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Changes in canopy cover and forest structure following dormant season and early growing season prescribed burns in the Southern Appalachians, USA

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Abstract

Background Fire seasonality is important for forest managers to consider when restoring historical disturbance regimes and recovering native ecosystem structure and composition, but it is less understood and less frequently studied than other aspects of fire ecology. In the Southern Appalachians, historical fires likely occurred most often in late spring and early summer when fuels were dry and canopy conditions were conducive to fire; however, most prescribed fires today occur during the dormant season (January–March). Because fire behavior can vary seasonally, it is important for forest managers to understand the practical applications of fire season in order to burn at a time that meets management objectives. Therefore, we investigated the effect of fire seasonality on forest structure and land cover diversity in the Southern Appalachians.

Results Using a complete randomized block design, we analyzed leaf-on canopy cover imagery with ArcGIS Pro to compare canopy cover and forest structure between growing and dormant season burns. We compared imagery between three blocks, each with an unburned control unit, dormant season burn, and growing season burn, and found an average of 8.84% (SE = ± 1.46) reduction in canopy cover in growing season treatment units from pre-burn (2017) to post-burn (2019) compared to 5.21% (SE = ± 1.51) reduction in dormant season treatment units and 0.01% (SE = ± 0.009) reduction in unburned controls. Canopy cover reductions corresponded with substantial increases in early- and mid-successional habitat, edge length, and land cover diversity — especially in growing season burn treatment units.

Conclusions Our results indicate that early growing season burns are more effective than dormant season burns at enhancing forest structural heterogeneity. Early growing season burns, therefore, may be a viable option for forest managers looking to expand their burn season and achieve restoration and management goals faster than traditional dormant season burns.

Keywords Burn seasonality, Ecological restoration, Prescribed fire, Structural diversity, Wildlife habitat

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Resumen

Antecedentes La estacionalidad del fuego es importante de considerar por parte de los gestores forestales cuando se restauran los regímenes históricos de disturbios y se recupera la estructura y composición de los ecosistemas nativos. Sin embargo, esta estacionalidad se entiende poco y es poco estudiada en relación a otros aspectos de la ecología del fuego. En los Apalaches del Sur, los fuegos históricos ocurrían más frecuentemente en la primavera tardía y en el verano temprano, cuando los combustibles estaban secos y las condiciones del dosel eran propicias para el fuego. Sin embargo hoy, la mayoría de las quemas prescriptas se realizan durante la estación de reposo (enero – marzo). Dado que el comportamiento del fuego puede variar estacionalmente, es importante para los gestores forestales comprender las aplicaciones prácticas de las quemas en las distintas estaciones, de manera de quemar en momentos que permitan lograrse metas de manejo. Con ese objetivo, investigamos el efecto de la estacionalidad del fuego en la estructura de los bosques y en la diversidad de la cobertura del suelo en los Apalaches del Sur.

Resultados Utilizando un diseño de bloques completos al azar, analizamos imágenes de las hojas en la cobertura del dosel con ArcGIS-Pro para comparar la cobertura del dosel y la estructura del bosque entre quemas realizadas en la estación de crecimiento y en la de reposo. Comparamos las imágenes entre tres bloques, cada uno con una unidad de control sin quemar, una quema en la estación de reposo y una quema en la estación de crecimiento, y encontramos un promedio de 8,84% (ES = ± 1,46) en la reducción de la cobertura del dosel en la estación de crecimiento en unidades de tratamiento de pre-quema (2017) hasta post-quema (2019) comparado con una reducción del 5,21% (ES = ± 1,51) en tratamientos en la estación de reposo y 0,01% (ES = ± 0,009) de reducción en los controles sin quemar. La reducción de la cobertura del dosel se correspondió con incrementos sustanciales en hábitats con sucesiones tempranas y medias, longitud de los bordes, y diversidad en la cobertura del suelo-, especialmente en las unidades de tratamiento de quemas en la estación de crecimiento.

Conclusiones Nuestros resultados indican que las quemas en la estación de crecimiento temprana son más efectivas que las quemas en la estación de reposo, ya que mejoran la heterogeneidad estructural del bosque. Las quemas en la estación temprana, por lo tanto, pueden ser una opción viable para los gestores forestales que buscan expandir la época de quemas y lograr objetivos de restauración y manejo más rápidamente que los obtenidos mediante las quemas tradicionales en la estación de reposo.

