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Characterizing Effects of Prescribed Fire on Forest Canopy Cover in the George Washington and Jefferson National Forests

Jean Lorber, Melissa Thomas-Van Gundy, and Steve Croy

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Abstract

On the George Washington and Jefferson National Forests, managers have used prescribed fire to create and maintain early-successional and open forest conditions across large areas. We used a landscape-scale and image-based approach to assess the extent that prescribed fires, including repeated fires, have created these forest conditions and put the results in context of the new George Washington National Forest management plan. At the landscape level, early-successional forest made up an average of 5 percent of burn unit area after one burn, 9 percent after two fires, 17 percent after three fires, and 14 percent after four fires. On average across all burn unit acreage, open forest made up 5 percent of the area after one burn, 7 percent after two burns, 9 percent after three, and 8 percent after four fires. The forest plan desired condition of 12 percent of the area in early-successional forest was met after three or four fires and was exceeded in some individual burn units. It is harder to achieve open-forest than early-successional conditions using prescribed fire alone. We also examined possible drivers of canopy gap creation in these forests. Vegetation type and heat load index, a topographic-based measure of solar radiation received by a site, were important predictors of where canopy gaps formed after prescribed fire.

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Quality Assurance

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Cover Photo

View of aerial ignition of the Middle Mountain burn unit in 2010. This unit was included the analysis reported here, with 7 percent of the area becoming early successional habitat and 2 percent becoming open forest after one burn. Photo by Sam Lindblom, The Nature Conservancy, used with permission.

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INTRODUCTION

Fire has a long history in the eastern United States, particularly in oak and oak-pine forests (Lafon et al. 2017, Patterson 2006). A recent synthesis of the state-of-knowledge on fire in the Appalachians describes the fire history as one of frequent burns and spatially extensive in areas supporting oak (*Quercus*) and pine (*Pinus*) forests (Lafon et al. 2017). Reconstructing fire regimes and even basic fire return intervals in the central Appalachian forests is substantially hampered by Euro-American settlement and land use. As settlers moved west, Native American populations were disrupted by disease, conflict, and displacement (Mann 2005, Ruffner and Abrams 2002). As technologies improved, forest harvesting for timber, charcoal, and other products accelerated from the colonial era to the 1900s, with mountainous areas generally the last to be cleared during this industrial logging period (Lewis 1998). These actions largely removed Native Americans, who used fire for a variety of reasons, while eliminating much of the fire history recorded by trees. However, isolated stands of old, remnant trees still exist in the Appalachian Mountains (Nowacki and Trianosky 1993), allowing a glimpse of past fire regimes captured in fire scars. For instance, a tree-ring study estimated fire-return intervals of about 3 to 15 years in pine-dominated stands in Virginia until 1930 (Aldrich et al. 2010). Historically in this area, most fires occurred in the dormant season and fire scars across multiple stands demonstrated that area-wide fires spread among the pine-dominated ridges (Aldrich et al. 2010). Even shorter return intervals were seen in the tree-ring record at another ridge and valley site in Virginia. With a fire chronology beginning in 1794, the mean composite fire interval recorded in pines was 2.2 years, mostly during the dormant season with larger fires occurring every 12–13 years (Hoss et al. 2008). Similarly, at a ridge and valley forest in western Maryland, white (*Quercus alba*) and chestnut oaks (*Q. montana*) recorded a modal fire interval of about 8 years over a 400-year period, with most of those fires in the dormant season (Shumway et al. 2001).

Other less direct evidence exists for fire in the central Appalachians (Lafon et al. 2017). Dating of soil charcoal has shown fire to be a driver of vegetation for 4,000 years and that fire was not confined to dry oak-pine ridges (Fesenmyer and Christensen 2010). The presence of fire-dependent and fire-adapted species is indirect evidence of fire in these forests. Species with obvious fire-dependent traits such as serotinous cones (Table Mountain pine [*Pinus pungens*] and pitch pine [*P. rigida*] in some areas) are found in the central and southern Appalachians, including the forests of western Virginia (Della-Bianca 1990, Little and Garrett 1990). Pitch pine is also one of the few pines that resprout from basal buds after fire. Oak species found in the mountain forests of Virginia exhibit many fire-adapted traits (Abrams 1992). With adaptations to disturbance and water stress, oaks possess traits that enhance survival following repeated fire. In general, mature oaks have thick bark (Harmon 1984) and deep root systems (Hinckley et al. 1981), and they have the ability to compartmentalize stem injury and resist rotting (see Abrams 1990, 1992; and Lorimer 1985 for reviews). Also, seedlings can resprout from root collar buds after topkill (Huddle and Pallardy 1999, Peterson and Reich 2001, Waldrop and Lloyd 1991) forming advanced regeneration. The presence of fire-adapted species in early land surveys has been used to infer the spatial extent of fire as a disturbance regime in West Virginia (Thomas-Van Gundy and Nowacki 2013).

The loss of fire as a disturbance agent through deliberate suppression since the 1930s and a cultural shift in the importance of fire in hardwood forests have resulted in observable change. Eastern forests are shifting in species composition (Dyer 2006, Fei et al. 2011, Nowacki and Abrams 2015), most noticeably in the understory where shade tolerant and/or fire-sensitive species, such as red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), and blackgum (*Nyssa sylvatica*), have generally increased in abundance (Steiner et al. 2008). On more mesic sites, and some dry sites, shade intolerant, rapidly growing species such as yellow-poplar (*Liriodendron tulipifera*) and black birch *(Betula lenta*) often outcompete oaks after timber harvest or other canopy disturbance. Where pine species are a component of eastern forests, declines in pine regeneration and species composition changes are also occurring, particularly in the yellow pines (*P. rigida, P. virginiana, P. echinata, and P. pungens*) (Harrod et al. 1998). In ridgetop pine communities, the Appalachian endemic Table Mountain pine is not regenerating in the absence of periodic fire (Williams and Johnson 1990).

The reduction in the fire frequency of eastern oak forests over the past 80 years has meant that many of the fire-adapted advantages of oak and pine species are not realized. This is essentially the underlying cause driving the "mesophication" of eastern forests (Nowacki and Abrams 2008). The result is a positive feedback cycle in which the removal of fire has resulted in a landscape that is increasingly fire-proof and less amenable to either the restoration of the historic fire regime or the maintenance of oak-dominated forests.

Managers of National Forest System lands in the East are increasing their use of prescribed fire to return this historically important disturbance to oak and oak-pine forests (Brose et al. 2001). Much of this increase is due to information generated from research supported by the Joint Fire Science Program and Landscape Fire and Resource Management Planning Tools (LANDFIRE) initiated as part of the National Fire Plan after the 2000 fire season. The George Washington (GWNF) and Jefferson National Forests (JNF) have a history of prescribed fire, with treatment acres expanding annually since 1998. The GWNF Revised Land and Resource Management Plan (GWNF Plan) (USDA Forest Service 2014) recognizes the need for fire in the restoration and maintenance of oak, oak-pine, and pine forests and woodlands. Specifically, fire is to be "used in a controlled, well-planned manner to manage vegetation, restore fire-dependent ecosystems and species, create desired wildlife habitat conditions, and modify uncharacteristic fuel conditions resulting from extended absence of fire and/or tree mortality from nonnative insects and disease" (USDA Forest Service 2014). As stated in the GWNF Plan, a fire-return interval of 5 to15 years is desired in oak systems for creating open canopy structure and maintaining historic species composition. For pine-dominated systems, a target fire-return interval of 3 to 9 years is desired.

In the JNF forest plan (JNF Plan) (USDA Forest Service 2004), forest-wide direction includes restoring fire regimes to forests and grasslands within or near the historical range for the restoration and maintenance of fire-adapted ecosystems. Objectives for dry and xeric oak forests, woodlands, savannas, and xeric pine and pine-oak forests and woodlands call for maintaining a prescribed fire cycle of 4 to 12 years (USDA Forest Service 2004). In dry-mesic oak forest and dry and dry-mesic oak-pine forest communities, the JNF plan objectives are for a burn cycle of 8 to 20 years (USDA Forest Service 2004). Prescribed fires can be used in either the growing season or dormant season on both the GWNF and JNF.

The wildlife habitat conditions created through the use of prescribed fire include patches of early-successional forest to benefit a variety of animal species. In general, fire increases sources of food for browsers and frequent fires favor herbaceous plants over woody ones (Van Lear and Harlow 2002). However, burning "for wildlife" is an unclear objective as some species do benefit (for example, turkey [*Meleagris gallopavo silvestris*], white-tailed deer [*Odocoileus virginianus*], reptiles) while others experience negative effects (for example, ground nesting birds and salamanders) depending on season of burn and fire intensity

(Harper et al. 2016). In the GWNF and JNF Plans, the goal of creating open canopy structure through the use of prescribed fire suggests management for a certain suite of wildlife species. For example, these open canopy conditions should benefit songbirds including loggerheaded shrike (*Lanius ludovicianus*), eastern bluebird (*Sialia sialis*), prairie warbler (*Setophaga discolor*), and various sparrows (Harper et al. 2016). In a study in the mountains of North Carolina, researchers found that on sites with high severity fire and mechanical treatments of the subcanopy, breeding bird species richness and density were higher compared to other treatments, though the treatments may have temporarily reduced habitat for ground nesting birds (Greenberg et al. 2013). For wildlife that benefit from fire, which includes many game and nongame species, the lack of fire in the forests of the central hardwoods and Appalachians is a greater limiting factor than applying fire without knowing the exact fire frequency, severity, or seasonality to benefit any given species (Harper et al. 2016).

Along with creating and maintaining an open canopy, returning fire to these forests also results in changes to the understory and herbaceous layer. The herbaceous layer is broadly defined as the stratum composed of all vascular species that are less than 3 feet in height, including tree regeneration, shrubs, graminoids (grasses and sedges), and forbs (Gilliam 2007). Most of the plant diversity in a forest is found in the herbaceous layer. Since litter from herbaceous species often decays faster than tree litter, the herbaceous layer is important in nutrient cycling (Gilliam 2007). Creating an open canopy structure through a prescribed fire increases the amount of light reaching the forest floor, resulting in changes to the herbaceous layer beyond the immediate fire effects to the canopy and subcanopy.

