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Pine woodland fire dynamics mirror industrial history at New River Gorge National Park and Preserve, West Virginia, USA

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ABSTRACT

Fire is an important biophysical process in pine (*Pinus*) and mixed pine-oak (*Quercus*) forests and woodlands across the Central Appalachian Mountains. Decades of fire exclusion, however, particularly on public lands, have resulted in a well-documented homogenization of species composition and forest structure. Our objective was to inform management and restoration efforts by expanding on previous dendroecological research at New River Gorge National Park and Preserve and adjacent Babcock State Park in southern West Virginia. Specifically, we assessed pine woodland fire activity in the context of local industrial history, land management, and regional drought. Samples cut from 110 fire-scarred pine trees, distributed across four sites, were used to develop a fire-scar record that spans the period 1842–2010; however, sample depth diminishes rapidly before the 1860s. Fires occurred frequently and extensively in the early–mid 20th century, coinciding with peak coal production and population density. Eleven major fires, or years when at least two trees and 25 % of samples recorded a fire scar at an individual site, were documented in the tree-ring record, but none occurred during the federal land management era (1978–present). Synchronous fire events recorded at two or more sites were associated with drier than average September–May ('dormant season') climate conditions. Our results indicate that, since the late 19th century, fire activity in pine woodlands at the New River Gorge has been driven primarily by human ignitions associated with industrial activities, and that periods of drought have amplified landscape-scale fire occurrence. Land managers should consider these historical fire patterns when developing restoration strategies that may include prescribed fire, thinning treatments, and managed wildfires.

1. Introduction

Smoke was reported rising from the slopes of Backus Mountain near Prince, West Virginia on Monday, November 6, 2023. By the time it was contained fourteen days later, the Steep Valley Fire had burned approximately 890 hectares within New River Gorge National Park and Preserve (NERI). It was the largest wildfire in 46 years of record-keeping since the Park was established as a national river in 1978 (National Interagency Fire Center, 2024). During this time, the average area burned by all other wildfires within NERI and adjacent Babcock State Park was just 9 hectares ($n = 283$), while 80 % of these fires burned fewer than 2 hectares. The Steep Valley Fire, therefore, was an exceptional event on the New River Gorge landscape in recent history—an anomaly within the broader context of fire exclusion on public lands across the Appalachian region since the mid-20th century (Lafon et al., 2017). This suppression-oriented management has had deleterious effects on some fire-adapted plant communities and associated wildlife habitat, including reduced herbaceous diversity (Vander Yacht et al., 2020; Saladyga et al., 2022) and a lack of adequate oak (*Quercus*) and pine (*Pinus*) species regeneration (Lorimer et al., 1994; Cain and Shelton, 1995; Abrams, 1998; McEwan et al., 2011; Alexander et al., 2021). Within NERI and Babcock State Park, for example, there are over 230 hectares of state-listed (S1 and S2) fire-adapted pine woodlands (Vanderhorst et al., 2007; NatureServe, 2024), but less than one fire per year on average has burned any portion of these plant communities since 1978 (National Interagency Fire Center, 2024). Continued fire exclusion will likely lead to a further decline in biodiversity and homogenization of forest structure across the landscape. Therefore, an expanded analysis of historical fire activity in these pine woodlands is needed to identify and update management objectives.

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Fire-scar records derived from tree rings inform resource managers of historical fire regime characteristics, including variation in the frequency, severity, extent, and season of fire occurrence (Swetnam et al., 1999). Across the Central Appalachian Mountains, numerous fire-scar studies demonstrate variability in pine and mixed pine-oak fire regimes. In Virginia, for example, multiple centuries of frequent fire ended abruptly in the Blue Ridge with the establishment of the George Washington and Jefferson National Forests in the early 20th century (DeWeese, 2007; Aldrich et al., 2014). A similar pattern has been documented on the Monongahela National Forest in West Virginia (Hessl et al., 2011), but fire-scar records from state and private lands tell a different story. On a wildlife management area in the Potomac Highlands, frequent fires in pine-oak forests and woodlands have persisted into the modern era (Saladyga and Maxwell, 2021), but these fires were significantly less extensive than in the century before state management. Further south in the Cumberland Mountains of West Virginia, recent mixed-severity arson fires on private timber land have promoted pine regeneration and increased understory diversity, while fire-sensitive tree species such as red maple (*Acer rubrum* L.) have increased in abundance on state-managed land where fire has been excluded for several decades (Saladyga et al., 2022). All factors influencing these regional fire regimes intersect at the New River Gorge, where a matrix of federal, state, and private land intermingles with a history of industrial land use and a contemporary tourism-based economy.