Background

The structure and composition of much of the forested southeastern USA was shaped and defined by varying degrees of fire. Prior to human settlement in the region, lightning-caused fires occurred sporadically during the spring and summer months when conditions were conducive to ignition via lightning strikes (Knapp et al. 2009). After indigenous people migrated to the Southeast ~ 10,000 years ago, they began the practice of setting intentional fires to promote open forest conditions that would benefit grazing animals such as bison, elk, and deer (Van Lear and Waldrop 1989). In some places, native people even increased the fire frequency, resulting in a heterogeneous landscape that was host to a wide variety of habitat types ranging from pine to mixed oak and pine, to mixed oak hardwood stands (Nowacki and Abrams 2008). Some habitat types burned more frequently than others, depending on physiographic region, topography, and species composition, but areas with high levels of fire tolerant oaks and pines likely burned at least every 6–8 years while other regions with fewer fire tolerant species burned infrequently or not at all (Delcourt and Delcourt 1987; Lafon et al. 2017). Along the southern Blue Ridge escarpment of the Southern Appalachians, ecosystems were mainly oak/pine dominated forests with several species that had adapted to a frequent fire regime and were able to either survive fire, like the Table Mountain Pine (*Pinus pungens* L.), or quickly re-establish after fire had occurred (Lafon et al. 2017). When European settlers moved to the region they adapted the use of fire, maintaining and increasing the fire frequency of the Southeast.

Over time, settlers in the Southern Appalachians also introduced the practice of large-scale, unregulated logging, primarily for timber production but also to create more open agricultural land and to provide fuel (Ryan et al. 2013). The slash leftover from logging led to fuel build up that caused fire frequency and severity to increase (Flatley et al. 2013). Negative views of fire grew throughout the early 20th century, prompted by the increase in wildfires across North America, and caused the newly created US Forest Service to adopt an official policy of fire suppression beginning in the 1920s (Van Lear and Waldrop 1989). This policy halted the traditional disturbance regime of the region, resulting in widespread changes in forest composition and structure (Abrams 2005).

In the eastern USA, a primary result of the fire exclusion of the last century has been “mesophication,” which is defined as a positive feedback loop where "micro-environmental conditions (cool, damp, and shaded conditions; less flammable fuel beds) continually improve for shade-tolerant mesophytic species and deteriorate for shade-intolerant, fire-adapted species" (Nowacki and Abrams 2008). In the Southern Appalachians, mesophication results in the degradation or loss of critical oak/pine ecosystems, which were generally diverse in forest stand age and species composition, had higher densities of dead trees and tree snags than unburned sites, and had rich understory diversity (Schulte and Niemi 1998; Alexander et al. 2021). In the absence of fire, ecosystems are altered as species like red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), and blackgum (*Nyssa sylvatica* M.), become more abundant within the ecosystem (Hanberry and Nowacki 2016; Lafon et al. 2017) by outcompeting oaks and preventing the growth of shade intolerant pines once mature. The loss of fire contributes to homogenization in stand structure and age (Greene et al. 2016). As the effects of fire suppression have been increasingly documented and studied, forest managers in recent years have begun implementing prescribed fires to reduce fuels, restore historical disturbance regimes, and enhance landscape heterogeneity (Ryan et al. 2013).

Restoring historical disturbance regimes and re-implementing fire as a management tool has proven to be useful in creating canopy gaps (Lorber et al. 2018), promoting the re-growth of shade-intolerant, fire-tolerant species, increasing the density of tree snags and dead trees, and increasing wildlife diversity (Harper et al. 2016; Izbicki et al. 2020; Rosche et al. 2021). Canopy cover may therefore be a critical feature in restoring forest heterogeneity. Specifically, creating early and open canopy conditions, defined by Lorber et al. (2018) as early successional (< 30% canopy cover) and mid to late successional open habitat (30–60% canopy cover), while reducing closed canopy (> 60% canopy cover) conditions may be important for a variety of floral and faunal species in the Southern Appalachians. However, much is still unknown about the practical applications of fire to meet management objectives. Fire seasonality, or the time of year a fire is set, is one aspect of fire ecology that is particularly under-researched.

Historically, fires likely occurred during both the growing season (e.g., during spring and summer when vegetation is opening buds or in leaf) and the dormant season (e.g., during the winter when vegetation is not putting out new growth). Lightning caused fires likely occurred mostly in the late spring and early summer, when conditions were drier and more conducive to ignition, while human caused fires probably occurred mostly in the fall, winter, or early spring (Knapp et al. 2009). Today, managers burn primarily in the dormant season, mostly to prevent the likelihood of fire escaping and causing wildfires, but also because studies on fire seasonality and how it affects habitat and/or wildlife are more limited than other aspects of fire ecology, like intensity or severity (Knapp et al. 2009).However, research has suggested that growing season burns may be more effective than dormant season burrns for promote historical structural diversity within this region (Sparks et al. 2002). However, there is a need for further research on the effects of burn seasonality on forest structure.

An improved understanding of how fire seasonality influences ecosystem heterogeneity could be important in creating and implementing effective forest management strategies throughout the year. Forest managers would benefit from increased knowledge on burn seasonality, so they can schedule burns in a season that would best meet their management objectives. Understanding how season of burn influences forest heterogeneity will also be important as scientists and managers work to restore fire adapted plant communities.