Even a single fire can cause grass species cover to increase depending on landscape position (Elliott et al. 1999, Glasgow and Matlack 2007); however, multiple fires are usually needed to sustain this change, otherwise the grass-cover increase may disappear within a decade (Elliott et al. 2009). Fire generally increases plant species diversity and richness in forests across the eastern United States (Bowles et al. 2007; Elliott et al. 1999, 2009; Holzmueller et al. 2009; Hutchinson et al. 2005a). Due to their early spring emergence, the abundance or cover of spring ephemerals are not significantly impacted by dormant-season prescribed fire (Bowles et al. 2007, Kem 2013).

Along with a general increase in grasses, others have found tick-trefoil (*Desmodium* spp.), goldenrod (*Solidago* spp.), and blueberry (*Vaccinium* spp.) to be significantly associated with sites where multiple prescribed fires have occurred (Holzmueller et al. 2009). In addition, others have found sedges (*Carex* spp.), bearded shorthusk (*Brachyelytrum erectum*), American burnweed (*Erechites hieraciifolius*), woodland sunflower (*Helianthus divaricatus*), and panic grasses (*Panicum boscii*, *P. commutatum, P. dichotomum*) to be associated with sites with multiple burns (Hutchinson et al. 2005a). These species, along with species like little bluestem (*Schizachyrium scoparium*), big bluestem (*Andropogon gerardii*), and Indian grass (*Sorghastrum nutans*) could be used as indicators of success in creating woodland conditions. During a field review of some recent prescribed fire units on the GWNF, many savanna or woodland-indicator species were noted in the herbaceous layer that had established naturally in the areas of multiple prescribed fires. These species included anisescented goldenrod (*S. odora*), roundleaf throughwort (*Eupatorium rotundifolium*), horseflyweed (*Baptisia tinctoria*) and a hoarypea (*Tephrosia* spp).[1]

[1] Cecil Frost, Blue Star Consulting, Rougemont, NC; personal communication.

Objectives of this Work

Land managers and national forest stakeholders may benefit from knowing how prescribed fire on the GWNF and JNF has impacted forest structure and if progress is being made toward meeting GWNF forest plan goals. Determining the landscape-scale effects of prescribed fire or wildfire can be done through remotely sensed data. One method is the calculation of a normalized burn ratio from Landsat imagery taken before and after a fire (Key and Benson 2006, Miller and Thode 2007, Wimberly and Reilly 2007). We chose a more direct method of determining initial fire effects through the use of digital aerial photography to map the creation of canopy gaps (overstory tree mortality) after prescribed fire. In this analysis, we document changes in forest structure from prescribed fires and examine these changes to determine if structure goals are being achieved. Given the history of prescribed fire on the two national forests, we were able to describe the canopy conditions resulting from a single prescribed fire, two fires, and three or more fires in the same management unit. In this report, we display and discuss: 1) the results of mapping canopy gaps after prescribed fire from aerial photography, 2) descriptions of forest structure after prescribed fire from on-the-ground plot data, and 3) an analysis of factors associated with canopy gap creation.

Canopy mortality pattern resulting from the Falling Rock wildfire in the James River Face Wilderness in April of 2010. The photo was taken about 3 months after the fire. The reference conditions and goals for the prescribed fire program on the two national forests are based on recreating these patterns. Photo by Steve Croy, retired, USDA Forest Service.

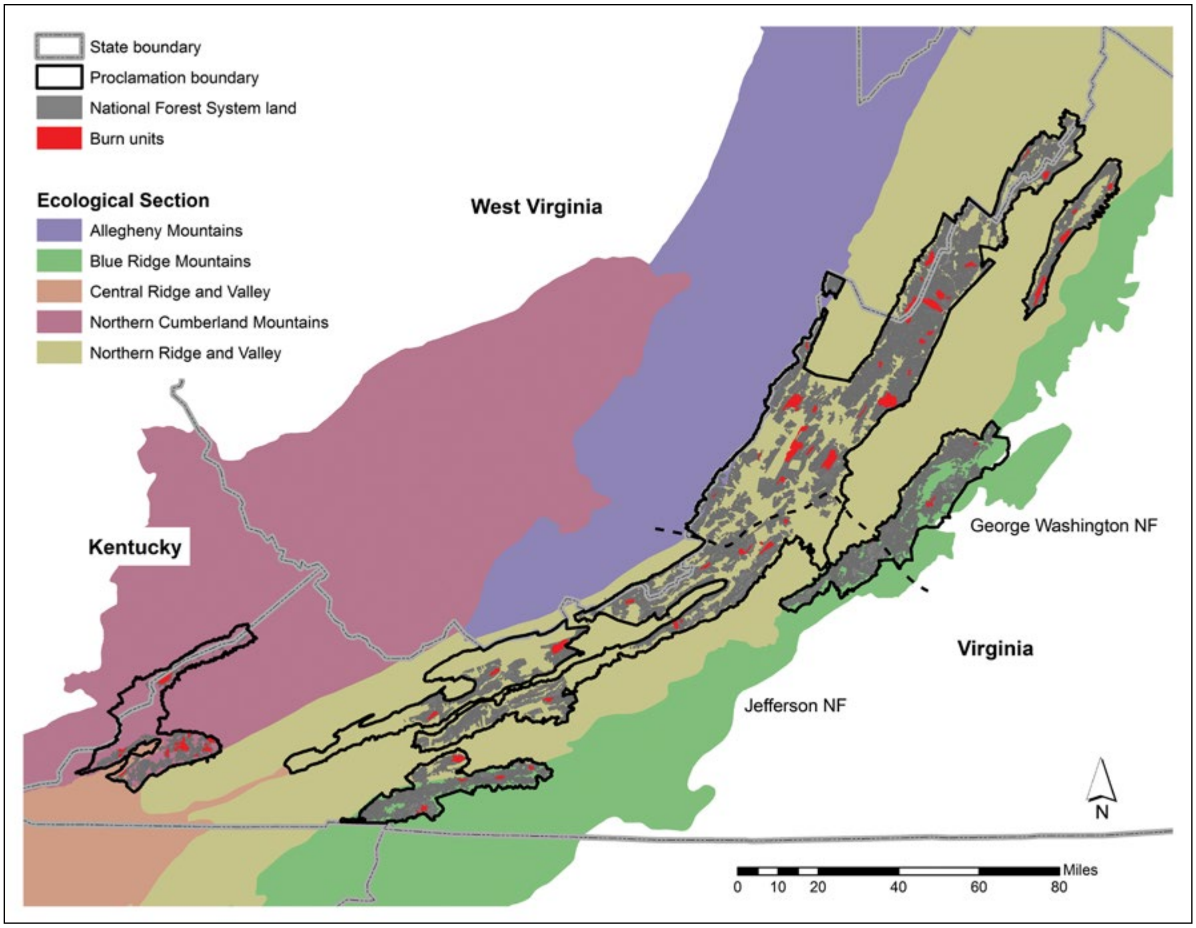

Figure 1.—Location of the George Washington and Jefferson National Forests in relation to physiographic provinces. Burn units that were examined are shown in red.

METHODS

Study Area

All examined burns units were located in the GWNF and JNF, in Virginia, West Virginia, and Kentucky (Fig. 1). The GWNF covers 1.1 million acres and is primarily located in the Northern Ridge and Valley physiographic section with its eastern portion located in the Blue Ridge Mountains section. The Northern Ridge and Valley section is characterized by long, parallel ridges of sandstone parent materials, interspersed with valleys of limestone parent materials (Cleland et al. 2007). The JNF covers 0.8 million acres and is primarily located in the Northern Ridge and Valley section, with portions in the Northern Cumberland Mountains in the west. Over the last 25 years, the region around the GWNF and JNF averaged around 40 inches of precipitation annually, spread relatively evenly throughout the year. The frost-free period is typically mid-April to mid-October (NOAA 2016).

Seventy-five burn units were examined, covering over 85,000 acres (see appendix 1 for details about individual burn units used in this analysis). These 75 units experienced a total of 117 burn events, primarily from the late 1990s through 2014. None of these units showed evidence of widespread tree mortality or disturbance prior to known burn event(s) based on review of preburn aerial photography. Only burn units over 250 acres were included in our examination, as larger-scale burns allow for a greater possible expression of landscape-mediated fire effects; the median unit size was 743 acres.

Table 1.—Canopy cover thresholds and desired conditions, adapted from Table 2-4 of the George Washington National Forest's 2014 Revised Land and Resource Management Plan (USDA Forest Service 2014). Landscape targets apply to oak-dominated community types.

Defined thresholds	Forest canopy condition	Description	Desired portion of landscape
EARLY Adjusted canopy cover of <30%	Early successional or regenerating forest	Stands developing after a major disturbance or timber harvest, generally less than 11 years in age in the most common systems, but can be up to 35 years	12%
OPEN Adjusted canopy cover of 30–50%	Mid- or late-successional open canopy forest	Stands beyond regeneration that stay in a relatively open canopy (canopy closure of 25–60%)	67%
CLOSED Adjusted canopy cover >50%	Mid- or late-successional closed canopy forest	Stands…with a largely closed canopy (all layers) greater than 60%, includes natural canopy gaps	21%

All burns were conducted during the end of the dormant season or early in the growing season, typically during April and May. Smaller units (<500 acres) were typically hand-ignited. Larger units were hand-ignited along the perimeter, followed by aerial ignition of the interior. Ignition was usually finished in 1 day, although several of the largest units (>2,000 acres) continued to burn for several days after ignition.

Ecological communities within the burn units represented the full range of the Appalachian forest. The primary matrix-forming forest was dry to dry-mesic mixed oak stands, composed of chestnut oak, northern red oak (*Q. rubra*), scarlet oak (*Q. coccinea*), and white oak. On more xeric ridgetops or southwestern slopes, large patches of pitch pine and Table Mountain pine were found. The most common community on the GWNF is oak forest and woodlands, comprising 756,000 acres or 64 percent of total area (USDA Forest Service 2014, see Table 2-3).

GIS Canopy Cover Assessment

We defined three levels of live canopy cover using thresholds adapted from the GWNF Plan representing the desired canopy structures (Table 1): EARLY, OPEN, and CLOSED. We made adjustments to the categories of EARLY and OPEN since they overlapped as described in the GWNF Plan. We defined the minimum basal area for OPEN as 30 ft^2/acre, more in the range of residual basal area for a two-aged stand (Miller et al. 2006). This minimum basal area translates to a minimum canopy closure of 39 percent (using Buckley et al. 1999), which we rounded up to 40 percent. The maximum canopy closure for OPEN was left unchanged at 60 percent.