Within the last two decades, two fire-scar studies conducted within NERI and Babcock State Park focused on small portions of legacy pine woodland communities. Maxwell and Hicks (2010) and Saladyga (2017) found that fires historically burned every 1–13 years with a mean return interval of 4–5 years from the late 19th century to the early 2000s, but limited sample size prevented broader characterization of fire activity across the landscape. This historical context, due in part to limited scope, has not been incorporated into management plans at NERI or Babcock State Park. Additionally, the current fire management plan at NERI has restricted prescribed burns to under 8.1 hectares annually (Miller, 2005) and does not include chemical or mechanical thinning, which may be necessary alongside prescribed fire to meet restoration goals (Waldrop et al., 2016; Arthur et al., 2021; Knapp et al., 2024). Acknowledging these needs, resource managers at NERI are in the process of developing a new Fire and Vegetation Management Plan that specifically addresses dry pine and oak forests within the Park as well as across boundaries with adjoining landowners (e.g., West Virginia Division of Natural Resources), particularly where landownership bisects these plant communities. Understanding the biophysical conditions, including the historical fire regimes that have maintained and facilitated these communities, is foundational to the planning process and, ultimately, management of the New River Gorge landscape.

This expanded study of fire history at the New River Gorge was motivated by increased interest in the use of fire as a management tool in the National Park system to restore and maintain structural and biological diversity in forest ecosystems and fire-adapted plant communities. We use both previously published and newly developed fire-scar chronologies to evaluate the relative influences of land use, forest management, and climate on fire activity in pine woodlands. We hypothesized that a ‘wave of fire,’ not unlike the one linked to patterns of settlement and industrial activity in Pennsylvania (Stambaugh et al., 2018), swept across the New River Gorge landscape during a period of intensive resource extraction and population growth beginning in the early 20th century—while the decline in fire activity in recent decades is unique in the historical record. In addition, climate can be an important driver of fire spread, but we did not expect to find significant relationships between regional drought and individual fire events. Drought, however, may establish the antecedent conditions necessary for the spread of fires burning at multiple sites in a given year. Results of this study will aid in the development of a new federal fire management plan for NERI and will provide additional historical context for fire use in pine woodlands across the Central Appalachian Mountains.

2. Material and methods

2.1. Study area

New River Gorge National Park and Preserve (NERI) was first established as New River Gorge National River in 1978 and was recently redesignated as a national park in 2021. It includes nearly 30,000 hectares of land area and about 85 km of the New River, which cuts a 450-meter-deep gorge through the Allegheny Plateau in southern West Virginia. The Park contains many historical sites, including abandoned mine complexes and the remains of over 50 company-owned coal towns (National Park Service, 2024). The region was primarily agrarian until after the Civil War when completion of the Chesapeake and Ohio (C&O) Railroad in 1873 provided economic incentive to extract the area’s coal and timber resources at industrial scales. Development of the New River Coalfield subsequently intensified in the late 19th century and the population in Fayette County more than doubled between 1900 and 1920 (United States Census Bureau, 2024). Coal production peaked during World War II, but this boom era did not last. By the end of the 1950s, mines operating within present-day Park boundaries ceased production and the region entered a post-industrial period defined by population loss and consistently high rates of poverty and unemployment (Appalachian Regional Commission, 2024). Today, tourism is the primary driver of the local economy and interest in NERI continues to increase with a record 1.7 million visitors in 2023 (National Park Service, 2024).

Earlier fire history studies at the New River Gorge focused on two pine-dominated communities, including the imperiled (S2) Cliff Top Virginia Pine (*P. virginiana* Mill.) Forest and the critically imperiled (S1) Western Plateaus Pitch Pine (*P. rigida* Mill.) Woodland (Vanderhorst et al., 2007; NatureServe, 2024). Endless Wall (ENW; 38°3′26″N, 81°3′5″W) is located along the rim of a prominent sandstone cliff feature at the northern end of NERI where Virginia pine, blackgum (*Nyssa sylvatica* Marsh.), sourwood (*Oxydendrum arboretum* L.), and multiple oak species dominate the overstory (Maxwell and Hicks, 2010a; Fig. 1A). At Glade Creek (GLC; 37°59′26″N, 80°57′8″W) in adjacent Babcock State Park (est. 1937), pitch pine is the dominant pine species, while scarlet oak (*Quercus coccinea* Muenchh.), red maple, sourwood, and blackgum are also present in the canopy (Saladyga, 2017; Fig. 1A). Both sites are near former mines and company towns that were established in the 1870s–1880s but then abandoned in the 1950s.

