forests

MDPI

Article

Prescribed Fire First-Order Effects on Oak and Maple Reproduction in Frequently Burned Upland Oak–Hickory Forests of the Arkansas Ozarks

Mohammad Bataineh *, Brant Portner, Matthew Pelkki and Robert Ficklin

College of Forestry, Agriculture, and Natural Resources, University of Arkansas at Monticello, 110 University Court, Monticello, AR 716561, USA

* Correspondence: bataineh@uamont.edu; Tel.: +1-870-460-1449

Abstract: Alteration of the fire regime in upland oak–hickory (*Quercus* L. spp.–*Carya* Nutt. spp.) forests of the Central Hardwood Region is a major factor for the current shifts in species' composition and oak recruitment and regeneration failures. The reintroduction of fire into these ecosystems requires a better understanding of fire effects on oak and co-occurring competitors. First-order (i.e., during and immediately after) fire effects on oak and red maple (*Acer rubrum* L.) topkill and resprouting at neighborhood scales were evaluated in frequently burned upland oak–hickory forests. A groundline threshold of 5 cm provided oaks with high (60%) survival probability ($p < 0.001$). White (*Quercus alba* L.) and post (*Quercus stellata* Wangenh.) oak survival odds were 21 and 14 times higher than that of red maple ($p = 0.01$ and 0.03), respectively. Three and twelve months after burn, oaks had three to six times more sprouts per clump than red maple. Frequent fires may continue to topkill the maples, while maintaining oak dominance in the reproduction pool and, thus, providing higher recruitment potential into the overstory. Burns with fire behavior that is very low to low in these frequently burned systems may provide greater control in favoring oaks and selecting against red maple, especially if groundline diameter thresholds are considered.

Keywords: regeneration; red oak; white oak; resprouting; fire–oak; upland oak; prescribed burn; repeated burning

check for updates

Citation: Bataineh, M.; Portner, B.; Pelkki, M.; Ficklin, R. Prescribed Fire First-Order Effects on Oak and Maple Reproduction in Frequently Burned Upland Oak–Hickory Forests of the Arkansas Ozarks. *Forests* **2022**, *13*, 1865. https://doi.org/10.3390/f13111865

Academic Editor: Tara L. Keyser

Received: 16 October 2022
Accepted: 4 November 2022
Published: 7 November 2022

1. Introduction

The oak–hickory (*Quercus* L.-*Carya* Nutt.) forest type is a major component of the Eastern Deciduous Forest, covering nearly 17 million ha [1]. This ecologically and economically important forest type has evolved with fire as a key disturbance [2]. After a historical legacy of frequent fire for much of the last 10,000 years, suppression of fire since the early 1900s has resulted in the proliferation of mesophytic, shade-tolerant, fire-sensitive species in these systems [3]. Declines in oak density and regeneration and recruitment failures ensued as a lack of gap-creating disturbance, increases in understory shade, and increases in competition with fire-sensitive species occurred across these systems [4].

The reintroduction of fire to promote oak reproduction, restore disturbance regime and woodland structures, and prevent phase shifts and mesophication has been advocated [3,4]. The reintroduction and role of fire in oak systems constitute the main premise in the fire–oak hypothesis [5] and builds on an existing body of fire history studies that highlight frequent low-severity dormant season fires as the historical fire regime [4,6]. Frequent burning favors oak and selects against red maple (*Acer rubrum* L.) [7]. However, the degree of this differential selection depends on several factors, including landscape context, initial stand conditions, stage of stand development, availability and condition of seed source or reproduction pool, and burn regime characteristics (frequency, season, and severity). Despite an overall reduction in red maple due to lower survival following single and repeated fires, it appears that their resprout numbers may remain high [8] or remain competitive [9,10]. This inconsistency in outcome with fire use led to calls to refine thinking about the relationship of fire and oak forests to better incorporate the ecological context and facilitate when and where to apply fire on the landscape [11]. The most frequent explanation of differing fire outcomes is, arguably, that relating to burn characteristics [9,12], especially quantifying the treatment "dosage" level (i.e., heating magnitude and duration) that plagues fire-effect studies, among other factors [13,14].

If reliable prescribed burning guidelines are to be developed, a better understanding of fire effects on oak and co-occurring competitors is needed. Differential survival of reproduction and postfire resprouting rates among co-occurring species are some of the important factors in determining fire effects, along with establishment rates of new germinants and differential height growth. pPostfire annual survival of the red oak group (Erythrobalanus spp.) advance reproduction (<60 cm) was about 15%–30% higher than that of the white oak group (Leucobalanus spp.) and red maple following single and biennial burns [9]. Seedlings with larger initial groundline (GLD) diameter had greatest survival, with red and white oak subgenera seedlings >5 mm having around 80% survival [9]. A GLD threshold of >2 cm is often recommended to ensure higher post-fire competitive status of oaks [4,11,15]. High (>90%) survival and postfire resprouting (50%–80%) rates of advance reproduction (<15 cm basal diameter and <15 m in height) were reported for red and white oak groups, including high survival of seedlings <2 cm in basal diameter, following a single dormant season burn in the Missouri Ozarks [16]. Repeated burning, three or four times, reduced survival probability over time, but the white oak group's survival was notably higher (10%–20%) than that of the red oak group. Within the red oak group, the survival of black oak (*Q. velutina* Lam.) was higher (10%) than that of blackjack (*Q. marilandica* Münchh.) or scarlet oak (*Q. coccinea* Münchh.) [16]. Scarlet oak advance reproduction (<50 cm in height) had higher survival than red maple and chestnut oak (*Q. montana* Wild.) following repeated burning, three or four times, on xeric ridgetops of the Cumberland Plateau [10]. Survival of advance oak reproduction (<15 cm basal diameter) was higher than that of shortleaf pine (*Pinus echinata* Mill.) and blackgum (*Nyssa sylvatica* Marshall) but lower than that of mockernut (*Carya tomentosa* (Lam.) Nutt.) and pignut (*C. glabra* (Mill.) Sweet) hickories 10 years after repeated burning on an annual or quadrennial basis [17]. The white oak group had a slightly higher survival ratio than the red oak group, and the initial stem size appeared to be an important determinant of survival and growth responses [17]. Notably, survival ranking of white and red oak groups in response to fire appear to differ based on the size characteristic of the advance reproduction pool. Moreover, inconsistencies in response to fire may be related to differential oak species response that may be masked by pooling oaks into white and red oak groups.