The next adjustment was to transform the canopy closure into canopy cover, as the latter most accurately describes the metric obtained when using overhead imagery (Korhonnen et al. 2006). Using Fiala et al. 2006, we adjusted canopy closure values for OPEN downward by a conservative 10 percentage points for a final range of 30–50 percent <u>canopy cover</u>. We defined canopy closure for EARLY as less than 30 percent cover.

Using these categories, author Lorber examined leaf-on imagery from 2003 to 2016 (Farm Services Agency 2013 through 2016); imagery covered both preburn and post-burn time periods for each burn. Using ArcMap 10.2 (ESRI 2013), all imagery was examined at a scale of 1:5000; any visually distinct area showing canopy mortality was hand-digitized and classified as EARLY or OPEN (Figs. 2 and 3). The remainder of the burn unit was considered CLOSED. For most burn events, several years of post-burn imagery were assessed to account for delayed tree mortality (Yaussy and Waldrop 2010). Patches of canopy mortality, or canopy gaps, smaller than 0.25 acres were not readily detectible, making this size the default threshold for gap detection. Areas of EARLY or OPEN conditions existing in preburn imagery, typically rock outcrops or barrens, were ignored for this analysis. Young forest was considered EARLY only if it was clear that fire killed the canopy, thus creating new EARLY forest. To minimize variability, one person digitized all gaps and relied on cover class estimation guides for calibration (NWCG 2017).

Units with multiple known burns predating the imagery were still included; however, canopy gaps could not be attributed to a specific burn. Therefore, the record of canopy gap formation was left incomplete (e.g., no first burn results), beginning only with the first prescribed burn that occurred when imagery was available.

Multiple sources of information about biotic and abiotic conditions within the burn units were compiled in ArcMap 10.2 (ESRI 2013) to describe the types of forests in which the EARLY and OPEN conditions were created. Current vegetation and stand age were obtained from the Field Sampled Vegetation (FSVeg) database, the stand-level database maintained by the Forest Service (https://www.fs.fed.us/nrm/). For the potential vegetation types, the ecological zones (ecozones) models developed for the GWNF (Simon 2011) and the JNF (Simon 2013) were used. These models integrated a suite of abiotic and biotic factors to predict the potential vegetation types at a 10-m pixel scale. For our analysis, the FSVeg forest type categories and ecozones were grouped along a gradient of site productivity and moisture (appendixes 2 and 3).

Heat load index (HLI) (Evans 2014) was calculated for the study area from a 30-m digital elevation model. This index incorporates latitude, slope, and aspect to estimate annual solar radiation at a given point. HLI has been shown to be related to fire effects and fire severity (Arkle et al. 2012, Holden et al. 2009) and was used to describe patterns of canopy creation.

Plot Data

On-the-ground data from within the burn units were used to validate the results of the GIS-based canopy classification. Data were obtained from a vegetation monitoring dataset maintained by the Central Appalachian Fire Learning Network (FLN; https://www.conservationgateway.org/ConservationPractices/FireLandscapes/FireLearningNetwork/RegionalNetworks/Pages/CentralApps.aspx). The FLN has been monitoring over 300 plots since 2008, sampling several layers of vegetation at each plot both before and after prescribed burn treatments. Plots were established in burn units on both George Washington and Jefferson National Forests, located randomly in ArcGIS using Hawth's tools (Beyer 2004). Plots were established at least 100 feet from a road or trail and 100 feet apart to avoid duplicate sampling. Plot centers were georeferenced in the field with a handheld global positioning system unit and marked with steel rebar. The 80 plots that were examined in this study included all plots that had been burned once and that had both preburn and post-burn data.

The plots had a nested design with subsampling to capture the condition of the overstory, midstory and understory. The overstory was sampled using a variable-radius BAF 10 prism at the nested plot center to determine the basal area of live and dead trees >5 inches diameter at breast height (d.b.h.). The midstory was sampled using a 0.01-acre circular plot (radius

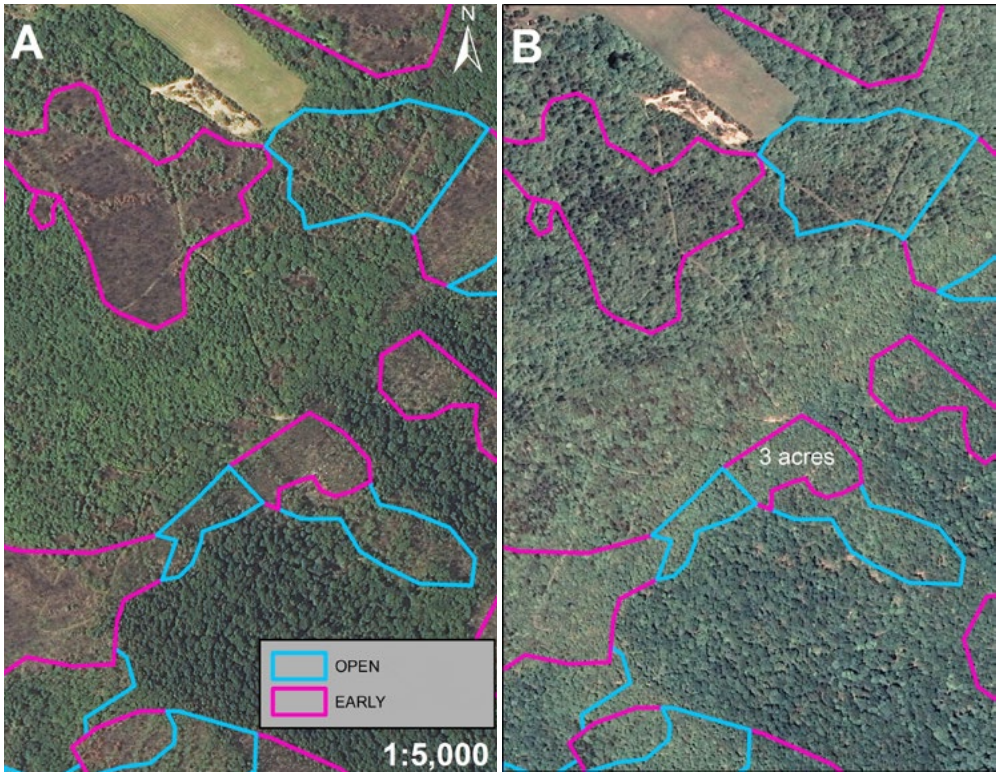

Figure 2.—Example of canopy gap delineation using post-burn, leaf-on imagery from the National Agricultural Imagery Program (A). Gap boundaries are superimposed on preburn imagery (B).

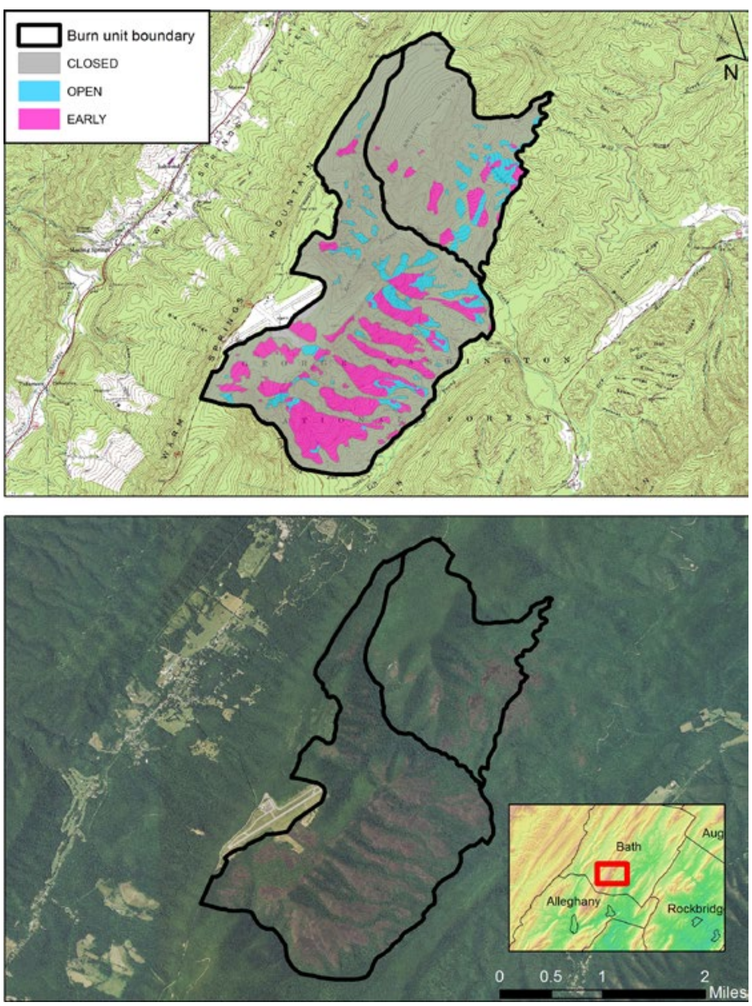

Figure 3.—Example of burn unit canopy assessment showing the three mapped canopy conditions.

of 11.8 feet), in which all woody tree and shrub stems >3.3 feet tall were counted and their d.b.h. recorded in two size classes: <1 inch and 1-4 inches. Canopy cover was also estimated from this plot center: the presence or absence of overhead cover (>5 feet tall) was determined at five points along each of four transects (20 points total) located in the cardinal directions from each plot center using a sighting tube (densitometer). Canopy cover was then calculated as the percentage of the 20 points where overhead cover was present. The understory was sampled within four, 10.75-square feet subplots located 11.8 feet from plot center in four cardinal directions. For analysis purposes, data from the four subsamples were averaged for a single plot value. In these quadrats, all woody stems 0.5 to 3.3 feet in height were counted and the percentage spatial cover (above ground, not basal) of graminoids, forbs, woody trees/shrubs, woody vines, and nonnative invasive species was estimated using seven cover classes (0–1 percent, 1–5 percent, 5–25 percent, 25–50 percent, 50–75 percent, 75–95 percent, 95–100 percent) and then converted to the midpoint of each class.

The plots were assigned to one of the three canopy conditions—EARLY, OPEN, or CLOSED—after examination of leaf-on imagery as described above. Photo-point monitoring of the FLN plots provides examples of these three canopy conditions and the pre-burn condition. Figure 4 shows an example of a plot that transitioned from a CLOSED-canopy before a prescribed fire to an EARLY-successional forest. Figure 5 shows a plot that transitioned from a CLOSED-canopy before a prescribed fire to an OPEN-canopy. Figure 6 shows an example of a plot that remained in CLOSED canopy conditions after fire.