For this study, we used the National Agricultural Imagery Program's (NAIP) 'leaf on' imagery, in unburned control stands and stands burned in the dormant and early growing season, to answer the following questions:

1. Using canopy gaps as an indicator of forest heterogeneity, how does reduction of canopy closure differ by season of burn?
2. How does land cover diversity (amount and evenness of early, open, and closed canopy) differ by season of burn?
3. Does season of burn influence the amount of available edge habitat?

For question #1, we hypothesized that greater variability in fire behavior — as reported in a companion study (Vaughan et al. 2021) — would result in an greater variability in vegetation impacts (i.e. an increase in forest heterogeneity). Under this hypothesis, we predict that growing season burns will be more effective at reducing canopy closure and creating early successional and open canopy conditions compared to dormant season burns. For question #2, we hypothesized that reductions in canopy cover/promotion of early and open canopy conditions in early growing season burns would positively influence the heterogeneity of these units. Under this hypothesis, we predict that growing season burns will have greater land cover diversity compared to dormant season burns. For question #3, we hypothesized that greater total areas of early and open canopy conditions and higher levels of land cover diversity in growing season burns would positively influence the amount of edge habitat. Under this hypothesis, we predict that growing season burns will have greater total amount of edge habitat compared to dormant season burns. Knowledge obtained from these analyses can then be applied to guide management decisions for prescribed fire use in the Southern Appalachians, by understanding how season of burn influences key habitat components.

Methods

Study area

We conducted this study on public land managed by the US Forest Service in the southeastern USA across the Southern Blue Ride Escarpment of the Southern Appalachian Mountains. Treatment replicates used within the study were in the Chattooga River Ranger District (CR) of the Chattahoochee National Forest in Rabun and Stephens Counties, Georgia, and the Andrew Pickens Ranger District (AP) of the Sumter National Forest in Oconee County, South Carolina. Within this region, dominant ecological zones include Dry-Mesic Oak-Hickory Forests, Shortleaf Pine-Oak Forests and Woodlands, Mixed Oak/Rhododendron Forest, and Montane Oak-Hickory Forest. Variation in topography and elevation among and within units lead to a wide range in vegetation types in this study, but forest cover within treatment units consisted primarily of oaks (i.e., *Quercus alba* L., *Q. rubra* L.), hickories (i.e., *Carya glabra* M., *C. tomentosa* M.), and pines (i.e., *Pinus strobus* L.) in combination with significant encroachment from mesophytic hardwoods and ericaceous shrubs. Species like red maple (*Acer rubrum* L.), blackgum (*Nyssa sylvatica* M.), mountain laurel (*Kalmia latifolia* L.), and rhododendron (*Rhododendron maximum* L.) were often dense in the lower over-story and midstory, leading to a sparse or bare understory in most units. Where it existed, understory cover consisted primarily of ferns, grasses, various species of broadleaved forbs, and seedlings of mesophytic tree species.

Prescribed burns were implemented by the US Forest Service in coordination with Clemson University for a previous study (Vaughan et al. 2021, 2022) in either 2018 or 2019 (Appendix 1). Dormant season burns occurred between January 31 and April 5 and were defined as burns that took place before tree buds began to break dormancy. Early growing season burns occurred between April 18 and April 26 and were defined as burns that took place after bud break but before complete leaf-out. All were first-entry burns, meaning they were the first prescribed fires conducted in those units in recent history. Additional growing season burns were implemented in April 2021 in the two blocks located in the Andrew Pickens Ranger District (AP1 and AP2). Burns were set using various methods, including hand ignition using drip torches and aerial ignition using delayed aerial ignition devices from helicopters. A spot-fire technique was used for hand ignitions to simulate aerial ignition.

Study design

We conducted this study as a randomized block design, with three treatments (dormant season burn, growing season burn, unburned control) each replicated three times. Two replicates occurred in the AP District and one replicate occurred in the CR District, and one additional stand-alone dormant season burn occurred in the CR District for a total of ten treatment units (Fig. 1). To compare forest structure between dormant and growing season burns, we analyzed leaf-on imagery from the U.S. Department of Agriculture's National Agricultural Imagery Program (NAIP) from both pre-burn (2017) and one or two years post burn (2019) using ArcGIS Pro (2021). Analysis of canopy cover and designation of forest categorizations was based on a similar study conducted by Lorber et al. (2018).