There is a need to directly link fire behavior and heating patterns to individual plant and species responses at fine spatial scales [18–20]. Such linkage offers greater applicability in generalizing results from fire-effect studies by addressing the inherent variability in fire behavior within and among studies [4,13]. This approach is the foundation in first-order fire-effects models that use a mix of species and fire related attributes to predict immediate impacts [21]. Mortality, topkill, and postfire resprouting are localized neighborhood processes that are influenced by variability in fuel accumulation and consumption along with heat transfer at fine spatial scales. Individual-based models that link heating magnitude and duration to mortality, topkill, and postfire resprouting outcomes reflect a more mechanistic approach to understanding fire effects, which may have greater potential in simulating fire effects under future climate scenarios [19].

The objective of this study was to evaluate first-order (i.e., during and immediately after) fire effects on oak and red maple topkill (i.e., death of aboveground material regardless of resprouting) likelihood and resprouting (i.e., post-burn change in number of sprouts per clump) at neighborhood scales in frequently burned upland oak–hickory forests. Individual-based responses were linked to fire, fuel, soil moisture, and initial sizes to better inform prescribed burning activities and improve fire-effect models. Holding constant fire-induced heating, soil moisture, and fuel moisture and consumption parameters, we hypothesized that (1) oak individuals with a GLD of >2 cm would have higher survival likelihood than smaller oak individuals; (2) white oak species would have a higher survival likelihood than red oak species, and all oaks would have higher survival likelihood than red maple; and (3) red maple sprout density per clump would be reduced, while oak sprout density increased up to one year following fire.

2. Materials and Methods

2.1. Study Site

The study site is located within the University of Arkansas Savoy Experimental Forest in Washington County, Arkansas [22]. The site is an upland oak–hickory forest within the Ozark Highlands Ecoregion. The topography is gently rolling with an elevation range of 300 to 400 m above sea level. The mean annual temperature is 14 °C, while mean minimum and mean maximum temperatures are 8 °C and 20 °C, respectively. Annually, the region receives 117 cm of rainfall and 16 cm of snowfall. The annual frost-free period is 180–194 days. Soils consist mostly of the Clarksville–Nixa–Baxter and Captina–Nixa–Pickwick associations which are well drained and level to gently sloping soils formed mainly under hardwoods [23]. The predominant soil series of the area are the Nixa (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) with 3% to 8% slopes and the less prevalent Clarksville (Loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults) with 12% to 60% slopes [23].

The study was established within an area of 142 ha that was subjected to high-grading in 1996–1998 [22,24]. All merchantable trees >31 cm in diameter at breast height (1.3 m; DBH) were removed. Removals occurred mainly on gently sloping ridgetops. The pre-harvest stand originated following exploitative cuts in the early 1900s. Post-harvest residual overstory ranged from 324 to 348 trees ha^{-1} and was composed of low commercial quality white (*Q. alba* L.), black, and post (*Q. stellata* Wangenh.) oaks, as well as blackgum, hickory, and low proportions of other red oaks and red maples. Stand-level basal area was around 14 m^2 ha^{-1}, with a quadratic mean diameter of 23.4 cm, representing understocked conditions, below the B-line, based on Gingrich's stocking charts for upland hardwoods [25]. Site index was around 18 m for white oak, using a base age of 50 years. Advance reproduction of red maple, blackgum, black cherry (*Prunus serotina* Ehrh.), and flowering dogwood (*Cornus florida* L.) represented 50–60 percent of total number of stems, whereas oaks represented roughly 25 percent.

2.2. Study Design

This study was part of a long-term project initiated in 2004 to evaluate the use of single and repeated burning with and without herbicide application in improving composition and structure of high-graded oak–hickory stands [22,24]. One of six treatment levels was randomly assigned to each of 24 treatment units (0.8 ha each) in a completely randomized design. Treatment levels were combinations of a 2 × 3 factorial design that included prescribed burning (3 levels) and herbicide application (2 levels) as main factors. Prescribed burning levels included a single burn treatment, repeated burning at intervals of 3 years, and no burning. Herbicide treatment included herbicide application in fall of 2005 and no herbicide. Initial burning was conducted in 2005, with repeated burns in 2008, 2011/2012, and 2014/2015. The second and third burns had to be delayed to the following year for half of the replicates within each of the repeated burning treatments due to weather and other constraints. All burns were dormant season burns conducted in March or April, using ground ignition with a drip torch. Ignition pattern varied from backing and ring fires to strip-heading fires.

For this study, treatment units that represented repeated burning at ~3-year interval without herbicides (Units 6, 13, 17, and 19) were selected to examine topkill and resprouting responses. In 2017, as part of scheduled burns for the overall project, the selected burn units were sampled and prepared for data collection. Within each burn unit, ten to fifteen wildland fuel cells (each 9.3 m^2) where fuels were sufficiently uniform in abundance and distribution were established [26]. Wildland fuel cells were randomly selected from a potential sampling frame of 720 cells within each burn unit, excluding a five m buffer around each unit. Reducing clustering of sampled cells was considered, and an attempt was made to have a uniform spatial distribution of sampled fuel cells to account for the directionality of fire (i.e., head versus backfire and effect of shifting winds). However, the spatial distribution of advanced reproduction dictated the final location of the fuel cells. Wildland fuel cells were systematically searched for advanced reproduction to represent the entire range of available species and sizes. If a cell contained no oaks or red maples, the search continued. Within selected fuel cells, individual oak and red maple stems were tagged.

