks building resilience to future fires.

For forest and community planners, predictions of increased wildfire from climate change are often broad and generalized. Geographically specific outcomes are inherently difficult to model for heterogenous landscapes such as the southern Appalachians (Robbins et al. 2022), and the need for downscaling is particularly urgent as there is a high potential for wildfire, vulnerable assets, and communities at risk. The 2016 wildfire season offers insight into this complex hazard and how future fire may be manifest locally with both readily anticipated outcomes and unanticipated surprises. This local scale manifestation of what was arguably predictable based on limited experience with contemporary wildfire and an unexpected, but normal wind event provides a strong lesson learned. Such outcomes are likely to recur, and by understanding the mechanisms involved with each, researchers can focus efforts on those areas that are least well understood. In this region, the most notable novelty arose from extreme weather during the Chimney Tops 2 that led to the tragic loss of lives and structures. However, in a historical context, novel management outcomes have and will increasingly result from shifting forest composition and structure, as resulted from long-term mesophication and non-native invasive species.

As most of these fires were of human origin, shifting prevention efforts can radically change the region's fire future, just as they did a century ago when enforcement and education changed cultural behavior and perceptions. As the wildland urban interface is rapidly expanding, future fire outbreaks during similar weather may have worse consequences. Hazardous smoke from the region's fires led to cross-regional impacts in several metropolitan areas that are also expanding (Zhao et al. 2019). Over time, population growth and shifting weather may affect how the region's forests are actively managed through use of prescribed fire. Insights into how extreme wildfire events manifest can help prioritize where, how, and how often these actions can be undertaken.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix 1

We created a burn severity map based on the relativized change in the normalized burn ratio (RdNBR) following (Miller and Thode 2007) using cloud, shadow, and snow-masked medoid composites of Landsat normalized burn ratio (NBR) acquired one year before and one year after fires using Google Earth Engine (Gorelick et al., 2017). We validated this with field data from sixty plots where we had one year post-fire observations and were able to assess which trees were killed by the fire. We used the lm function in R (R Core Team 2019) to assess the relationship between RdNBR and percent tree mortality, then determined thresholds for low (<25 %), moderate (25 to 75 %), and high severity (greater than 75 %) based on the percent basal area mortality (Fig. A.1). Overall classification accuracy was 78.3 % (Table A.1).

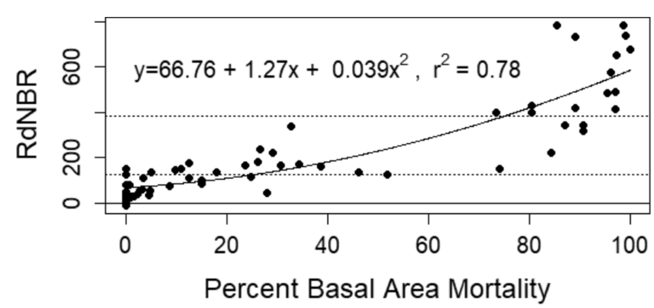

Fig. A.1. Relationship between percent basal area mortality and the relativized change in the normalized burn ratio with thresholds for low (<123 RdNBR), moderate (123 to 382 RdNBR), and high severity (greater than 382 RdNBR) indicated with the dotted line.

Table A.1
Confusion matrix for burn severity classification based on sixty field plots.

	Low	Mod	High		
Low	24	1	0	96.0 %	
Mod	7	10	4	47.6 %	Observed
High	0	1	13	92.9 %	
	77.4 %	83.3 %	76.5 %	78.3 %	
		Predicted			

We used the randomForest package (Liaw and Wiener 2002) in R (R Core Team 2019) to create a random forest model for predicting fire severity (RdNBR) with four topographic variables derived from a thirty meter digital elevation model: elevation, slope, aspect, and topographic position index (Figs. A.2 and A.3). Random forest is a machine learning algorithm that creates ensembles of regression trees and is suitable for complex, non-linear relationships between the response and predictor variables (De'ath and Fabricius 2000). A total of 2464 pixels were randomly sampled with a minimum distance of 150 m between them to avoid spatial autocorrelation. We used the tuneRF function to determine the optimal number of predictors to use in each candidate model. The final parameters used specified two predictors (mtry = 2) at each split and 500 trees.