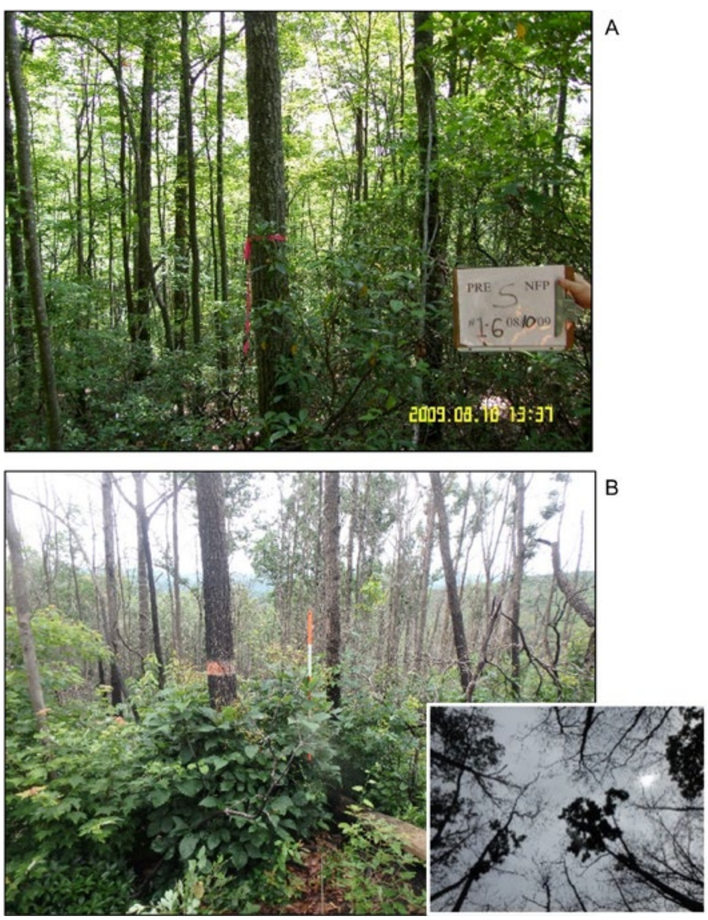

Figure 4.—Photo of a CLOSED canopy plot (A) that became EARLY successional after one burn (B) (North Fork Pound, plot 1-6). Note the overhead canopy gap photo inset in B.

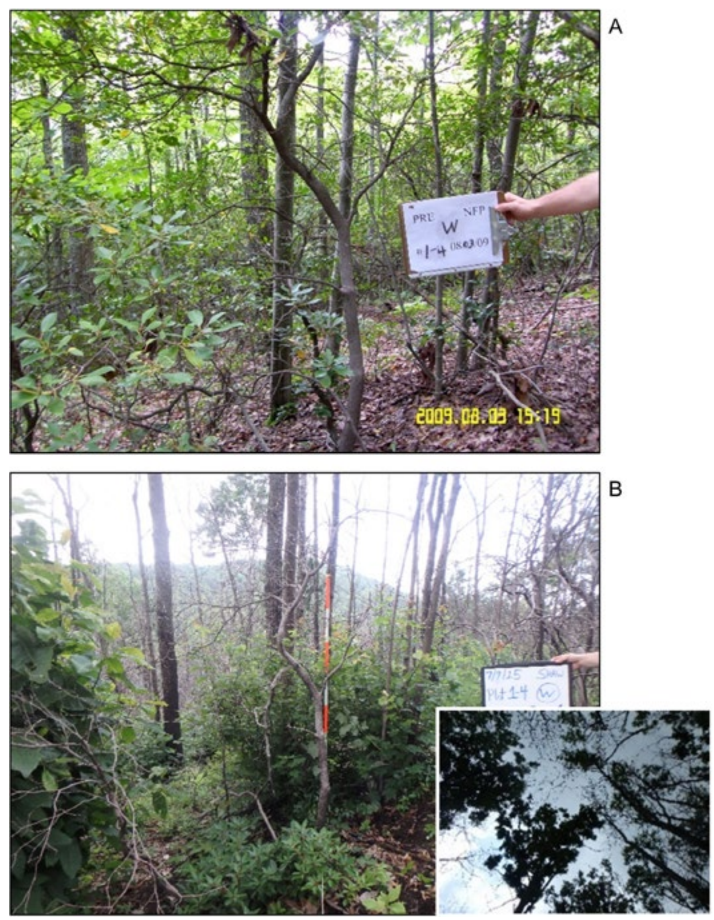

Figure 5.—Example of a CLOSED canopy plot (A) that became OPEN canopy after one burn (B) (North Fork Pound, plot 1-4). Note the overhead canopy gap photo inset in B.

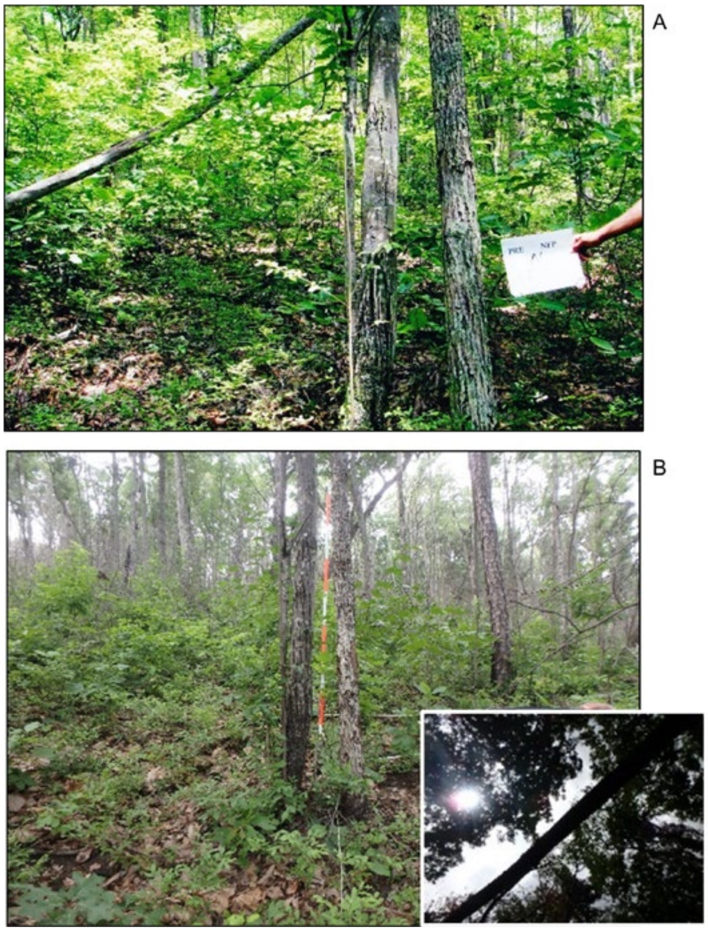

Figure 6.—Example of a CLOSED canopy plot (A) that remained CLOSED after one burn (B) (North Fork Pound, plot 2-2). Note the overhead canopy gap photo inset in B.

Analysis

To determine whether repeated burning had an effect on forest structure, we first calculated the percentage of the unit that was in an EARLY or OPEN condition after each successive burn. These percentages were averaged by burn history category (e.g., one burn, two burns, etc.), with each burn unit serving as an equally-weighted sample. We also calculated the mean and median gap size for EARLY and OPEN conditions by burn history category. All summary statistics and comparative tests were conducted using JMP® software (SAS 2013).

We conducted a means-separation test for percentage EARLY and percentage OPEN for all pairwise comparisons of burn history categories (e.g., one burn versus two burns). Due to unequal sample sizes among the categories, we used Tukey's Honestly Significant Different (HSD) test, which is a conservative test of means separation in this circumstance. Tukey's HSD test assumes a comparison of independent datasets, which is not completely accurate in this case; some burn units are found in several burn history categories (see Table 2).

In addition, we conducted a matched-pairs analysis, using only those burn units common to multiple burn history categories (Table 2). The inferential power of this approach is superior as it focuses on the same set of burn units, before and after a specific burn. We used a paired t-test to determine whether the post-burn percentages of EARLY and OPEN were different from pre-burn amounts.

Table 2.—Burn units used in canopy gap analysis, categorized by burn history

Burn history category	Number of units	Area (acres)	Units in common with 1 burn	Units in common with 2 burns	Units in common with 3 burns	Units in common with 4 burns
1 burn	58	69,707	all	24	6	1
2 burns	36	33,946		all	10	4
3 burns	15	14,204			all	7
4 burns	7	4,566				all

To determine whether the GIS-mapped canopy condition represented different on-the-ground conditions after one burn, we grouped the 80 FLN plots based on the three GIS-mapped conditions (EARLY, OPEN, or CLOSED) at plot center. We then calculated mean values for several common metrics of forest structure and conducted a means-separation test of all three canopy conditions. Due to unequal sample sizes among the categories, we used Tukey's HSD test.

To identify possible drivers of EARLY and OPEN creation after a first burn, we examined the effects of HLI, FSVeg forest type, and ecozone type on the amount of gap (EARLY or OPEN) formation. For the seven ecozones and six FSVeg forest type categories, we calculated the percentage of area in each unit that became EARLY and OPEN. Categories with less than 10 acres in a burn unit were omitted from the analysis.

For HLI, we conducted a simple polynomial regression of HLI and percentage of area in gaps (EARLY and OPEN combined) for units in the Northern Ridge and Valley section, testing for model significance and fit-of-model (SAS 2013). For FSVeg forest type and ecozones , we conducted an overall test for significance using a one-way ANOVA of the mean percentages of post-burn EARLY, OPEN, and EARLY+OPEN (SAS 2013). We also conducted a means-separation test on the categories of each variable using Tukey's HSD test.

RESULTS

Creation of Canopy Gaps

After a single burn, an average of 5 percent of the burn area was classified as EARLY and an average of 5 percent was classified as OPEN. There was large variability among burn units, ranging from 0 to 40 percent in EARLY and 0 to 34 percent in OPEN (Table 3 and Fig. 7). The maximum amount of combined EARLY and OPEN in an individual burn unit was 54 percent of the unit area. Mean gap size after one fire was 7 acres for EARLY and 5 acres for OPEN (Table 4). There was great variation in gap size for both canopy conditions although median gap sizes were the same at 3 acres for both EARLY and OPEN conditions. However, 91 percent of the area in EARLY gaps and 85 percent of the area in OPEN gaps occurred in gaps that were greater than or equal to their respective median gap size.