Across all four burn units, 223 stems were tagged that represented six species of oak (n = 164 individuals) and red maple (n = 59 individuals). Oak species were white oak (n = 41), post oak (n = 39), black oak (n = 14), blackjack oak (n = 9), northern red oak (*Q. rubra* L.; n = 46), and southern red oak (*Q. falcata* Michx.; n = 15). To ensure a representative sample uniformly distributed across all available sizes of the advance reproduction pool within each burn unit, reproduction was stratified into two main size classes: (1) seedlings (0.3 m < height < 1.3 m); and (2) saplings (1.3 m < height and DBH < 11.5 cm) with three to five GLD classes of equal width within each.

Prescribed burns were conducted independently for each unit over a three-day period (Table 1). The ignition pattern for all but one unit was circular (ring) ignition without spot fires in the center of the unit. Due to higher wind speeds and air temperature, Burn Unit 19's ignition pattern was strip heading with an average strip width of 20–25 m.

Table 1. Weather, mean fuel moisture, mean soil moisture, and fire behavior characteristics for four dormant season prescribed burns conducted as part of a frequent burning regime at 3-year interval in upland oak–hickory forests of the Arkansas Ozarks.

Variable	**Burn Unit**			
	6	**13**	**17**	**19**
Burn date (M/D/Y)	4/7/2017	4/7/2017	4/8/2017	4/9/2017
Start time (H:M)	12:46	18:40	13:53	14:21
Days since last rain	4	5	6	6
Soil moisture (%) [1]	21 ± 4	19 ± 2	18 ± 2	19 ± 2
Litter moisture (%) [1]	46 ± 14	17 ± 14	9 ± 9	24 ± 13
Duff moisture (%) [1]	71 ± 18	36 ± 20	37 ± 31	33 ± 14
Air temperature (°C)	20	21	28	27
Relative humidity (%) [2]	30	37	36	50
Wind speed (kph)	2.1	1.9	1.6	5.6
Wind direction from origin	E	NW	SE	SW
Flame lengths (m)	0.6	0.3	0.9	1.0
Rate of spread (m/min)	1.2	0.6	2.4	1.8
Fireline intensity (kW/m)	88	20	217	252
Heat per unit area (kJ/m^2)	4402	1956	5430	8414

[1] Means followed by standard deviation. [2] Around time of ignition.

2.3. Measurements

Although the reproduction GLD, height, and number of sprouts per clump were part of the long-term monitoring component, unit-level rather than individual-based measurements were conducted as part of the long-term study. In this study, each selected individual stem was tagged to allow for individual-based monitoring. The GLD and total height were measured before burning for this study. For individual stems that were part of a sprout clump, only the largest central-most stem was tagged and measured. The number of sprouts in a clump was also counted and recorded. Three months after burning, the topkill and number of sprouts of surviving root stocks were recorded. The number of sprouts was reassessed one year after burning.

To characterize fire behavior and measure fire-induced heating, thermocouple probe temperatures were recorded before, during, and after the passage of flaming fronts. Although reported thermocouples do not accurately reflect flame temperature due to material-dependent thermophysical properties [14] and thermal inertia [27], their data integrate temperature and duration [28] and correlate highly with fire heat flux, accurately reflecting fuel consumption and flame residence times [29]. The relatively low cost and labor input also allow for thermocouple routine deployment in prescribed burning to better quantify fire effects than mere qualitative characterization (e.g., low versus high severity fires). Moreover, the deployment of thermocouples with data loggers allows for time–temperature integration and consequently the calculation of various fire behavior metrics reflecting the magnitude and duration of heating effects such as residence time above a specific threshold or the arithmetic product of degree times seconds [28–30].

Four relatively thick (4.8 mm diameter) HOBO® type-K thermocouple probes were used within each wildland fuel cell [26]. Thermocouple probes were placed at ground-level and 30 cm aboveground. Ground-level probes were placed horizontally directly under the litter layer, while aboveground probes were placed vertically, perpendicular to ground surface. Thermocouple data loggers were buried outside each fuel cell to reduce disturbance and were set to record at 1 s intervals starting 30 to 60 min before ignition. Thermocouples were removed after the completion of each burn.

Within each wildland fuel cell, pre- and post-burn fuel loadings were estimated by using two transects (4.3 m each), following the procedure outlined in Reference [31]. Fuel loading transects intersected at the center of the fuel cell. Dead and downed woody debris was tallied in four time-lag-size classes, namely woody 1 h (0.1–0.6 cm diameter at intersection), 10 h (0.6–2.5 cm), 100 h (2.5–7.6 cm), and 1000 h (>7.6 cm). Woody 1-hour and 10-hour classes were tallied along the first 0.9 m of each transect, whereas 100 h class was tallied along the first 1.8 m of each transect. The 1000-hour class was tallied along the entire length of each transect and was classified as sound or rotten. Litter (including freshly fallen leaves, dead herbs, dead shrubs, and acorns) and duff (organic soil horizons, including fermentation and humus layers) were collected separately from 30 cm^2 quadrats, placed near but outside each wildland fuel cell, and reflected the fuel conditions of these cells. Litter and duff samples were weighed fresh before burning, oven dried to a constant weight at 60 °C for three days, and reweighed dry to estimate fuel moisture. The depths of litter and duff were also recorded to the nearest mm in a representative location around each tagged reproduction individual.

The pre-burn soil moisture was estimated prior to ignition, using a FieldScout® Time Domain Reflectometer 300 (TDR; Spectrum Technologies Inc.). TDR probes (12 cm long) were fully inserted at three locations within each wildland fuel cell, and the volumetric soil water content was recorded as an average for each cell.