2.2. Site selection

We used leaf-off aerial imagery, vegetation maps, and ground-based surveys in March 2023 to identify new sites suitable for fire history reconstruction. Since this work expands on previous studies (Maxwell and Hicks, 2010a; Saladyga, 2017), it was necessary that the new sites be similar in forest structure and vegetation composition to ENW and GLC (i.e., xeric pine dominance). We also looked for sites where at least 25 fire-scarred pine trees were available for sampling within an approximately 2-km linear section of the plant community. Based on these requirements, we selected two new sites within NERI and one site near GLC at Babcock State Park (Fig. 1A). No samples collected from trees at these new sites or previously published sites were located within fire perimeters delineated by the National Park Service and the West Virginia Division of Natural Resources since 1978 (National Interagency Fire Center, 2024). Fire perimeter data, or any geographically referenced records of fire occurrence, are not available for the period before federal land management at the New River Gorge.

Ephraim Creek (EPC; 37°59′24″N, 81°0′58″W) is located upslope and just south of Sewell, an abandoned town and coke oven complex situated along the C&O Railroad line on the New River. The other new NERI site is Mollys Creek (MOC; 37°56′ 54″N, 81°3′43″W), located about 1 km south of the town of Thurmond, a historic commercial center with a railroad depot that now functions as a visitor’s center. Manns Creek

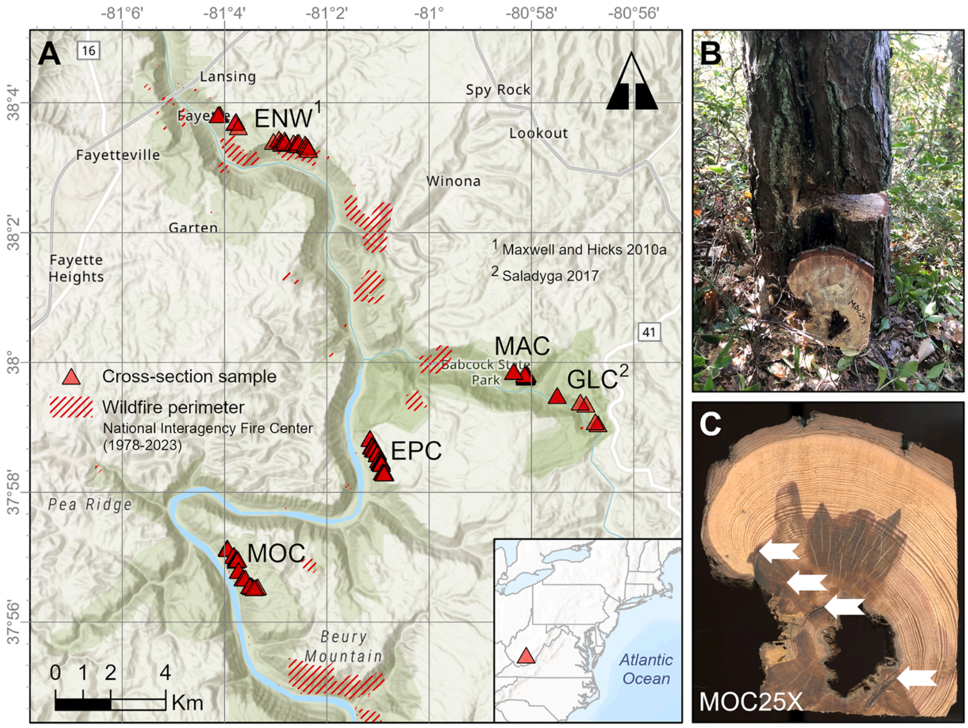

Fig. 1. (A) Fire history site and sample locations at New River Gorge National Park and Preserve and Babcock State Park in West Virginia: Endless Wall (ENW; Maxwell and Hicks, 2010a), Glade Creek (GLC; Saladyga 2017), Manns Creek (MAC), Ephraim Creek (EPC), and Mollys Creek (MOC). The two sites at Babcock State Park (GLC and MAC) have been combined into one composite site (GLC-MAC) for our analyses. (B) Partial cross section cut from a fire-scarred pine tree (*P. rigida*) at MOC. (C) Sanded and dated sample with four dormant season fire scars (1842, 1887, 1898, and 1942).