After two fires, an average of 9 percent of the burn area was classified as EARLY and 7 percent was classified as OPEN (Table 3, Fig. 7). Here again there was large variability among burn units, with the portion of EARLY conditions ranging from 0 to 52 percent, and a range of 0 to 24 classified as OPEN. The maximum amount of combined EARLY and OPEN in an individual unit was 64 percent of unit area. The mean size of gaps was 7 acres (EARLY) and 4 acres (OPEN) (Table 4). The median EARLY gap size was 2 acres with 92 percent of the gap acreage occurring in gaps greater than or equal to 2 acres and the median OPEN gap size was also 2 acres with 84 percent of gap area occurring in gaps greater than or equal to this.

Table 3.—Mean percentage (± one standard error) of burn unit area classified as EARLY canopy gaps, OPEN canopy gaps, and combined gaps, by burn history category. Means in a column followed by the same letter are not statistically different (Tukey's HSD, p=0.05).

Burn history category	Mean percentage EARLY ± SE (range)	Mean percentage OPEN ± SE (range)	Mean percentage ALL GAPS ± SE (range)
1 burn	5 ± 1 a (0–40)	5 ± 1 a (0–34)	11 ± 2 a (0–54)
2 burns	9 ± 2 ab (0–52)	7 ± 1 a (0–24)	16 ± 3 ab (0–64)
3 burns	17 ± 5 b (0–54)	9 ± 1 a (1–16)	26 ± 6 b (2–64)
4 burns	14 ± 7 ab (1–54)	8 ± 2 a (1–14)	22 ± 8 ab (8–64)

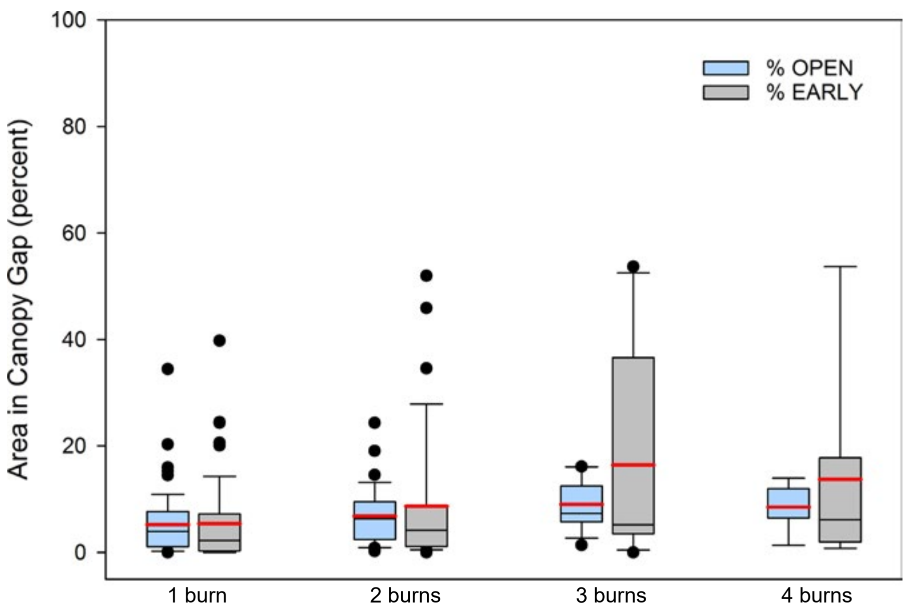

Figure 7.—Percentage of burn area in EARLY or OPEN gap formation after prescribed burning, by burn history category. The mean value of each burn/canopy combination is denoted by a red line, the black line is the median. The 90th and 10th percentiles are defined by the bars and dots represent outliers.

Table 4.—Attributes of EARLY canopy gaps and OPEN canopy gaps, by burn history category

	EARLY			OPEN		
Burn history category	Mean gap size (acres)	Median gap size (acres)	Percentage of gap acreage ≥ median gap size	Mean gap size (acres)	Median gap size (acres)	Percentage of gap acreage ≥ median gap size
1 burn	7	3	91	5	3	85
2 burns	7	2	92	4	2	84
3 burns	14	3	95	5	3	86
4 burns	8	2	94	5	3	84

Table 5.—Matched-pairs analysis of canopy gap formation within the same burn units. In each pairwise comparison, means (± one standard error) in a column followed by the same letter are not statistically different (paired t-test, p=0.05).

Burn history category	Total area (acres)	Mean percentage EARLY ± SE	Mean percentage OPEN ± SE
1 burn (n=24)	24,810	5 ± 2 a	5 ± 1 a
2 burns (n=24)		10 ± 3 b	6 ± 1 a
2 burns (n=10)	8,360	17 ± 6 a	8 ± 1 a
3 burns (n=10)		18 ± 6 b	9 ± 1 a
1 burn (n=6)	5,356	15 ± 7 a	10 ± 5 a
3 burns (n=6)		25 ± 10 a	9 ± 2 a

For units in the three-burn category, a mean of 17 percent of the area was classified as EARLY, with a range of 0 to 54 percent. Nine percent was categorized as OPEN conditions with a range of 1 to 16 percent (Table 3 and Fig. 7). The maximum amount of combined EARLY and OPEN in an individual unit was 64 percent of unit area. Mean gap size in EARLY was 14 acres and OPEN was 5 acres (Table 4). Median gap sizes in these units were 3 acres for EARLY and 3 acres for OPEN conditions, with 95 percent and 86 percent of gap acreage occurring in gaps greater than or equal to these respective medians (Table 4).

For the units in the four-burn category, the mean percentage of area in EARLY conditions was 14 percent with a range of 1 to 54 percent—similar to units in the three-burn category. An average of 8 percent of the area was classified as OPEN conditions, with a range of 1 to 14 percent, also similar to the three-burn category (Table 3 and Fig. 7). The maximum amount of combined EARLY and OPEN in an individual unit was 64 percent of unit acreage. Mean canopy gap sizes were smaller than the three-burn category for both EARLY (8 acres) and OPEN (5 acres) conditions (Table 4), although the means were not compared statistically due to the low number of units. Median gap size was similar to all burn classes at 2 acres for EARLY and 3 acres for OPEN, with 94 percent and 84 percent of the acreage within gaps greater than or equal to the respective medians (Table 4).

In the creation of EARLY canopy gaps, significantly more area was created with three burns than with a single burn; this was the only significant pairwise comparison (p=0.012). Mean EARLY gap size was also greatest in the three-burn category. There were no statistically significant differences for the creation of OPEN canopy gaps across burn categories, when examined as a percentage of the burn units (Table 3).

Changes in the area of EARLY and OPEN forest were sometimes seen between preburn and post-burn in units that were burned multiple times (matched pairs tracked through time) (Table 5). Following 23 burn units from post-first burn to post-second burn, the area of EARLY forest increased significantly (6 percent versus 10 percent of unit acreage, respectively), but the area of OPEN forest did not increase significantly (5 percent versus 6 percent of unit acreage, respectively). For the 10 burn units where conditions from post-second burn to post-third burn were compared, EARLY forest area increased significantly (17 percent versus 18 percent of unit acreage, respectively), but OPEN forest did not increase. No differences in EARLY or OPEN were seen for the six burn units from post-first burn to post-third burn. In this case, we think the small sample size and large variability overwhelmed any actual changes that occurred (Table 5).

Table 6.—Forest structure attributes 1 year after the first prescribed burn, by post-burn canopy condition, as determined using GIS methodology. Means (± one standard error) in the same row that are followed by the same letter are not statistically different (Tukey's HSD, p=0.05).

Sampling strata	Attribute	Canopy condition		
		EARLY (n=10)	OPEN (n=10)	CLOSED (n=60)
Overstory	Live basal area (ft^2/acre)	18 ± 6 a	56 ± 9 b	83±4 c
	Canopy cover (%)	26 ± 8 a	68± 7 b	87± 3 c
Mid-story	Live woody stems/acre (1–4 inch d.b.h.)	11 ± 11 ab	0 a	214± 37 b
Understory	Live woody stems/acre (<1 inch d.b.h. and >3.3 ft tall)	1,800 ± 392 a	2,180± 630 a	1,136± 243a
	Live woody stems/acre (0.5–3.3 ft tall)	170,758 ± 36,720 a	150,141 ± 35,749 a	47,535 ± 5,787 b
	Nonwoody vegetative cover (%) (<3.3 ft)	7 ± 3 a	1 ± 0.3 a	9 ± 3 a

Field Verification of Canopy Gap Structure

Field data collected 1 year after a burn verified the accuracy of GIS-mapped canopy conditions; mean forest structure metrics differed among plots considered EARLY, OPEN and CLOSED (Table 6). Basal area in EARLY plots averaged 18 ft^2/acre, OPEN plots averaged 56 ft^2/acre, and CLOSED plots averaged 83 ft^2/acre of basal area. Similarly, there are fewer stems per acre in the mid-story of the EARLY and OPEN plots than the CLOSED plots, with OPEN plots differing significantly from CLOSED (Table 6). However, because of high variability among burn units, differences between OPEN and EARLY were not statistically significant. Large numbers of live stems 0.5 to 3.3 feet tall were found in the understory of EARLY and OPEN plots, with more than three times the number of stems per acre of CLOSED plots (Table 6). The numbers of taller understory stems (less than 1 inch d.b.h.) were similar for all canopy conditions, but greater numbers were found in OPEN plots. Nonwoody vegetative cover did not vary by canopy condition, with values ranging from 1 to 9 percent.

Drivers of EARLY and OPEN Conditions

The creation of EARLY and OPEN canopy conditions described above pertains to all ecozone and FSVeg forest types combined. To begin determining drivers of canopy mortality from prescribed fire, we compared the creation of EARLY and OPEN canopy conditions by ecozone (Table 7 and Fig. 8) and by current FSVeg forest type (Table 8 and Fig. 9). Ecozone was statistically related to the area of combined EARLY and OPEN conditions (canopy gaps) found after the first prescribed burn in a burn unit ($p<0.0001$). The overall trend was greater area of canopy gaps created in more xeric ecozones (Table 7, Fig. 8). For instance, 22 percent of the dry pine/oak ecozone area was converted to a canopy gap (percentage of all gaps), while only 3 percent of cove area experienced sufficient canopy mortality to create canopy gaps. The percentage of canopy gaps in the dry pine/oak was statistically greater than all other categories except barrens (13 percent). When EARLY and OPEN conditions were considered

Table 7.—Mean percentage of area in EARLY and OPEN forest after one prescribed burn by ecozone. Means in the same column that are followed by the same letter are not statistically different (Tukey's HSD, p=0.05). Any ecozone group with <10 acres in a burn unit was omitted from the dataset.