The fire behavior parameters were recorded during each prescribed burn, and weather conditions were recorded prior to and during burning. The air temperature, relative humidity, eye-level wind speed, and wind direction from origin were recorded by using a handheld Kestrel® 3000 weather meter (Table 1). Ranging wooden poles coated with fire-resistant paint with alternate gradations at 30 cm intervals were used as sighting reference within each burn unit. Poles were spaced at a 10 × 10 m grid across each burn unit. The timing of the flame front passage from one pole to another was recorded, and the rate of spread was calculated. Flame height and average flame angle were estimated by using ranging pole gradations as reference. Flame length was calculated from flame height and average angle. Heading, backing, and flanking fires' flame length and rate of spread were estimated separately and recorded in the field as an average across each burn unit. The fireline intensity was calculated from flame length estimates for each burn unit [18,32]. Heat per unit area was calculated from fireline intensity and rate-of-spread estimates [18,32].

2.4. Analytical Approach

For each wildland fuel cell, time-integrated temperatures reflecting heating magnitude and duration were calculated from thermocouple data. For time-integrated temperatures, the area under the curve was calculated by using a threshold of 60 °C to reflect only fire-induced heating, above ambient, and provide a biologically meaningful cutoff that is associated with lethal temperature to plant tissue [28,33,34]. Time-integrated temperature above 60 °C was calculated for each thermocouple placement, ground-level and at 30 cm aboveground, separately. Fuel consumption was calculated by subtracting post-burn from pre-burn fuel loads for each fuel cell. Fuel loads for downed wood were calculated by using the formulas presented in Brown (1974). Downed wood, litter, and duff loads were converted to unit area estimates. Subsequently, fuel consumption was calculated for the four downed wood time-lag-size classes, litter, and duff. Difference in litter and duff thickness was also calculated as a measure of fire severity and fuel consumption. Pre-burn litter and duff moisture content estimates were calculated as the difference between fresh and dry weight in proportion to oven-dry weight.

Topkill response three months post-burn was modeled as a binary variable with surviving individuals (no topkill) receiving a value of one and topkilled individuals receiving a value of zero. A logistic model was fit to model the probability of survival as a function of individual stem size (GLD and height), species identity, component fuel consumption (9 variables), pre-burn litter and duff moisture, soil moisture, and time-integrated temperature above 60 °C for each of ground-level and 30 cm–aboveground thermocouples (2 variables). A logit link function was used. For model selection, an automatic stepwise backward selection was used to reduce the number of explanatory variables based on Akaike's Information Criterion, AIC. Additional variables were dropped from the model if their coefficients were not significantly different from zero according to an analysis of deviance test. Explained deviance, a coefficient of determination analog, was calculated as the proportion of deviance accounted for by the optimal model to that of the null model, a model containing only an intercept [35].

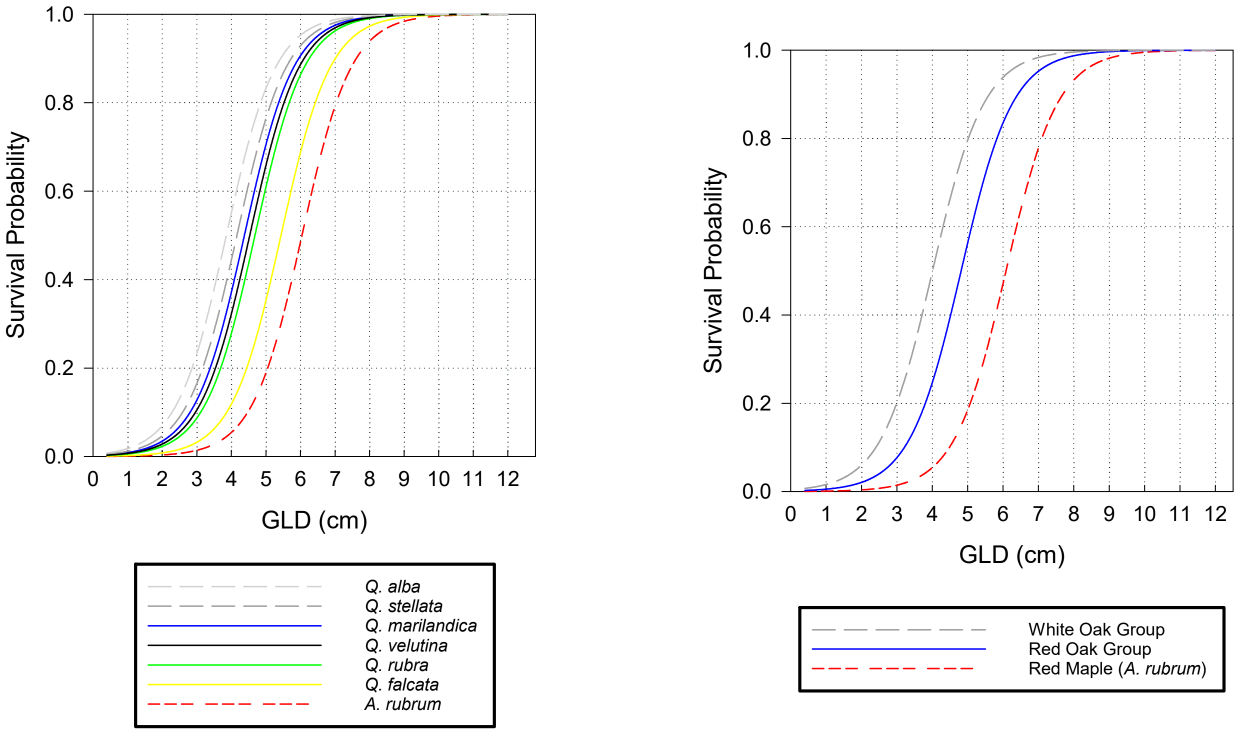
Change in number of sprouts per clump and resprouting response, three months and one year after burning, were modeled separately. A linear model was fit to each resprouting response, using the same explanatory variables used for survival. An automatic stepwise backward selection was also used, and nonsignificant explanatory variables were dropped from the model. Interaction terms were not included due to the small number of observations in relation to the number of explanatory factors. Residuals from all models were examined for patterns, and no indication of a trend in residuals was detected. For the optimal models, differential responses of species and effects of explanatory variables were tested at an alpha level of 0.05. To provide better linkage to other studies, oak species were grouped into white and red oak groups, and the analysis was repeated for each survival and resprouting response.