In each unit, we hand-digitized areas of early and open canopy conditions in pre-burn (2017) and post-burn (2019), based on the amount of visible canopy cover and adapted from Lorber et al. (2018). All areas not visually distinct as early or open were defined as closed and were not digitized. We included areas of early and open conditions in post-burn imagery only when it was clear that these conditions did not exist prior to the first burn, and areas of early and open conditions from pre-burn imagery were only included in the analysis on canopy cover reduction. For all other analyses, we excluded pre-burn areas of early and open so as to ensure that the forest structure from 2019 imagery was the result of burning. After delineating these conditions in the entire unit, we then created 30, 1.21 ha polygons (based on the average area of early and open conditions across all units), in each unit as a means of sampling change to habitat structure across treatment units. AP2 growing unit was an exception to this design, as its small size only allowed for 15 polygons. We placed each polygon randomly throughout the unit using the Create Random Point, Buffer, and Buffer to Feature Envelope tools in ArcGIS Pro. Some polygons were adjusted after random placement to avoid overlap with neighboring polygons. After placement, the total area of early, open, and closed conditions within each polygon were totaled. To reduce bias, all units were hand-digitized at 1:5000 zoom by the same observer.

Data analysis

We compared the effectiveness of burn seasonality in reducing canopy cover and creating more open and early successional habitat by conducting a one-way analysis of variance (ANOVA) using the aov() function in the *R*

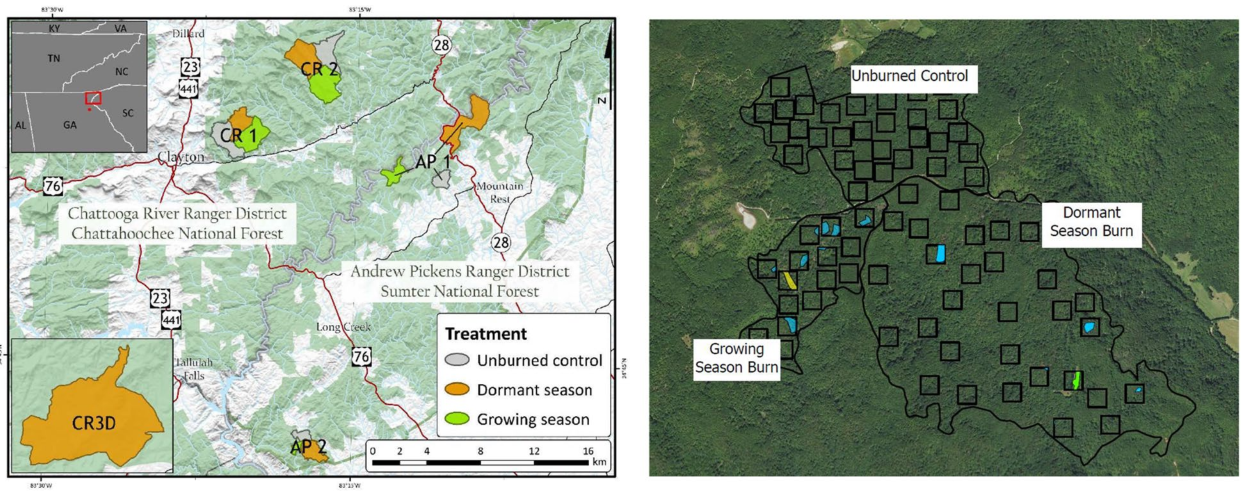

Fig. 1 Left: map showing the three blocks, each comprised of the three treatment units (with the additional stand-alone dormant burn) with "AP" referring to the Andrew Pickens Ranger District and "CR" referring to the Chattooga River Ranger District. Right: map of AP2 control, growing, and dormant treatment units generated via NAIP Imagery and analyzed on ArcGIS Pro. Blue areas represent open canopy, or mid-successional open habitat (30–60% canopy cover), and yellow areas represent early canopy, or early successional habitat (< 30% canopy cover). Areas not indicated by yellow or blue polygons represent closed canopy (> 60% canopy cover), with the exception of areas that contained open or early canopy prior to burning (green polygon in the dormant season unit)

Stats Package (R Core Team 2013) in R (R Team 2021). We used this function to compare the percent decrease in closed canopy conditions among our dormant season burn units, growing season burn units, and unburned control units from 2017 (pre-burn) to 2019 (post-burn). We chose to analyze the percent decrease in closed canopy rather than the percent increase in early or open canopy conditions so we could see the effectiveness of the burns in reducing canopy cover overall, as well as because most plots analyzed started with no early or open canopy conditions and therefore, we could not compute percent change. In order to pin-point more specific differences between the treatment types in reduction of canopy cover, we then ran an additional ANOVA on the change in total area of open canopy post-burn. We chose to analyze open rather than early or both categories because early conditions were more tightly correlated with the decrease in canopy cover, and because this category is most heavily zero-inflated and therefore more challenging to meet the assumption of normality even when the data were transformed. Additionally, when analyzed in combination with the percent decrease of canopy cover, analyzing the total area of open canopy gave us insight to the complete forest structure, including early canopy conditions.