(MAC; 37°59′48″N, 80°58′5″W) is located just upslope from the former Manns Creek narrow gauge railway (ca. 1886–1956) and within 2 km of GLC—samples collected at GLC and MAC were combined into one composite site for our analyses. Each of the new sites is classified as a Cliff Top Virginia Pine Forest (Vanderhorst et al., 2007) with Virginia pine as the dominant pine species. Site elevations range from 520 to 600 m along the rim of the New River Gorge and 720–790 on the cliffs above Manns Creek and Glade Creek, while slopes are south to southwest facing and range from nearly flat to 70 % across all sites (Table 1). Mean annual temperature is 11.5 °C and monthly temperatures range from 0.0 °C in January to 21.9 °C in July (1991–2020; National Oceanic and Atmospheric Administration, 2024a). Mean annual precipitation is 121.4 cm, with monthly totals ranging from 7.7 cm in October to 13.7 cm in July (1991–2020; National Oceanic and Atmospheric Administration, 2024a).

2.3. Fire-scar data and analysis

We sampled fire-scarred pine trees at the new sites (EPC, MOC, and MAC) between October 2023 and January 2024. A partial cross section was cut from living trees and snags exhibiting external evidence of fire scarring (i.e., basal injury or "cat face") using a chainsaw (Fig. 1B; Arno and Sneck, 1977; Speer, 2010). Full sections were cut from fire-scarred stumps when present. All samples were processed and dated using standard dendrochronology methods (Stokes and Smiley, 1968; Speer, 2010). Samples were first air-dried and then surfaced with progressively finer grit sandpaper (40–1200) so that cells were clearly visible under magnification. Each sample was then visually crossdated against two local reference chronologies (Maxwell and Hicks, 2010b; Saladyga et al., 2015) using skeleton plots and the list method (Schweingruber et al., 1990; Yamaguchi, 1991). We used additional methods to verify visual crossdating of samples cut from remnant wood lacking a known outer-ring year (i.e., stumps and snags). High-resolution (2400 dpi) digital images of these cross sections were captured with a large-format scanner (1200XL, Epson, Suwa, Japan) and then uploaded into the program CooRecorder 9.8.1 (Larsson, 2016; Maxwell and Larsson, 2021) where annual rings where measured to the nearest 0.01 mm. Measurement series were statistically crossdated against the local reference chronologies using the program CDendro 9.8.1 (Larsson, 2016), and dating was quality checked in the xDateR application (Bunn, 2010).

Fire scars in each sample were identified by the presence of callus tissue, charred wood, and traumatic resin ducts (Fig. 1C; McBride, 1983; Speer, 2010). Compartmentalized injuries of other possible origins that did not have these attributes or correspond to a fire scar in at least one other tree at the same site were not included in subsequent analyses. We assigned each scar to a calendar year and, if possible, season of occurrence based on its relative position within an annual growth ring (e.g., Marschall et al., 2022)—early earlywood (E), middle earlywood (M), late earlywood (L), latewood (A), and dormant (D). Scars that occurred during the dormant season between annual growth rings were assigned to the calendar year after scarring to remain consistent with recent fire history studies in the region (e.g., Stambaugh et al., 2020; Saladyga et al., 2022). We adjusted dormant season scars in previously published fire-scar records (Maxwell and Hicks, 2010a, 2011; Saladyga, 2017) as

Table 1
Site information for Endless Wall (ENW), Glade Creek-Manns Creek (GLC-MAC), Ephraim Creek (EPC), and Mollys Creek (MOC).

Site variable	ENW	GLC-MAC	EPC	MOC
Tree species (n)	*P. rigida* (3) *P. virginiana* (18)	*P. rigida* (8) *P. pungens* (7) *P. virginiana* (16)	*P. rigida* (5) *P. virginiana* (26)	*P. rigida* (6) *P. virginiana* (21)
Elevation (m)	520–620	720–790	550–600	550–590
Slope (%)	5–50	5–70	5–55	10–70
Aspect	SSW	SSW	WSW	SW

needed. All fire-scar data were entered in FHX2 format and site composite fire interval statistics were calculated in Fire History Analysis and Exploration System (FHAES) software (Brewer et al., 2016). Mean fire interval (average number of years between fires), standard deviation, interval ranges, and Weibull median fire interval were calculated for all fire years beginning with the first scar recorded at each site. For each site, we also identified 'major fires' as years in which at least two trees and a minimum of 25 % of the samples recorded a fire scar. In addition, we generated a landscape composite of all fire years ('all fires') and years in which two or more sites recorded a fire scar ('synchronous fires') and calculated fire interval statistics as described above. We did not define periods of analysis for statistical comparison *a priori* (e.g., pre- or post-suppression era) because doing so would have oversimplified the multiple interacting factors that have influenced fire occurrence over time at the New River Gorge, particularly during the 20th century. Changes in human population density, land use, socioeconomic conditions, and state and federal land management have occurred simultaneously and in response to each other—and fire has not been completely excluded from the landscape.