Differences in individual stem sizes, topkill, and sprout numbers among species and species groups were determined by using a Kruskal–Wallis rank test, followed by a Tukey's multiple comparison procedure to separate means whenever a significant effect was found. Differences among burn units in fuel and fire behavior were also explored by using Kruskal–Wallis rank test and Tukey's multiple comparison procedure. All analyses were performed by using R version 3.0.2 [36].

3. Results

3.1. Survival

Regardless of the species, the survival probabilities increased with higher GLDs (Figure 1). An increase of 1 cm in GLD enhanced survival odds by four times (Table 2). A GLD of 5 cm provided oaks (except southern red oak) with 60% or higher survival probability (Figure 1). The same GLD provided the southern red oak with a 35% survival probability, while the red maple's survival was at 20% (Figure 1). Prior to burning and across all sampled advance reproduction stems (n = 223), the mean (± SD) GLD and total height were 3.2 ± 2.1 cm and 2.2 ± 1.6 m, respectively (Table 3). The white oak group's GLD was 0.9 and 1 cm larger than that of red maple and red oak group, respectively (p = 0.01). The red maple was slightly taller (0.7 m) than the red oak group. However, reproduction total height did not significantly differ among species or species groups (p = 0.2). GLDs of >5 cm appear to provide a higher survival likelihood during dormant-season prescribed fires in frequently burned systems like the ones examined in this study (Figure 1).



(**a**) (**b**)

Figure 1. Survival probability for: (**a**) seven individual species; and (**b**) three species groups as a function of groundline diameter (cm) following four dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks.

Table 2. Model parameter estimates, standard error (SE), p-values, and odds ratios for survival of advance reproduction following dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks.

Parameter	Estimate	SE	p-Value	Odds Ratio	Explained Variance (%)
	Survival 3 Months after Burning				
Intercept	−3.93	1.46	0.01	0.02	
White oak	3.06	1.18	0.01	21.37	
Post oak	2.63	1.20	0.03	13.92	
Blackjack oak	2.33	1.66	0.16	10.28	
Black oak	2.11	2.46	0.39	8.28	
Northern red oak	1.90	1.30	0.14	6.71	59
Southern red oak	0.85	1.64	0.61	2.34	
Groundline diameter (cm)	1.40	0.34	<0.01	4.05	
Litter depth (cm)	−0.39	0.19	0.04	0.68	
Time-integrated temperature above 60 °C (°C s^{-1})	−0.14	0.37	<0.01	0.32	

Table 3. Advance reproduction pre-burn size characteristics, and post-burn topkill and resprouting responses following dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks.

Species	GLD (cm) [1]	Total Height (m) [1]	Topkill (%) [1,2]	Pre-BurnSprouts [1]	Post-Burn Sprouts (3 Months) [1]	Post-Burn Sprouts (1 Year) [1]
White oak	3.9 ± 2.7	2.5 ± 1.8	52 ± 18	1 ± 0.5	3 ± 1.1	4 ± 0.7
Post oak	3.7 ± 2.2	1.7 ± 0.9	56 ± 30	1 ± 0.8	3 ± 1.7	4 ± 1.9
Blackjack oak	2.1 ± 0.8	1.5 ± 0.6	67 ± 47	2 ± 0.7	4 ± 0.5	4 ± 0.2
Black oak	4.0 ± 2.8	2.8 ± 2.1	56 ± 39	2 ± 0.7	2 ± 0.6	2 ± 0.6
Northern red oak	2.7 ± 1.7	1.8 ± 1.2	65 ± 19	2 ± 0.2	4 ± 0.6	4 ± 1.0
Southern red oak	2.3 ± 1.4	1.6 ± 1	96 ± 7	2 ± 1.5	5 ± 2.6	5 ± 2.1
White oak group	3.8 ± 2.5 a	2.1 ± 1.4 a	55 ± 19 a	1 ± 0.4 a	3 ± 0.8 a	4 ± 1.1 a
Red oak group	2.8 ± 1.9 b	1.9 ± 1.4 a	72 ± 15 a	2 ± 0.4 a	4 ± 0.8 b	4 ± 0.7 a
Red maple	2.9 ± 1.8 b	2.6 ± 1.9 a	61 ± 43 a	3 ± 1.4 b	1 ± 0.9 c	1 ± 0.8 b

[1] Means, with standard deviation, followed by the same letter within a column were not different ($p > 0.05$). [2] Mean across four burns.

Holding the GLD, litter depth, and time-integrated temperature constant, the survival odds of the white and post oaks were 21 and almost 14 times higher than that of red maple, respectively (Table 2). The survival of red maples was not significantly different from that of red oak species, despite higher survival odds for each of the four red oak species (2.34 to 10.28 odds). The four red oak species also did not significantly differ in their survival from white and post oaks ($p > 0.26$) or each other ($p > 0.45$). White and post oak survival did not significantly differ ($p = 0.65$), despite 35% lower survival odds for post oak as compared to white oak. Differential individual species trends were like those obtained by pooling oak species with 17.3 times higher survival odds for the white oak group compared to red maple ($p = 0.01$). No difference in survival between white and red oak groups was detected ($p = 0.17$). The survival probability was also not different between red oak group and red maple ($p = 0.11$). A GLD threshold of 5 cm appears to provide oaks, especially white oaks, with high survival in upland sites with frequent low-severity fire, while red maples experience higher topkill rates (Figure 1).