We then compared forest heterogeneity between treatment units using the Shannon-Weiner Diversity Index, using total area of early, open, and closed in each 1.21 ha subplot in place of species and abundance. We chose the Shannon-Weiner Index because it is commonly used to assess land cover diversity (Antwi et al. 2008). We calculated the diversity index for each of the 30 plots in all ten treatment units in Microsoft Excel, and then compared diversity between treatments using a one-way ANOVA in R. Additionally, we compared the amount of edge habitat (length of delineated early and open polygons) between treatment types. For all analyses, where results were significant, we ran a Tukey's Honestly Significant Difference Test to determine where differences in means occurred. We assumed all 1.21 ha plots were independent of each other and assumed to have equal variance, and we checked the distributions of our dependent variables for normality. To meet the assumption of normality, we transformed our canopy cover data using a cube-root transformation, and assumed our data was robust to a small violation of normality. We evaluated the null hypothesis (that changes in canopy cover or landscape diversity did not differ among treatments) at $\alpha = 0.05$.

Results

Canopy cover

Prior to the first burn, most units had no discernable canopy gaps when analyzed at the 1:5000 scale. Exceptions to this were mainly limited to clear cuts and/or rock outcrops and were generally less than 3% of the total unit area. The total area of subplots analyzed within each unit was 36.45 hectares (ha), totaling in 109.35 ha for each treatment type, except dormant treatments which had an additional unit resulting in a total of 145.8 ha analyzed (Fig. 1). Results of the one-way ANOVA on percent decrease in closed canopy conditions between pre-burn and post-burn imagery indicated that treatment type had a significant effect on canopy cover (Table 1). The average percent decrease in closed canopy conditions was highest overall in growing season treatment plots (Fig. 2). Similarly, the analysis on the total area of open conditions created by the fire indicated a significant influence of treatment type in creating mid-successional open canopy conditions (Table 1). Growing season treatment units had an average of 0.053 ha of open canopy conditions in each subplot following the burn treatment compared to 0.015 ha in dormant season burn units and < 0.001 ha in unburned controls. In many instances, areas of early canopy were within large continuous patches combined with open canopy, while open canopy was also likely to be found by itself in small, scattered patches. The percent of the total area of our treatment units represented by open canopy conditions was highest in growing season treatment units, while the percent of total area represented by early canopy conditions was highest in dormant season treatment units (Fig. 3), which might be attributed to the single dormant season burn in our CR2 District. This burn took place in early April and had a much higher recorded intensity compared to our other dormant season burns, which could have contributed to greater fuel consumption.

Table 1 Summary of statistics from one-way analyses of variance on canopy cover changes by treatment type (unburned control, dormant season burn, or early growing season burn). Based on leaf-on imagery from the Chattooga River and Andrew Pickens Ranger Districts analyzed on ArcGIS Pro

Analysis	DF	Sum sq.	Mean sq.	*F* value	*P*(> *F*)
% decrease closed	2	41.85	20.924	20.18	< 0.001
Total area (ha) open	2	1.682	0.841	26.07	< 0.001
Landcover diversity	2	4.64	2.318	17.3	< 0.001
Edge length (m)	2	189.4	94.72	21.86	< 0.001

Land cover diversity and edge habitat

Results of the one-way ANOVA comparing landscape diversity indicated a significant effect of burn treatment on the total amount and distribution of early, open, and closed canopy conditions between units using the Shannon-Weiner diversity index (Fig. 4). The mean land cover diversity from treatment subplots was lowest in the unburned control units, averaging at 0.006, compared to 0.07 in dormant season burn units, and was highest in growing season burn units at 0.32. Treatment type also had a significant effect on the total length of edge habitat