Ecozone group	Mean percentage EARLY	Mean percentage OPEN	Mean percentage ALL GAPS
Barrens (n=15)	7 ab	6 abc	13 abc
Dry pine/oak (n=38)	14 b	9 c	22 c
Dry oak heath (n=59)	7 a	7 bc	14 b
Dry-mesic oak (n=57)	4 a	5 abc	9 ab
Mesic oak (n=48)	4 a	4 ab	8 ab
Cove (n=55)	2 a	1 a	3 a
Floodplains (n=18)	0 a	0 a	0 a

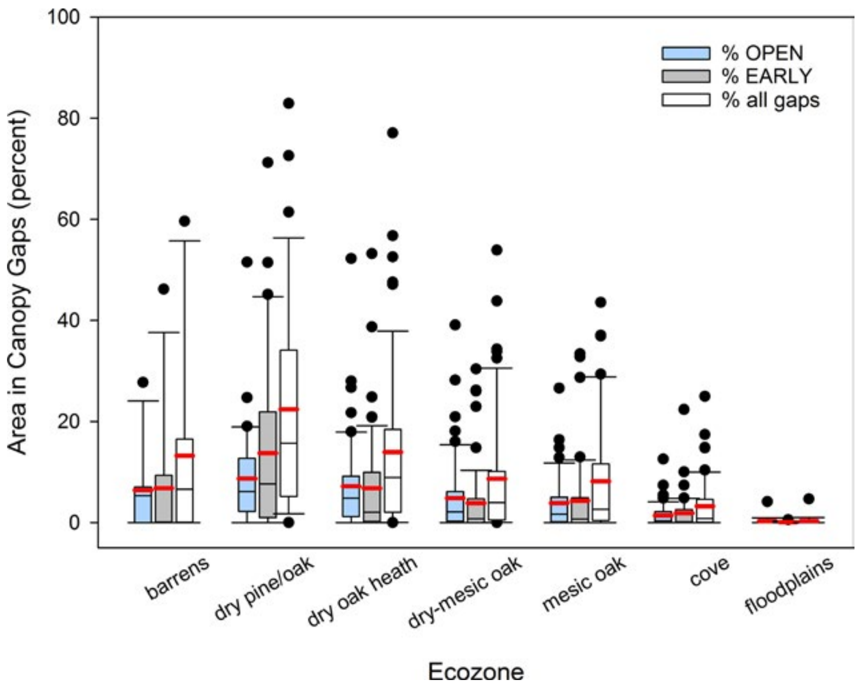

Figure 8.—Percentage of EARLY and OPEN canopy after one prescribed burn (n=59), by ecozone group. The mean value of each ecozone group/canopy combination is denoted by a red line, the black line is the median. The 90th and 10th percentiles are defined by the bars and dots represent outliers.

individually, the trends are similar for the combined gaps, although fewer of the means separation tests are significant.

FSVeg forest type was statistically related to the area of combined EARLY and OPEN conditions found after the first prescribed burn ($p< 0.0001$). Like the ecozones, greater areas of canopy gaps were created in the more xeric forest types (Table 8, Fig. 9). For instance, 22 percent of dry pine/oak acreage became a canopy gap, while only 5 percent of cove acreage became a canopy gap. The percentage of canopy gaps in dry pine/oak was statistically greater than all other categories except dry oak heath (14 percent). When EARLY and OPEN conditions were considered individually, these trends basically are the same, although fewer of the means separation tests are significant.

The topographic variable HLI was a strong predictor of the area of combined EARLY and OPEN conditions (canopy gaps) found after the first prescribed burn (Fig. 10). The percentage of area in canopy gaps increased with increasing HLI, best described by a quadratic model, which was significant and had an adjusted R-squared value of 0.939.

Table 8.—Mean percentage of total area in EARLY and OPEN forest after one prescribed burn by current FSVeg forest type. Means in the same column that are followed by the same letter are not statistically different (Tukey's HSD, p=0.05).

FSVeg forest type	Mean percentage EARLY	Mean percentage OPEN	Mean percentage ALL GAPS
Barrens (n=7)	0 b	1 ab	1 a
Dry pine/oak (n=31)	12 a	10 a	22 b
Dry oak heath (n=46)	9 ab	6 ab	14 ab
Dry-mesic oak (n=35)	4 b	5 ab	9 a
Mesic oak (n=57)	3 b	4 b	7 a
Cove (n=20)	2 b	3b	5 a

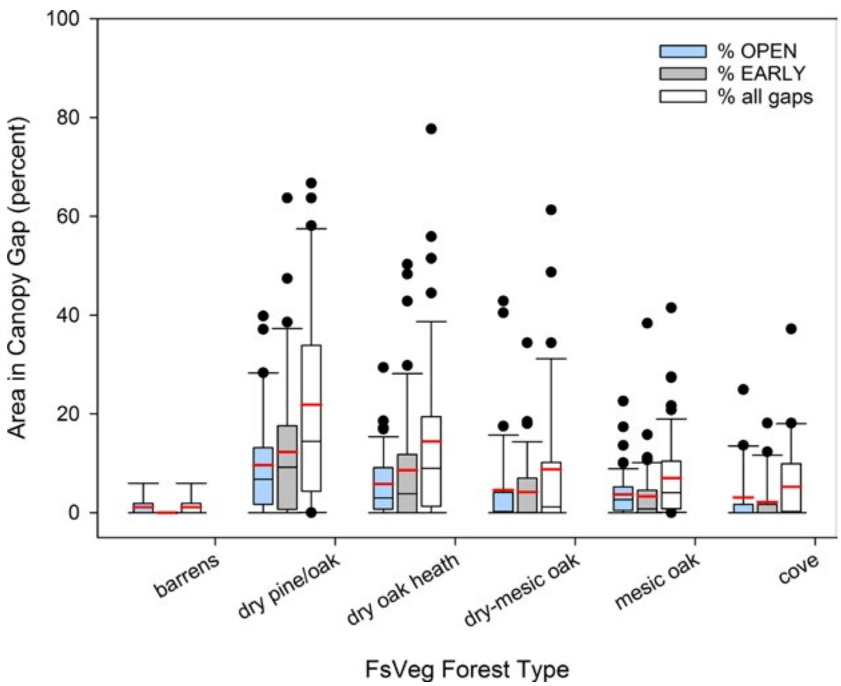

Figure 9. Percentage of EARLY and OPEN canopy forest in units after one prescribed burn (n=59), by FSVeg forest type (FSVeg group). The mean value of each FSVeg group/canopy combination is denoted by a red line, the black line is the median. The 90th and 10th percentiles are defined by the bars and dots represent outliers.

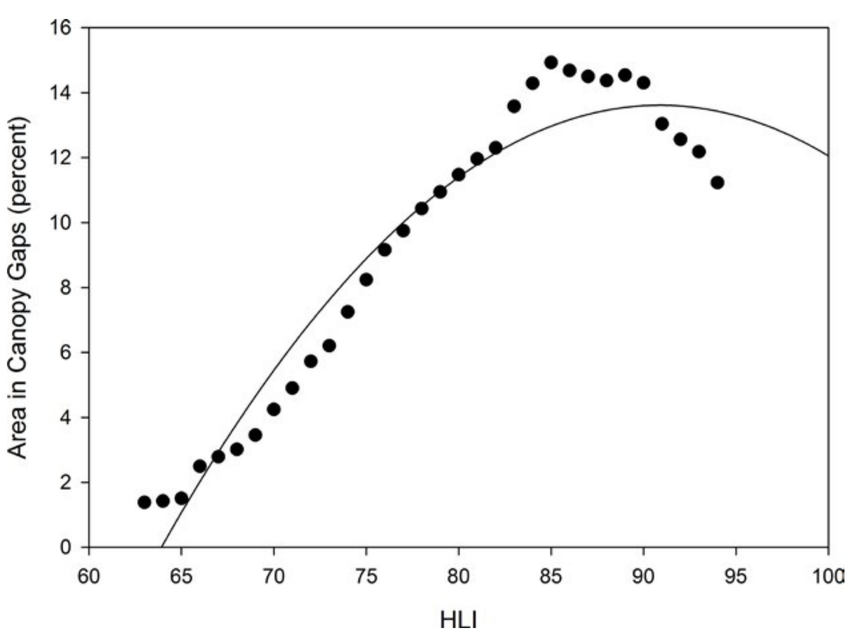

Figure 10.—The percentage of area in canopy gaps (dots) by heat load index (HLI), fit to a quadratic model (solid line). The relationship between the amounts of area in canopy gaps created after one burn across HLI, a measure of a sites' exposure, is linear to an inflection point and then stabilizes. The relationship was significant and had an adjusted R-squared value of 0.939.

DISCUSSION

Our primary goal was to quantify the scale of change displayed over many large prescribed burns that represent the modern burning program on the two national forests. This new landscape-scale dataset can inform monitoring and research on vegetation and wildlife in EARLY and OPEN habitat areas created by prescribed fire. In addition, this dataset is unique for the eastern oak and oak-pine forests and could be a source of information for other assessments and research into fire effects.

On average, these burn units have been moderately affected by fire, becoming more heterogeneous in terms of forest structure and age. Depending on the number of burns, an average 11 percent (1 burn category) to 26 percent (3 burns category) of the burn unit became newly-created EARLY and OPEN forest (Table 3). These new canopy gaps were also created at a biologically-meaningful scale: most gap acreage occurred in patches greater than 2 acres (Table 4). In these larger canopy gaps, the increase in light reaching the forest floor should create a mix of grasses, forbs, and shrubs, helping achieve ecosystem restoration and wildlife habitat goals, including early-successional habitat for many bird species (Harper et al. 2016). These gaps also appear suitable for regeneration of shade intolerant and intermediate tolerant species such as oaks. Silvicultural guidelines for group selection methods give a minimum size range for gaps as 0.1 to 0.6 acres, and caution that smaller gaps likely close quicker depending on site quality (Johnson et al. 2009). It should be noted that the range of results from individual burns was quite variable (see Figs. 8 and 9) and likely related to site-level factors such as fuel, weather, and ignition patterns. For example, the first burn of the Grindstone unit (in 2006) resulted in no visible canopy gaps, while the first burn of the nearby Hone Quarry unit (in 1999) resulted in 40 percent of its acreage becoming EARLY.