Accumulation of litter by one more cm in depth reduced reproduction survival odds by 34%, holding all other factors constant (Table 2). Generally, high fuel load consumption directly relates to higher fireline intensities [32,37] and is considered a reasonable surrogate for total energy released in wildland surface fires [29]. Across all species, survival odds were reduced by 68% for each 10,000 °C s^{-1} increment in time-integrated temperature above 60 °C for 30 cm aboveground thermocouples (Table 2). Survival probabilities decreased almost linearly with the 30 cm aboveground thermocouple-integrated temperature above 60 °C (Figure 2). Integrated temperatures around 10,000 °C s^{-1} were associated with survival probabilities above 40% for white and red oak groups, except for southern red oak. The same threshold was associated with a 20% and 10% survival probability for southern red oak and red maple, respectively (Figure 2).

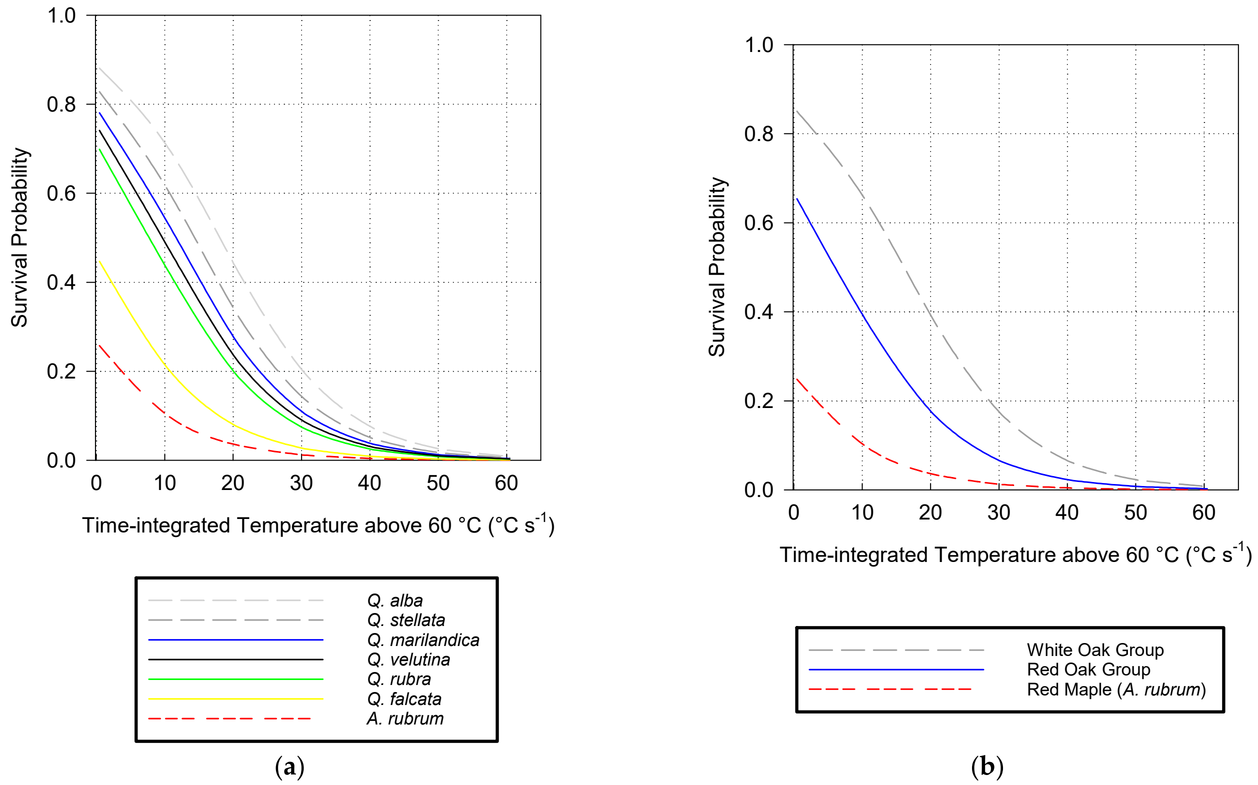


Figure 2. Survival probability of for (**a**) seven individual species and (**b**) three species groups as a function of time-integrated temperature above 60 °C, at 30 cm aboveground in 10,000 °C s^{-1} increments, during four dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks.

3.2. Resprouting

Before burning, the red maple trees had one and two more sprouts per clump, on average, as compared to the white and red oak groups, respectively ($p < 0.01$; Table 3). Three months post-burning, the red oak group had the highest number of sprouts per clump, followed by the white oak group and red maple (Table 3). One year after burning, the white and red oak groups had a similar number of sprouts per clump, and each had higher number of sprouts than red maple (Table 3).

Species' identity was the only significant variable explaining the change in sprout number per clump three and twelve months after burning (Table 4). Three months after burning, white and red oak species had two to five times the number of sprouts per clump as compared to red maple, mainly due to the topkill of red maple (Table 4). One year after burning, white and red oak species had three to six times higher sprout density per clump than red maple (Table 4).

Table 4. Model parameter estimates, standard error (SE), and *p*-values for change in advance reproduction sprout number following dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks.

Parameter	Estimate	SE	*p*-Value	Explained Variance (%)
	Resprouting 3 Months after Burning			
Intercept	−2.17	0.44	<0.01	
White oak	4.00	0.68	<0.01	
Post oak	4.25	0.69	<0.01	25
Blackjack oak	4.39	1.20	<0.01	
Black oak	2.31	1.00	0.02	

Table 4. *Cont.*

Parameter	Estimate	SE	*p*-Value	Explained Variance (%)
		Resprouting 3 Months after Burning		
Northern red oak	4.50	0.66	<0.01	25
Southern red oak	5.17	0.97	<0.01	
		Resprouting 1 year after burning		
Intercept	−2.63	0.47	<0.01	30
White oak	5.41	0.74	<0.01	
Post oak	4.88	0.75	<0.01	
Blackjack oak	5.52	1.30	<0.01	
Black oak	2.77	1.08	0.01	
Northern red oak	5.38	0.72	<0.01	
Southern red oak	5.49	1.05	<0.01	

3.3. Fire Behavior

Burn units did not differ in pre-burn loading for duff (p = 0.5), litter (p = 0.74), woody 1 h (p = 0.17), combined litter and 1 h (p =0.62), and 10 h (p =0.53) fuels. Across all units, the pre-burn mean litter loading was 2.6 ± 1.3 ton ha^{-1}, whereas duff and woody 1-hour loadings were 3.9 ± 1.6 ton ha^{-1} and 0.2 ± 0.2 ton ha^{-1}, respectively. The pre-burn mean loadings (± SD) for 10 h, 100 h, 1000 h sound, and 1000 h rotten fuels were 2.0 ± 1.7, 4.5 ± 6.3, 10.4 ± 29.7, and 5.5 ± 12.8 ton ha^{-1}, respectively.