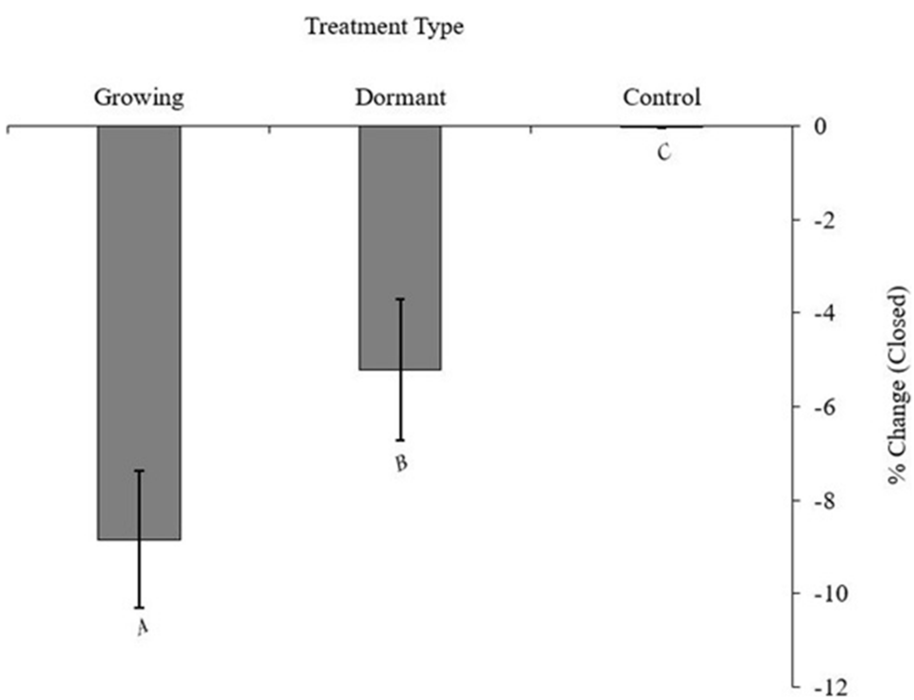

Fig. 2 Average percent decrease in closed canopy conditions (> 60% canopy cover) from pre-burn (2017) to post-burn (2019) across all 3-acre subplots in control, dormant, and growing treatment units from the Chattooga River Ranger District and the Andrew Pickens Ranger District. Error bars represent the standard error of the mean. Canopy cover hand digitized using US Department of Agriculture NAIP imagery at a 1:5000 level scale in ArcGIS Pro. Letters represent where significant (< 0.05) differences occurred

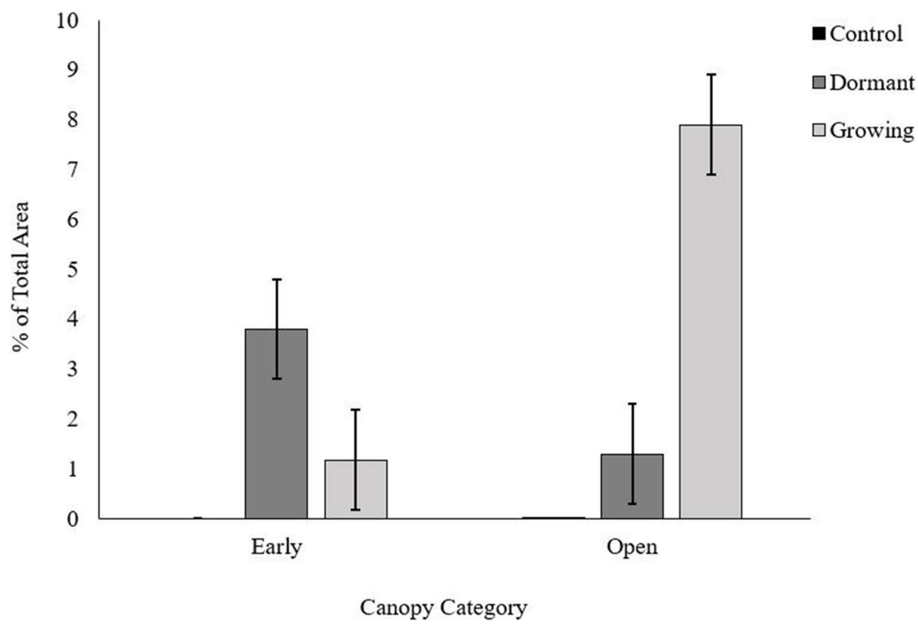

Fig. 3 Percent of total area represented by early and open canopy conditions in unburned control, dormant season burn, and early growing season burn units from the Chattooga River Ranger District and Andrew Pickens Ranger District. Canopy cover analyzed using US Department of Agriculture NAIP imagery, and areas of early (< 30% cover) and open (30–60% cover) canopy digitized at a 1:5000 level scale in ArcGIS Pro. Error bars represent the standard error of the mean