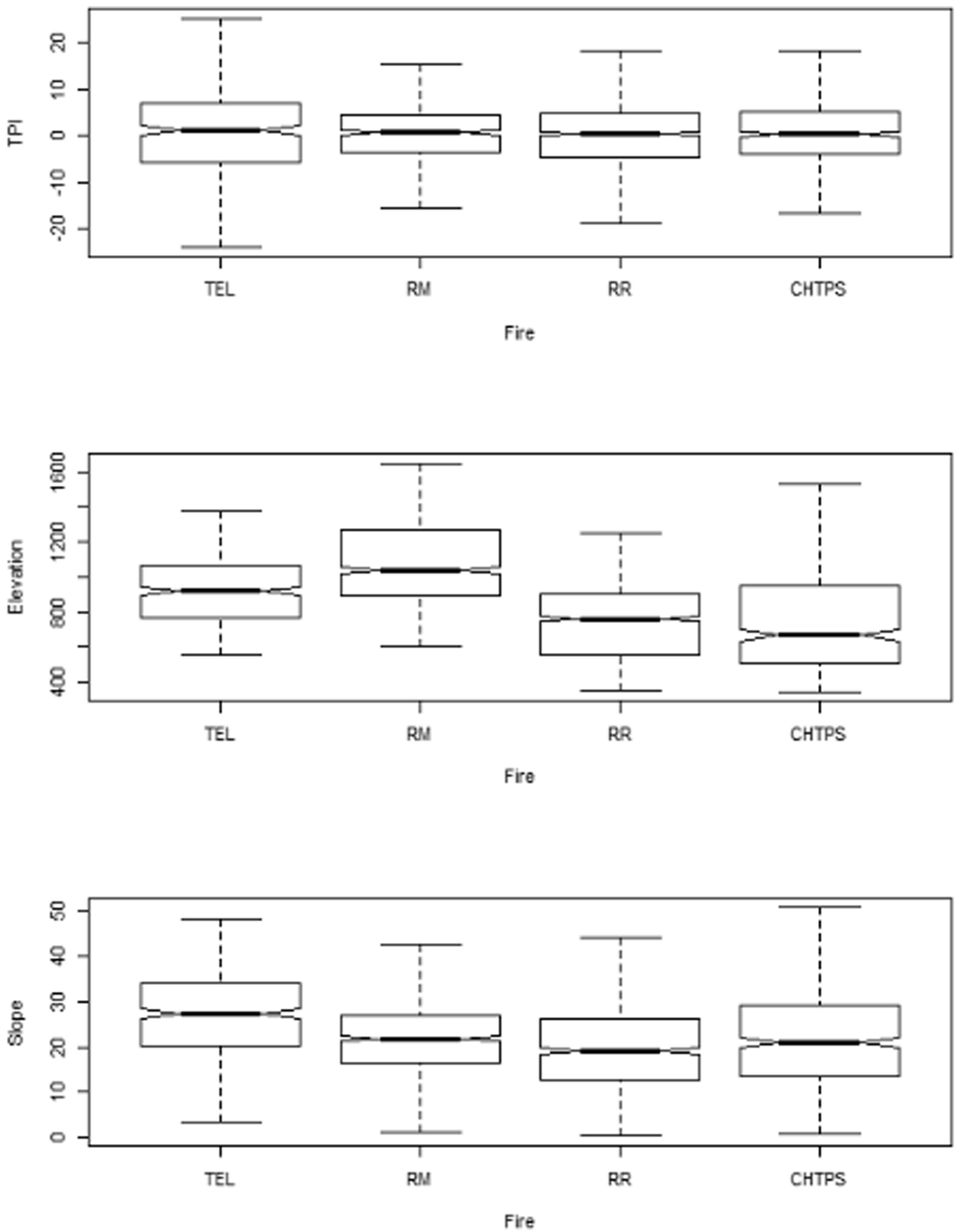

Fig. A.2. Boxplots of topographic position index (TPI), elevation (meters), and slope for the Tellico (TEL), Rock Mountain (RM), Rough Ridge (RR), and Chimney Tops 2 (CHTPS) fires.

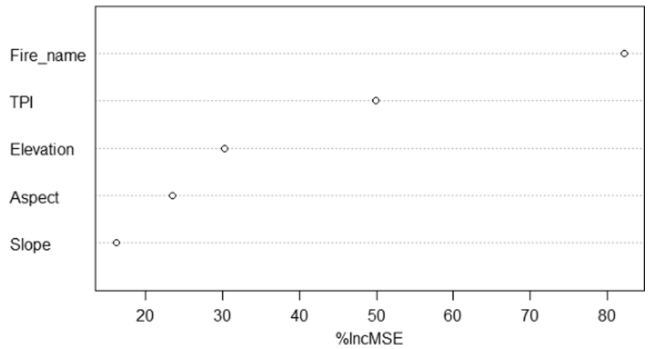

Fig. A.3. Variable importance plot from a random forest model predicting burn severity (RdNBR). The model accounted for 37.67% of the total variance.

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