We calculated two decadal (11-year moving sum) time series to assess landscape-scale fire frequency in relation to changes in land use and population density since the 1860s (e.g., Bigio et al., 2022; Marschall et al., 2022). These time series included (1) the number of fires per decade and (2) the number of synchronous fires per decade in the landscape composite. We then transformed both time series into standard z-scores ($z = (x - \text{mean})/\text{standard deviation}$) and identified time periods of significant fire frequency when the number of fires per decade exceeded a z-score of 1.64, $p < 0.05$ (Bigio et al., 2022). We compared significant periods of increased fire frequency to locally important changes in land use and population density, including the completion of the C&O Railroad in 1873, mine closures and population loss in the 1950s, and the establishment of New River Gorge National River in 1978.

Finally, we used superposed epoch analysis (SEA) in FHAES to assess interannual relationships between regional drought and fire occurrence (e.g., Flatley et al., 2013; Stambaugh et al., 2020). All fire years and synchronous fire years in the landscape composite were separately compared to mean September–May ('dormant season') instrumental Palmer Drought Severity Index (PDSI; 1895–2023) for West Virginia Climate Division 4 (National Oceanic and Atmospheric Administration, 2024b). The use of instrumental PDSI data instead of reconstructed June–August PDSI data (Cook et al., 2010) allowed us to focus the analysis on the effect of dormant season drought that is coincident with the fall and spring fire seasons, although this excluded some 19th-century fire events from the analysis. In the SEA, we tested for unique moisture conditions (wet or dry) during a five-year window that lagged two years before and after a fire year. Statistically significant departures in mean PDSI were identified as those exceeding the 95 % confidence interval derived from 1000 simulated events.

3. Results and discussion

3.1. Site fire histories

We dated 132 fire scars in 83 samples collected at the new sites (MAC, EPC, and MOC) for a cumulative total of 207 fire scars in 110 samples across all sites (Fig. S1–S4). These fire scars represent 69 unique fire years between 1842 and 2010 (Fig. 2). Samples collected from six trees did not contain visible fire scars or could not be crossdated due to the presence of significant heart rot or compressed micro-rings. Seasonality was determined for 94 % of all dated fire scars, with the vast majority (84 %) occurring between annual rings during the dormant season. At MOC, 20 fire scars (45 %) occurred during the growing season (E, M, or L). This relatively high proportion of growing season events is not typically observed in Appalachian fire-scar records (Lafon et al., 2017), but in this case might be attributed to the proximity of MOC to the town of Thurmond, a major railroad depot, where the potential for human ignitions would have been high throughout the year. The overall preponderance of dormant season scars across all sites, however, suggests most fires were anthropogenic in origin. Lightning is an unlikely cause of these dormant season fires since it is typically associated with summer (growing season) thunderstorms (Lafon, 2010). Additionally, lightning is the documented cause of fewer than 1 % of all wildfires in Fayette County in the modern record (1992–2020; Short, 2022).

Individual site fire-scar records ranged from 119 years (1915–2003) at ENW to 169 years (1842–2010) at MOC, with fires occurring most frequently, every 3–4 years, at ENW (Table 2; Fig. S1). Longer fire-scar records at GLC-MAC, EPC, and MOC were possible because of the presence of more survivor trees, the likely result of less frequent or less severe fires compared to ENW. At these sites, the fire-scar record extends to the mid-19th century and site composite mean fire intervals are one to four years longer than at ENW (Table 2; Fig. S2–S4). Frequent fires at ENW have been linked to industrial activities at the nearby Nuttallburg mine complex which likely resulted in an abundance of ignitions from

Table 2
Site composite fire interval statistics for Endless Wall (ENW), Glade Creek-Manns Creek (GLC-MAC), Ephraim Creek (EPC), and Mollys Creek (MOC). MFI = mean fire interval; SD = standard deviation; WMFI = Weibull median fire interval.