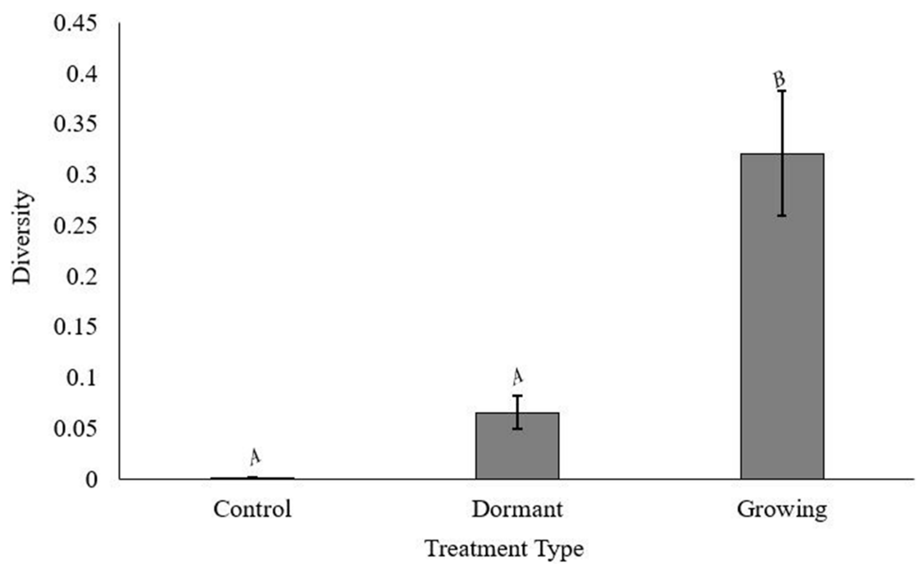

Fig. 4 Mean land cover diversity calculated using the Shannon-Weiner Diversity Index across all 3-acre subplots in unburned control, dormant season burn, and growing season burn treatment units in the Chattooga River Ranger District and Andrew Pickens Ranger District. Land cover diversity calculated from the total area of early (< 30% canopy cover), open (30–60% canopy cover), and closed (> 60% canopy cover). Error bars represent the standard error of the mean. Letters represent where significance (< 0.05) occurred

within each subplot (Fig. 5). The average length of open and early polygons in growing season treatment units was 141.30 m, while the average length in dormant season treatment units was 104.81 m and in unburned controls was 0.544 m.

Discussion

The last century of active fire suppression has altered ecosystems and habitat in the southeastern USA, creating a landscape that is vastly different today than it was hundreds of years ago. Our pre-burn imagery, which

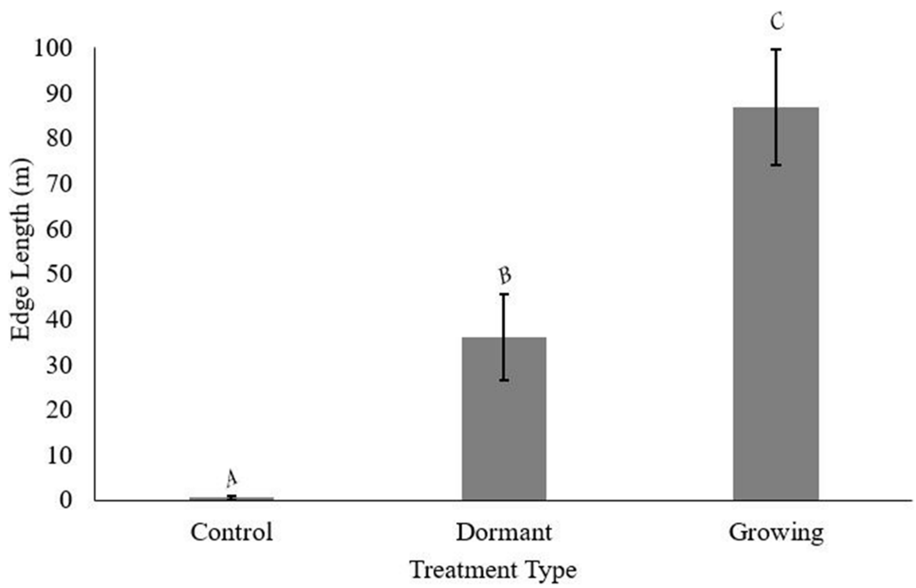

Fig. 5 Mean length (m) of edge habitat within each 3-acre subplot from post-burn (2019) imagery of dormant season and growing burns in the Chattooga River and Andrew Pickens Ranger District. Error bars represent the standard error of the mean. Data collected from the US Department of Agriculture NAIP imagery digitized at a 1:5000 level scale

had nearly 100% closed canopy structure in most treatment units, is indicative of this, and highlights the need for active fire on this landscape. The differences in the reduction of canopy cover and the associated production of early and mid-successional open habitats we found between our growing and dormant season burn units also indicate that seasonality can be a significant factor in determining the impacts of fire on forest structure. Structural changes resulting from burning and the reduction of closed canopy conditions are important in improving habitat heterogeneity, but particularly early growing season burns appear to be most effective in creating these changes. However, several studies have indicated that a single fire may not be sufficient in reducing canopy cover and restoring former forest heterogeneity (Olson and Platt 1995; Cronan et al. 2015), and so while seasonality appears to be important in influencing structural changes post-burn, increased number of burns could likely be important regardless of season. Because the fires in our treatment units were first-entry burns, the homogenous forest structure and closed canopy conditions prior to burning were likely the result of fire-sensitive mesophytic species, typically excluded from the canopy, being able to grow into the overstory and outcompete dominant oaks and pines (Hanberry et al. 2014, Lafon et al. 2017). In some treatments documented here, up to 13% of forest acreage was converted from closed canopy to early or open following the first burn, which is similar to results from the study conducted in the George Washington and Jefferson National Forests by Lorber et al. (2018).