Our analysis also showed that repeated burning did not necessarily result in increasing amounts of canopy gaps. Considering only those units that could be tracked over multiple burns (Table 5), the area of OPEN forest did not increase after any additional burns. The amount of EARLY forest did increase from one to two burns and from two to three burns, but only slightly. Considering both canopy gap categories together (Table 3), units with one burn had a statistically equal percentage of area in canopy gaps compared to units with two or four burns (11 percent versus 16 and 22 percent, respectively). Comparing these results to the existing body of prescribed fire research is difficult, due to methodological differences. Our use of a landscape-scale assessment is quite different from the plot-based research being conducted in the region. Our approach was less quantitative, but more spatially extensive; we broadly categorized post-burn structure, but assessed over 85,000 acres.

Methodology aside, our results agree with much of the stand-level or plot-based assessments. The fire effects documented here can be characterized as low to mixed severity. A fire is considered to be low severity if less than 25 percent of the dominant vegetation is consumed or killed directly by fire; mixed severity fire effects are defined as 25–75 percent mortality of dominant vegetation (Hann et al. 2008). In Ohio, multiple prescribed fires had little effect on the density and basal area of larger trees (Hutchinson et al. 2005b), and similar results occurred after two prescribed fires in West Virginia (Schuler et al. 2013). In other stand-level assessments, prescribed fire had little impact of first-year survival however, delayed mortality of overstory trees was documented for 4 to 5 years after the prescribed fire or fires (Waldrop et al 2008, Yaussy and Waldrop 2010). Predictably, mortality was related d.b.h and bark thickness and trees with low vigor preburn were more likely to die within the 4 year study period (Yaussy and Waldrop 2010). Note that when making these comparisons the purposes of the prescribed fires and the burn unit sizes in our analysis were much different than most of the plot-level/stand-level studies. Much of the current research is on prescribed fire as a silvicultural tool to promote oak regeneration with fire intensities intentionally restrained (when possible) to minimize overstory mortality to retain timber value. Since the primary objectives here were to open the canopy, enhance light penetration, and increase ground flora cover and diversity, a greater range of fire intensities and effects was expected and encouraged because high-value timber products were not the objective.

Where gaps occurred, we saw clear relationships that made ecological sense: canopy gaps were created on hotter and drier sites more frequently than on cooler, wetter sites. Individually, three different variables that describe site characteristics (potential vegetation, current vegetation, and annual solar radiation [estimated by HLI]) were all significant in explaining patterns of canopy gap formation. However, the low incidence of gap formation in barrens (Figs. 5 and 6) is somewhat puzzling. One explanation is that barrens sites are so xeric that they have relatively low fuel loading and therefore fire intensity is lower than in the heath-dominated understory of the next-driest type of dry pine/oak. The topographic-based HLI metric had a strong correlation with the variation of canopy gap formation; when HLI was higher, so was the percentage of canopy gap creation.

Other researchers have found a similar association of increased HLI with an increase in fire severity (Arkle et al. 2012, Flatley et al. 2011, Holden et al. 2009, Wimberley and Reilly 2007). HLI as a measure of solar radiation a site receives has a known impact of species composition (Martin et al. 2011), likely impacts biomass and therefore fuels available, and fuel moisture content, influencing fire severity. HLI was found to be an important predictor of increased fire severity in models for the pinyon-juniper-oak community after a wildfire (Holden et al. 2009). In that semi-arid landscape, moisture controls the productivity of vegetation, influences forest composition, and fire severity (Holden et al. 2009). While our study area is broadly described as temperate and not semi-arid, very dry microsite conditions do occur on some landforms.

The relationship between HLI and fire severity does not explain all of the observed variability found in our study area. Some units have no canopy gaps despite having plentiful hot, dry microsites. More research into the multiple drivers of canopy gap formation after prescribed fire is needed. It is likely that human decisions about burning operations, such as ignition types and patterns, and fire weather conditions coupled with phenological stage of vegetation will be important variables. Also, extended drought cycles can influence how a forest responds to prescribed fire (Littell et al. 2016). We know that some first prescribed fire entries occurred either during or at the tail end of the drought cycle of the late 1990s or early 2000s.

Management Implications for GWNF and JNF

Even though these burns were mostly conducted under past forest plans, it is still useful to compare their impacts using metrics and goals from the revised GWNF Plan, as it incorporated the most current ideas on using prescribed fire in the Appalachians. The 2014 GWNF Plan describes several desired conditions based on forest structure and age and sets goals for each condition, measured as a percentage of the overall landscape. In reviewing our results, we asked a simple question: "Are prescribed fires creating the desired conditions in the same percentages as given in the forest plan goal?"

Our analysis shows that burning one to four times resulted in on average 5 to 17 percent of a burn unit becoming EARLY forest, which is comparable to the GWNF Plan goal (12 percent). A few individual units far exceeded the EARLY acreage goal, with a maximum observed value of 54 percent of unit area. Since the Plan goals apply at the landscape level and not at the individual burn unit, instances where EARLY habitat created in an individual unit were greater than the target should not be viewed as detrimental to achieving overall forest plan goals.

Prescribed fire has not yet created OPEN forest at target amounts sought by the GWNF Plan. Our results show that single prescribed fires did not create large amounts of OPEN forest (5 percent) and even four burns (8 percent) resulted in a landscape short of the GWNF Plan goal of 67 percent. The maximum observed value for OPEN forest was 34 percent of unit acreage.

While large amounts of OPEN forest were not detected after one to four burns, we urge caution in interpreting these results. Creating open-canopy forests through burning could be a more gradual process than creating early-successional habitat patches. Delayed post-burn mortality documented in the Appalachians shows fire's ability to influence overstory canopy over time (Waldrop et al. 2008), which could eventually result in open-canopy woodlands.

These findings should not be seen as a failure of prescribed fire to meet goals and objectives, but perhaps as a lesson in goal setting. The 67-percent goal for OPEN forest landscape may be too specific and unnecessarily ambitious (Hiers et al. 2016) for the intent of the prescribed fire program, which includes increasing light to the forest floor and subsequent changes in plant communities. Given the long-term absence of fire in these forests, this goal may take much longer to reach, perhaps as many years as the area has gone without fire.

We found that the footprint of EARLY and OPEN patches resulting from the first burn did not tend to expand greatly after subsequent burns. If more gaps did develop, they were EARLY, not OPEN (Table 5). The lack of new gaps in subsequent burns is perhaps due to a uniformity in how a unit was burned. Managers may be executing multiple burns on the same unit with the same ignition pattern or burn prescription. In units where the initial fire had only minimal effects to the canopy (but canopy effects were desired), it might be beneficial to consider a different prescription, including changing season of the burn, for subsequent burns.

The potential for undesired effects from prescribed fire in non-fire-adapted communities seems to be limited. Very little EARLY or OPEN forest was created after one prescribed fire in mesic oak, cove, and floodplain communities (Tables 7 and 8). Even though no measures were taken to exclude these communities from burning, fire severity was seemingly held in check by the sites' mesic conditions. Based on these results, expecting topography to moderate severe fire effects in these possibly sensitive areas would seem valid.

CONCLUSIONS

After examining almost every large-scale prescribed burn conducted on George Washington and Jefferson National Forests over the past two decades, we determined that prescribed burning consistently created the desirable conditions of OPEN and EARLY forest. However, multiple burns did not always result in increased amounts of these conditions and the creation of OPEN forest was less than the landscape-level goal in the GWNF Plan. The GIS-based methodology used here was validated by field data. Forest patches delineated as EARLY, OPEN, or CLOSED canopy were found to have very different structural attributes, at both the canopy and understory levels.

This difficulty in creating open-canopy conditions through prescribed fire alone has also been seen in other eastern oak-dominated forests where prescribed fire was used to promote oak reproduction (Brose et al. 2013; Holzmueller et al. 2014; Hutchinson et al. 2012a, 2012b; Iverson et al. 2008). This may mean that commercial or noncommercial thinning may be needed to meet the goals for open-canopy conditions (Waldrop et al. 2016). However, timber harvesting is not an option on 60 percent of GWNF and JNF acreage due to either management designations or unsuitable conditions (e.g., erodible soils, steep slopes). In many remote areas, prescribed fire may be the only tool available to land managers, so more information is needed on burning techniques that have a high probability for creating open-canopy conditions.

This analysis sheds light on the heterogeneous nature of the effects of large-scale prescribed fire in the central Appalachian oak and oak-pine forests. Further research is needed to determine the drivers of canopy gap formation and understand why fire severity patterns for individual burn units differ so greatly. While the likelihood of a wildfire starting at any given place or time is controlled largely by fuel characteristics (Falk et al. 2011), fire severity or intensity is controlled by topography (Falk et al. 2007) and the interactions of topography and vegetation (Birch et al. 2015). We expect that identifying the variables that control fire severity for prescribed fires on the GWNF and JNF will help land managers predict the impacts of prescribed fires and will aid in tactical decisions about burning individual units.

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APPENDIX 1

Canopy Gap Results for Burn Units

Table 9.—After one prescribed burn, burn units and canopy gap results, by area and as percentage of total area.