Fire interval statistic	ENW	GLC-MAC	EPC	MOC
Tree-ring record	1898–2004	1842–2023	1837–2023	1815–2023
Number of fires	24	27	23	22
Earliest fire year	1915	1868	1854	1842
Latest fire year	2003	1988	2004	2010
MFI (years)	3.8	4.6	6.8	8.0
SD (years)	2.3	4.4	6.2	9.7
Range (years)	1–8	1–20	1–27	1–36
WMFI (years)	3.5	3.7	5.3	5.5

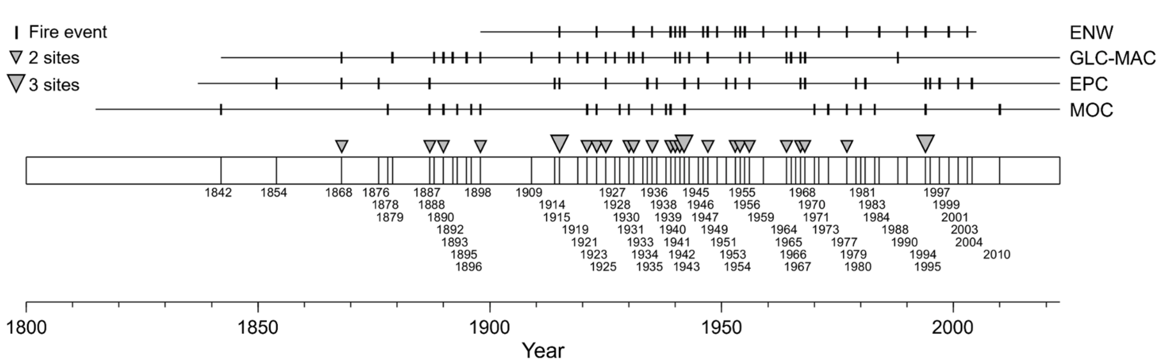

Fig. 2. Site composite fire event chronologies for Endless Wall (ENW), Glade Creek-Manns Creek (GLC-MAC), Ephraim Creek (EPC), and Mollys Creek (MOC). Each horizontal line represents the tree-ring record for an individual site, while the landscape composite timeline highlights years when at least one site recorded a minimum of one fire scar (i.e., fire event). The inverted triangles denote synchronous fires (min. 2 sites).

the time of its establishment to its closure in the 1950s (Maxwell and Hicks, 2010a; National Park Service, 2024). Compared to the other sites, ENW is also closest to human population centers, including the plateau communities of Lansing and Edmond (Fig. 1A). Prior to the late-1970s, travel across the New River from Lansing to Fayetteville, the county seat, required a steep descent into the gorge via narrow switchbacks on the slopes below ENW before crossing the one-lane Fayette Station bridge. This concentration of traffic would have provided additional opportunities for human ignitions until the New River Gorge bridge was completed in 1977, which reduced travel time across the gorge from 30 to 40 min to less than one minute.

Eleven major fires occurred between the 1880s and 1970s, but no more than three were recorded at an individual site and none occurred at more than one site in the same year (Fig. S1–S4). These results are consistent with other studies across the Appalachian Mountains (e.g., Flatley et al., 2013; Stambaugh et al., 2018; Saladyga and Maxwell, 2021), where fire regimes were historically characterized by frequent low-severity fires and occasional mixed- or high-severity events. Across all sites, the absence of major fires after 1971 indicates a change in the fire regime that corresponds to the beginning of the federal land management era. By the mid-1970s, these more extensive site-level events are no longer represented in the fire-scar records, a possible result of fragmented forest fuels that prevented fire spread (Lafon et al., 2005) as well as successful deployment of federal fire suppression resources after 1978.

3.2. Landscape-scale fire frequency

Analysis of landscape-scale fire frequency was limited to 164 years (1860–2023) since only eight samples distributed across three sites predated this period. During this time, fires burned at least one site every two years and there were 5–6 years between synchronous fire events on average (Table 3). Fire frequency for all fires exceeded the 95 % confidence interval in the 1930s–1940s (Fig. 3B), while synchronous fire frequency increased significantly during the 1920s–1940s (Fig. 3C). This 20th century 'wave of fire' (*sensu* Stambaugh et al., 2018), leading up to and including World War II, corresponds to the height of coal production in the New River Coalfield and peak population density in Fayette County (Mahan, 2004). Earlier in the records, there was a notable but not significant increase in fire frequency in the 1880s–1890s, immediately following the completion of the C&O Railroad (Fig. 3). Industrial-scale extraction of timber and coal was initiated at this time and these activities would have provided ample ignition sources across the landscape (Peters and Carden, 1926). After mine closures in the 1950s, fire frequency stays above the mean of approximately five fires per decade until the early 2000s, but none of these more recent fires were documented in the modern fire record (National Interagency Fire Center, 2024), which suggests these events were hyper-localized and did not require state or federal response (Fig. 3B). In contrast, synchronous fire frequency declined rapidly during deindustrialization before dropping below the mean in the 1970s (Fig. 3C). This trend was likely driven by reduced ignitions across the landscape due to mine closures and population loss.