As expected, fuel consumption was related to surface fireline intensities (Table 1; Figures 3 and 4). The litter load consumption was relatively similar among burns, except for Burn Unit 6, which had 5% lower consumption than Burn Unit 13 (p = 0.03; Figure 3). The duff consumption differed among burns and was 26%–47% lower for Burn Unit 6 (p < 0.01). The duff consumption was greater than 90% for Burn Units 17 and 19, both of which had relatively lower duff moisture content compared to Burn Unit 6, and both had higher fireline intensities and heat per unit area (Table 1). Post-burn litter and duff depth reductions differed among burns mainly due to greater consumption (1.2 to 2 cm) for Burn Unit 19 than Burn Units 13 and/or 17 (p < 0.04) (Figure 4). Litter and duff depths were intended as fuel consumption estimates at the individual stem level, and they reflected the relative patterns shown for litter and duff loading consumption among burns (Figure 3). The consumption of woody 1-hour, 10-hour, 100-hour, and 1000-hour fuels did not differ among burns (p > 0.05), due to the high within-burn variability (coefficient of variation ranging from 0.7 to 3.5) for these loadings. Across all burns, the mean (± SD) consumption for woody 1-hour, 10-hour, 100-hour, 1000-hour sound, and 1000-hour rotten fuels was 0.1 ± 0.1, 1.6 ± 1.4, 3.2 ± 4.7, 8.9 ± 26.9, and 5.0 ± 11.4 ton ha^{-1}, respectively. The consumption of woody fuel across all four burns was relatively high, with 68%, 79%, 71%, 80%, and 92% of pre-burn loadings consumed for each of 1-hour, 10-hour, 100-hour, and 1000-hour sound and 1000-hour rotten, respectively.

Fire behavior ranged from very low to low for burn units 6 and 13 and low–moderate for burn units 17 and 19 based on flame lengths and rate of spread [38]. The time-integrated temperature above 60 °C for ground-level thermocouples did not significantly differ (p = 0.08) among the four burns (Table 5). For the 30 cm aboveground thermocouples, the time-integrated temperature above 60 °C did not significantly differ among burns but was 2.5 times higher for Burn Unit 17 as compared to Burn Unit 6 (p = 0.09). Burn Unit 17 had a high fireline intensity and was conducted during a period of higher air temperature and lower relative humidity but lower wind speeds relative to the remaining burns (Table 1). Pre-burn litter moisture content was also lowest for Burn Unit 17 and resulted in a more uniform litter consumption (Table 1). The duff and litter moisture contents were highest for unit 6 (p < 0.01), which had the second lowest fireline intensity and the lowest time-integrated temperature above 60 °C at 30 cm aboveground, with moisture levels at 71 ± 18 and 46 ± 14%, respectively. The moisture content for duff and litter was obtained from samples collected before burning and was likely higher than that at ignition time, early afternoon for Burn Unit 6. The litter moisture content before burning was slightly higher for Burn Unit 19 compared to Burn Unit 17 ($p = 0.03$). The soil moisture content did not differ among burn units ($p = 0.11$) but showed a weak negative linear relationship ($p = 0.05$) with time-integrated temperature for ground-level thermocouples. The litter moisture content did not show a discernible pattern against time-integrated temperature for ground-level or 30 cm aboveground thermocouples ($p = 0.1$ for each). The duff moisture content was negatively correlated to time-integrated temperature from ground-level ($p = 0.04$) and 30 cm aboveground ($p = 0.01$) thermocouples. Litter and woody fuel consumption metrics did not show discernible patterns with time-integrated temperatures above 60 °C, but duff fuel consumption had a positive linear relationship ($p = 0.01$) with 30 cm aboveground thermocouple time-integrated temperatures.

Table 5. Mean and standard deviation for peak flame temperature by recording device and residence time during four dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks.

Thermocouple Time-Integrated Temperature above 60 °C	Burn Unit [1]			
	6	13	17	19
30 cm aboveground (°C s^{-1})	11,144.1 ± 3837.2 a	12,739.4 ± 9317.5 a	27,381.7 ± 20,809.5 a	24,982.1 ± 12,952.8 a
Ground-level (°C s^{-1})	26,872.0 ± 22,769.4 a	69,103.4 ± 59,165.7 a	56,094.6 ± 30,922.9 a	72,333.4 ± 44,398.3 a

[1] Means followed by the same letter within a row were not different ($p > 0.05$).