	Area (acres)				Percentage of Burn Unit		
Unit Name	EARLY	OPEN	CLOSED	Total	EARLY	OPEN	All GAPS
Back Valley	7	29	305	341	2	8	11
Big Branch	104	76	545	724	14	10	25
Big Cobbler	2	0	443	445	0	0	0
Big Wilson C	715	258	1,968	2,942	24	9	33
Big Wilson N	95	109	1,234	1,438	7	8	14
Big Wilson S	293	45	1,085	1,423	21	3	24
Brush Mtn	58	34	553	645	9	5	14
Brushy Ridge	50	63	608	721	7	9	16
Burns Creek	1	20	425	446	0	4	5
Cane Patch	0	0	743	743	0	0	0
Cole Mtn	0	1	1,052	1,053	0	0	0
Cub Run	356	246	2,784	3,385	11	7	18
Cubville	32	132	748	912	3	14	18
Dunkle Knob	15	20	663	698	2	3	5
Elkhorn	3	5	1,005	1,013	0	0	1
Ewing Mtn	35	45	612	692	5	7	12
Fenwick Mines	286	187	699	1,172	24	16	40
Flatwoods	57	146	1,307	1,511	4	10	13
Gauley Ridge	6	63	1,206	1,275	0	5	5
Glade Mtn	203	233	2,378	2,815	7	8	16
Glades	0	5	824	829	0	1	1
Grindstone	2	6	841	849	0	1	1
Gum Lick	37	60	622	718	5	8	13
Hall Spring	5	26	2,071	2,101	0	1	1
Heavener	12	29	983	1,024	1	3	4
Hone Qrry Spruc	0	23	1,426	1,449	0	2	2
Hone Qrry W	541	37	783	1,361	40	3	42
Jackson River	105	89	2,057	2,251	5	4	9
Lake Keokee	1	4	374	379	0	1	1
Little Fork	10	52	1,889	1,951	0	3	3
Little Neal	18	56	1,267	1,341	1	4	6
Little Schloss	191	316	1,050	1,557	12	20	33
Low Place	0	1	590	591	0	0	0
Mare Run	73	67	736	876	8	8	16
Middle Mtn	62	16	843	921	7	2	8
Mill Creek S	60	103	136	300	20	34	54
Mill Mountain	70	24	451	545	13	4	17
Mills Creek	16	41	319	377	4	11	15
Moody	1	1	255	257	0	0	1
Morris Hill	0	12	481	492	0	2	2
Neal Run	260	350	1,681	2,291	11	15	27
New Road Run	21	28	533	582	4	5	8

continued

Table 9.—continued

Unit Name	Area (acres) EARLY	OPEN	CLOSED	Total	Percentage of Burn Unit EARLY	OPEN	All GAPS
North Fork Pound	188	208	3,085	3,481	5	6	11
North New Road	41	47	4,274	4,362	1	1	2
North River	21	23	1,197	1,241	2	2	4
North Short Mtn	141	101	1,998	2,240	6	4	11
Patterson	14	20	2,216	2,250	1	1	2
Piney Mtn	90	95	985	1,170	8	8	16
Rocky Mtn	15	54	1,108	1,176	1	5	6
Round Mtn	3	9	1,442	1,454	0	1	1
Skegg Branch	42	39	731	811	5	5	10
Snake Den	64	25	606	696	9	4	13
Straight Fork	5	10	916	931	1	1	2
Tar Run	2	9	344	355	1	3	3
Tucker Gap	0	6	386	393	0	2	2
Upper Craig A	4	24	553	581	1	4	5
Upper Craig B	0	0	390	391	0	0	0
Wells Branch	31	18	692	741	4	2	7

Table 10.—After two prescribed burns, burn units and canopy gap results by area and as percentage of total area.

Unit Name	Area (acres) EARLY	OPEN	CLOSED	Total	Percentage of Burn Unit EARLY	OPEN	CLOSED
Beards Mtn	85	70	843	999	9	7	84
Brushy Knob	3	23	329	356	1	7	93
Elkhorn	9	12	992	1,013	1	1	98
Fenwick Mines	405	145	622	1,172	35	12	53
Flatwoods	57	146	1,307	1,511	4	10	87
Fore Mtn	40	242	987	1,268	3	19	78
Gauley ridge	12	78	1,185	1,275	1	6	93
Glades	16	13	799	829	2	2	96
Gum Lick	61	43	615	718	8	6	86
Hone Qrry Spruc	64	53	1,332	1,449	4	4	92
Hone Qrry W	625	92	644	1,361	46	7	47
Horse Heaven E	11	20	483	514	2	4	94
Horse Heaven W	9	29	521	559	2	5	93
Huff Hollow	78	131	1,292	1,502	5	9	86
Lake Keokee	2	7	370	379	1	2	98
Little Fork	91	109	1,751	1,951	5	6	90
Low Place	0	1	590	591	0	0	100
Mill Creek S	156	37	107	300	52	12	36
Mills Creek	91	40	246	377	24	11	65
Morris Hill		72	421	492	0	15	85
New Road Run	45	41	497	582	8	7	85
NFP Cane	3	4	436	444	1	1	98
NFP Laurel	81	117	283	481	17	24	59
NFP Phillips	50	62	382	494	10	13	77

continued

Table 10.—continued

Unit Name	Area (acres)				Percentage of Burn Unit		
	EARLY	OPEN	CLOSED	Total	EARLY	OPEN	CLOSED
North River	21	30	1,190	1,241	2	2	96
North Short Mtn	176	235	1,829	2,240	8	10	82
Patterson	20	72	2,160	2,251	1	3	96
Piney Mtn	293	96	781	1,170	25	8	67
Round Mtn	5	14	1,435	1,454	0	1	99
Short Mtn	45	65	1,461	1,571	3	4	93
Straight Fork	58	6	867	931	6	1	93
Tar Jacket	55	29	345	429	13	7	80
Tucker Gap	22	27	344	393	6	7	87
Upper Craig B	9	4	378	391	2	1	97
Walker Mtn	21	48	453	521	4	9	87
Wells Branch	35	19	687	741	5	3	93

Table 11.—After three prescribed burns, burn units and canopy gap results by area and as percentage of total area

Unit Name	Area (acres)				Percentage of Burn Unit		
	EARLY	OPEN	CLOSED	Total	EARLY	OPEN	CLOSED
Catback	130	149	1812	2,091	6	7	87
Evick Knob	13	45	277	335	4	13	83
Fenwick Mines	429	139	604	1,172	37	12	52
Hone Qrry Spruc	74	52	1,324	1,449	5	4	91
Hone Qrry W	658	76	627	1,361	48	6	46
Horse Heaven E	25	29	459	514	5	6	89
Horse Heaven W	10	32	517	559	2	6	92
Huff Hollow	78	176	1,248	1,502	5	12	83
Indian Grave	3	5	331	338	1	1	98
Mill Creek S	161	32	107	300	54	11	36
Morris Hill	0	79	413	492	0	16	84
New Road Run	47	38	497	582	8	7	85
Orebank	69	125	1767	1,961	4	6	90
Second Mtn	579	180	361	1,119	52	16	32
Tar Jacket	73	53	302	429	17	12	70

Table 12.—After four prescribed burns, burn units and canopy gap results by area and as percentage of total

Unit Name	Area (acres)				Percent of Burn Unit		
	EARLY	OPEN	CLOSED	Total	EARLY	OPEN	CLOSED
Catback Mtn	239	135	1,717	2,091	11	6	82
Evick Knob	15	47	274	335	4	14	82
Indian Grave	3	5	331	338	1	1	98
Mill Creek S	161	32	107	300	54	11	36
Tar Jacket	76	51	301	429	18	12	70
Horse Heaven W	11	37	512	559	2	7	92
Horse Heaven E	32	44	438	514	6	8	85

APPENDIX 2

Ecological Zones

Table 13.—Descriptions and area of ecological zones (ecozones) in the George Washington National Forest (GWNF) and Jefferson National Forest (JNF) (Simon 2011, 2013)

	Group	Ecozones (GWNF model)	Ecozones (JNF model)	Area (acres)
Low	Barrens	Alkaline woodlands, shale barrens, mafic glade and barrens	Shale barrens, pine-oak shale, acid glade, limestone-dolomite barrens	1,675
	Dry pine/oak	Low elevation pine, pine-oak heath, pine-oak shale woodlands	Shortleaf pine-oak, pine-oak heath	7,326
	Dry oak heath	Dry oak evergreen heath, dry oak deciduous heath	Dry oak evergreen heath, dry oak deciduous heath, dry calcareous forest	20,266
Site Productivity Site Moisture	Dry-mesic oak	High-elevation red oak, dry mesic oak, dry mesic calcareous forest	High-elevation red oak, dry mesic oak, dry mesic calcareous forest	16,460
	Mesic oak	Colluvial forest, montane oak-hickory slope, montane oak-hickory cove, montane oak-hickory (rich)	Colluvial forest, montane oak-hickory slope, montane oak-hickory cove, montane oak-hickory (rich)	14,605
	Cove	Northern hardwood slope, northern hardwood cove, acidic cove, rich cove	Northern hardwood slope, northern hardwood cove, acidic cove, rich cove , mixed oak-rhododendron, rich slope	12,051
High	Floodplains	Alluvial forest, floodplain forest	Alluvial forest, floodplain forest	771
	Total			73,154

APPENDIX 3

Field Sampled Vegetation (FSVeg)

Table 14.—Description and area of FSVeg forest types

	Group	FSVeg forest type	Area (acres)
Low	Barrens	Black locust, brush species	328
	Dry pine/oak	Pitch pine-oak, Virginia pine-oak, Table Mountain pine-hardwood, shortleaf pine, Virginia pine, pitch pine, Table Mountain pine	6,081
Site Productivity Site Moisture	Dry oak heath	Chestnut oak-scarlet oak-yellow pine , white oak-black oak-yellow pine, bear oak-southern scrub oak-yellow pine, post oak-black oak, chestnut oak, scrub oak, scarlet oak, chestnut oak-scarlet oak	21,736
	Dry-mesic oak	White pine-upland hardwood, upland hardwoods-white pine, northern red oak-hickory-yellow pine, white oak, northern red oak, chestnut oak-white oak-scarlet oak	3,900
	Mesic oak	White oak-northern red oak-hickory, yellow-poplar-white oak-northern red oak	32,616
High	Cove	White pine-hemlock, hemlock, hemlock-hardwood, white pine-cove hardwood, cove hardwoods-white pine-hemlock, bottomland hardwood-yellow pine, yellow-poplar, sweetgum-yellow-poplar, sugar maple-beech-yellow birch	1,515
	Total		66,176

Lorber, Jean; Thomas-Van Gundy, Melissa; Croy, Steve. 2018. **Characterizing effects of prescribed fire on forest canopy cover in the George Washington and Jefferson National Forests.** Research Paper NRS-31. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p. https://doi.org/10.2737/NRS-RP-31.

On the George Washington and Jefferson National Forests, managers have used prescribed fire to create and maintain early-successional and open forest conditions across large areas. We used a landscape-scale and image-based approach to assess the extent that prescribed fires, including repeated fires, have created these forest conditions and put the results in context of the new George Washington National Forest management plan. At the landscape level, early-successional forest made up an average of 5 percent of burn unit area after one burn, 9 percent after two fires, 17 percent after three fires, and 14 percent after four fires. On average across all burn unit acreage, open forest made up 5 percent of the area after one burn, 7 percent after two burns, 9 percent after three, and 8 percent after four fires. The forest plan desired condition of 12 percent of the area in early-successional forest was met after three or four fires and was exceeded in some individual burn units. It is harder to achieve open-forest than early-successional conditions using prescribed fire alone. We also examined possible drivers of canopy gap creation in these forests. Vegetation type and heat load index, a topographic-based measure of solar radiation received by a site, were important predictors of where canopy gaps formed after prescribed fire.

KEY WORDS: overstory mortality, fire severity, landscape-scale fire, canopy cover

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