Table 3
Landscape composite fire interval statistics for all fires and synchronous fires (min. 2 sites) during the 1860–2023 analysis period. MFI = mean fire interval; SD = standard deviation; WMFI = Weibull median fire interval.

Fire interval statistic	All fires	Synchronous fires
Number of fires	67	24
Earliest fire year	1868	1868
Latest fire year	2010	1994
MFI (years)	2.2	5.5
SD (years)	1.9	5.4
Range (years)	1–11	1–19
WMFI (years)	1.8	4.1

3.3. Fire-climate relationships

Our analysis of fire-climate relationships using SEA indicated no significant relationship ($p > 0.05$; $n = 56$; Fig. 4A) between dormant season instrumental PDSI and all fire events. However, synchronous fire events recorded at two or more sites showed a significant relationship with mean September–May drought conditions in the year of the fire ($p < 0.05$; $n = 21$; Fig. 4B). In an earlier study, Saladyga (2017) found no significant relationship between drought and fire occurrence at Babcock State Park when reconstructed June–August PDSI (Cook et al., 2010) was compared to fire events at a single site. The mismatch in seasonality (i.e., dormant season fires vs. growing season PDSI) and limited spatial scale likely account for an absence of fire-climate relationships. In our updated and expanded analysis, the significant association between dormant season drought and synchronous fire activity at multiple sites suggests climate is an important driver of fire at the landscape scale and that accounting for fire seasonality in SEA can improve our ability to disentangle these relationships.

Fire-climate relationships are generally absent in fire-scar studies across the Appalachian Mountains (Lafon et al., 2017) with some exceptions. For example, in the Ridge and Valley physiographic province where climate conditions are generally drier than on the Appalachian Plateau, Aldrich et al. (2014) found that reconstructed summer PDSI was significantly drier during fire years at two of three study sites. In central Pennsylvania, Stambaugh et al. (2018) used reconstructed summer PDSI in their analysis and found conditions to be drier than expected one year prior to regional fire years. In contrast, Saladyga and Standlee (2018) determined that high rates of unemployment in the Pennsylvania anthracite coal industry were a better predictor of fire occurrence than annual instrumental PDSI during the 20th century, indicating that climatic influences can be masked or overridden by other factors as seen in the Southern Appalachians (Flatley et al., 2013). Overall, while fire events in the tree-ring record tend not to show a significant relationship with drought in the Appalachian region, there is some variability, and if possible, the use of seasonal instrumental PDSI in fire-climate analyses can improve interpretations as demonstrated in this study.

4. Conclusions and management implications

Our expanded analysis of pine woodland fire dynamics at the New River Gorge confirmed that historical fire regimes were strongly influenced by industrial activities and amplified by regional drought, with landscape-scale fire activity peaking between the 1920s and 1940s. Our analysis, however, was limited by tree age, preventing an assessment of fire occurrence before industrialization (i.e., pre-1860). Nevertheless, results indicate that these plant communities, while resilient to a range of fire frequencies and severities, have been significantly impacted by federal fire suppression policies beginning in the late 1970s. Dormant season prescribed fires at low to moderate intensity, combined with thinning treatments to reduce fire-sensitive tree densities and increase light in the understory, may help restore and maintain these regionally unique communities (Knapp et al., 2024). Additionally, given the expected increase in wildfire incidents and area burned across the region (Donovan et al., 2023)—exacerbated by increasing visitation rates and potential climate change, as demonstrated by events like the Steep Valley Fire—a shift in management strategy is warranted. Instead of immediate fire suppression, resource managers at NERI and Babcock State Park could manage wildfires under controlled conditions to fulfill specific objectives when and where appropriate. This approach would align with historical fire patterns but would require coordinated planning with adjacent landowners due to the proximity of pine woodlands to public land boundaries. Inclusion of these adaptive management strategies in the new Fire and Vegetation Management Plan will be critical to promoting biodiversity and forest health across the New River Gorge landscape.