Early growing season burns were more effective in reducing canopy cover compared to dormant season burns, which is consistent with previous studies that have found burns conducted in April were most effective in reduction of mesophytic hardwood species compared to burns conducted during the dormant and late growing season (Brose and Van Lear 1998; Brose et al. 1999). Differences in canopy cover between our dormant and growing season treatment units may result because our burns took place during mid to late April, after buds were broken but before complete leaf-out. This, coupled with longer/warmer days in the growing season, likely resulted in a more rapid drying of fuels, thereby contributing to fires of higher intensity and severity, with subsequent impacts on canopy cover (Brose and Van Lear 1998; Vaughan et al. 2021). A study conducted in these same burn units by Vaughan et al. (2021) found that the proportion of burned area in growing season treatment units was significantly higher in growing season burns compared to dormant season burns, which aids in the understanding of our results and supports our hypotheses. Additionally, our study was able to document seasonality-driven changes in forest structure that were not captured in a plot-based study Vaughan et al. (2022) conducted in the same units. Delayed tree mortality that has been documented in previous studies (Waldrop et al. 2008, Yaussy and Waldrop 2010), may have contributed to canopy gap creation in some burn treatment units, as aerial imagery was analyzed from 2019, and several burns took place in 2018. It is possible that differences in canopy gap creation between early growing and dormant season burns may also become more evident with increasing time since fire, which would be consistent with several studies indicating that effects from a single fire often unfold over many years (Elliott et al. 2009). The increases in canopy openings resulting from fires would also likely have important management implications that extend beyond canopy structure alone.

Canopy gaps have been shown to improve structural variation and plant and wildlife diversity within forests (Muscolo et al. 2014), and this increased heterogeneity has been shown to improve with fire (Lorber et al. 2018; Greenberg et al. 2014). Specifically, fire seems to improve species diversity within forested landscapes through the regeneration of a dominant herbaceous understory as canopies open (Nowacki and Abrams 2008) (Fig. 6). A study conducted by Ling et al. (2020) found that diversity in forest ecosystems increased in management scenarios that utilized prescribed fire, compared to landscapes with no fire, and that evenness and species distributions increased in fire managed scenarios. Our results on land cover diversity are consistent with these findings, but our results also indicate a difference of fire seasonality on the amount and type of forest cover following fire. Land cover diversity indices were highest in growing season burn treatment units, indicating that these fires are more effective at not only closed canopy structure and creating early successional and open canopy forest conditions, but also at creating a more even distribution of closed, early, and open canopy throughout the burned stand. A single dormant season burn does not appear to be as effective at restoring forest structural and compositional diversity, which is consistent with other studies (Oakman et al. 2019, 2021). However, repeated dormant season burns may eventually meet management objectives in enhancing structural diversity in this region, particular if burns are of higher intensity (Waldrop et al. 2016). Because increases in landscape heterogeneity resulting from prescribed fire have important implications for both plant and wildlife diversity (Elliott et al. 2009, Harper et al. 2016), early growing season burns that are more effective in improving land cover diversity could be an increasingly important management tool.

The importance of edge habitat for many wildlife species, including species of management concern like Bobwhite Quail (*Colinus virginianus* L.) and White-tailed Deer (*Odocoileus virginianus* Z.), may also point to the utility of using early growing season burns for habitat management. Our results indicate that early growing season burns not only resulted in higher levels of habitat diversity, but also greater levels of edge habitat, which previous studies have documented as important for many wildlife species (Parkins et al. 2019; Proesmans et al. 2019). Length of edge habitat in dormant season burn plots was still significantly higher than unburned controls, so while growing season burns may be more effective in creating this important habitat feature, dormant season burns do offer some benefits if increased edge habitat is a management goal.

Conclusion

Our results indicate the effectiveness of prescribed fire in reducing canopy cover, improving heterogeneity, and restoring natural disturbance regimes in the Southern Appalachians even after a single burn. In particular, early growing season burns appear to be more effective

Fig. 6 Post-treatment photos of an unburned control unit (left), a dormant season burn unit (center) and growing season burn unit (right) showing differences in canopy openness and understory vegetation response

than dormant season burns in creating open and early successional habitat, improving land cover diversity, and increasing the availability of edge habitat. Dormant season burns should continue to be used where a greater retention of closed canopy conditions are necessary, but forest managers may look to expand their burn programs to include early growing seasonburns when reduced canopy closure and improved heterogeneity are primary goals. Additionally, dormant season burns may effectively create similar conditions of heterogeneity and landcover diversity to the growing season after additional burns, and future studies should seek to understand the effect of repeated burning on forest structure in this region.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-023-00184-5.

Additional file 1. Appendix 1. List of treatmentunits used in this study,organized by block and treatment, showing burn date(when applicable), area, and elevation.

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Authors' contributions
All authors contributed to the study conception and design, and data collection and analyses were performed by ALM. The first draft of the manuscript was written by ALM and all authors commented on previous versions of the manuscript. All authors read and approved the final version of the manuscript.

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Availability of data and materials
Please contact author for data requests.

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Competing interests
The authors declare that they have no competing interests.

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