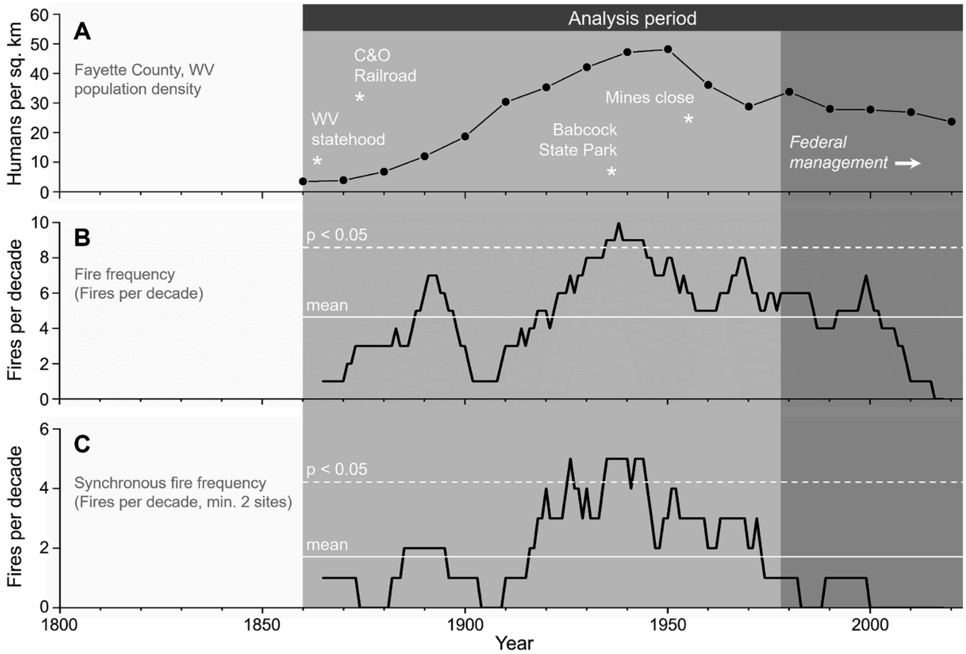

Fig. 3. Trends in population density and landscape-scale fire frequency (1860–2023): (A) Decennial census population density for Fayette County, West Virginia, (B) Number of fires per decade (11-year moving sum) for all fires, and (C) Number of synchronous fires (min. 2 sites) per decade (11-year moving sum). Additional historical context is noted in (A), including West Virginia statehood (1863), completion of the Chesapeake and Ohio Railroad through the New River Gorge (1873), establishment of Babcock State Park (1937), coal mine closures during the 1950s, and the federal land management era beginning in 1978 with the establishment of New River Gorge National River. Mean fire frequency and $p < 0.05$ significance levels are shown in (B) and (C).

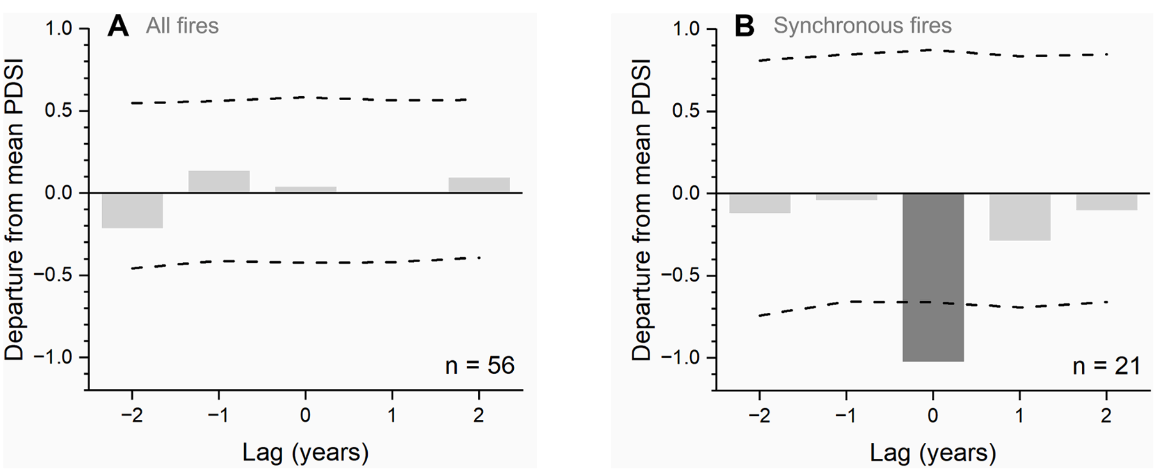

Fig. 4. Results of superposed epoch analysis (SEA) for (A) all fires and (B) synchronous fires (min. 2 sites) in the landscape composite. In both graphs, the vertical bars represent departure from mean September–May ('dormant season') Palmer Drought Severity Index (PDSI) lagged two years before and two years after a fire event. The dashed horizontal lines indicate the 95 % confidence interval and sample size is the number of events analyzed.

CRediT authorship contribution statement

Thomas Saladyga: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **R. Stockton Maxwell:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Douglas R. Manning:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100676.

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