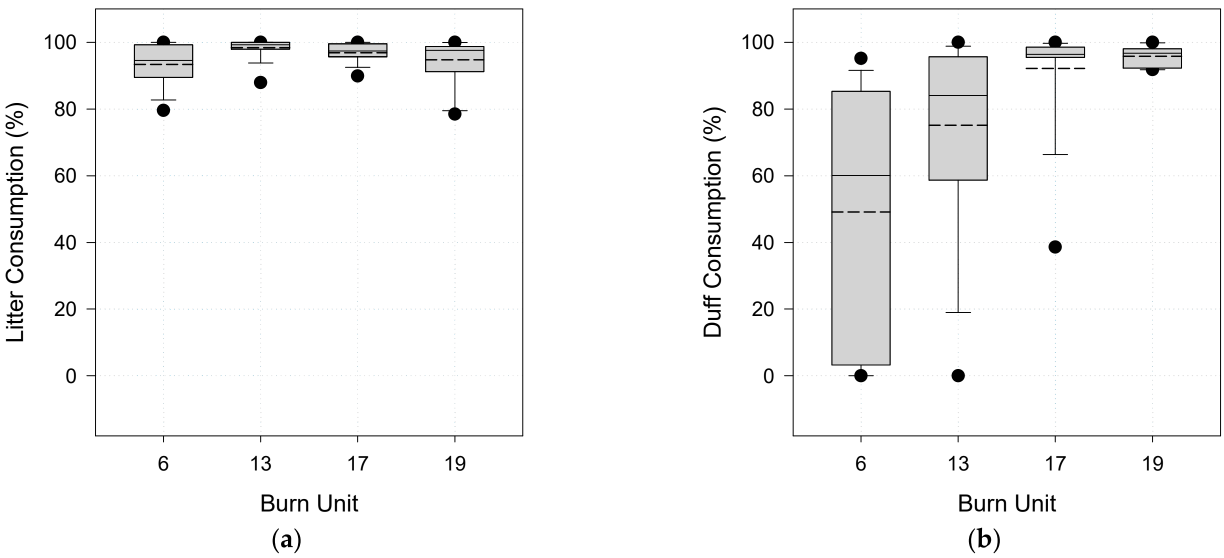


Figure 3. Box plot distribution of (**a**) litter and (**b**) duff consumption for each of four dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks. Each box represents the 25th, median (50th), mean (dashed line), and 75th percentiles. The error bars (whiskers) represent the 10th (below) and 90th (above) percentiles; filled circles represent outliers.

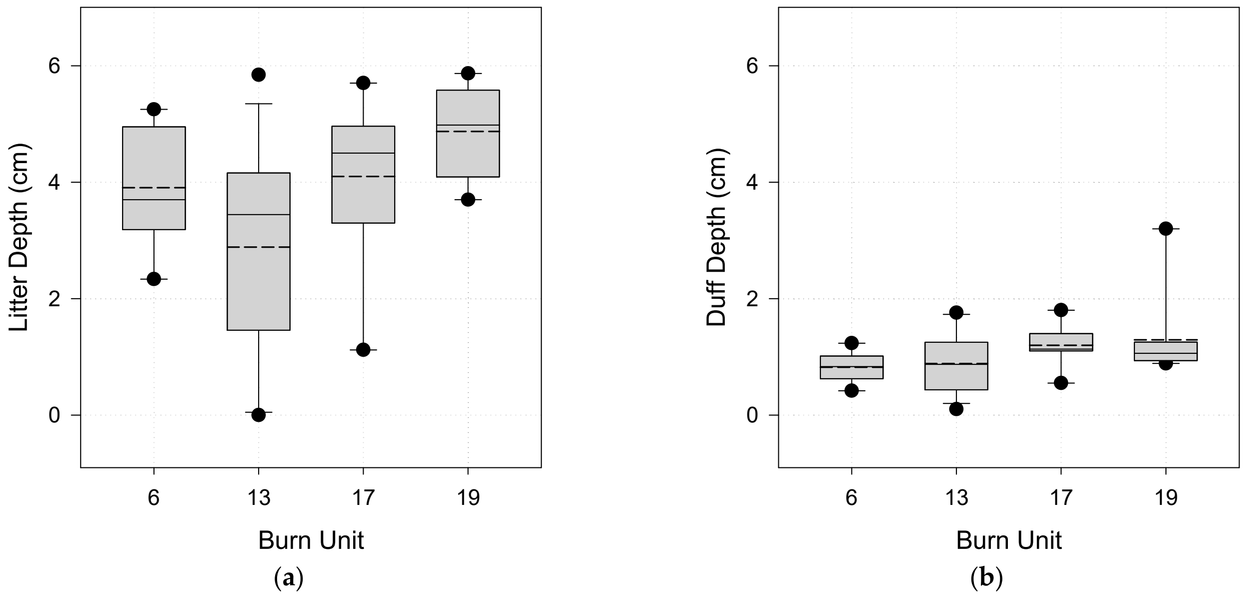


Figure 4. Box plot distribution of (**a**) litter and (**b**) duff post-burn depth reductions for each of four dormant season prescribed burns in frequently burned upland oak–hickory forests of the Arkansas Ozarks. Each box represents the 25th, median (50th), mean (dashed line), and 75th percentiles. The error bars (whiskers) represent the 10th (below) and 90th (above) percentiles; filled circles represent outliers.

4. Discussion

4.1. Survival and Groundline Diameter

Throughout the range of sampled GLDs, advanced oak reproduction had a higher likelihood of survival than red maple; however, the highest survival of oak was associated with GLDs of > 5 cm (Figure 1). This partially supports the hypothesis that oak stems with GLDs of > 2 cm would have higher survival probability than smaller stems. A larger-than-hypothesized GLD threshold of 5 cm or greater appears to provide oaks, especially the white oak group, with high survival (>60%) in upland sites with frequent low-severity burn regimes. Despite the fact that a smaller GLD threshold (>2 cm) is often recommended to ensure the high post-fire competitive status of oaks [11,15,39], it may be more advantageous to use larger groundline diameters to ensure that a higher proportion of the current pool of oak recruits remains available post-fire. Several studies concluded that repeated burning with no prolonged fire-free interval (10–40 years) would hinder oak recruitment into the overstory [39,40]. GLD thresholds like these serve as practical guidelines in determining when prescribed burning application can take place to ensure the high survival and recruitment of oak into the overstory. These thresholds may also have wide applicability in upland oak–hickory forests, as they are based on individual stems rather than stand characteristics. Northern red oak was reported to reach 5 cm in DBH within 6–12 years, whereas post oak reached that DBH within 26 years [41]. The reported mean annual diameter growth estimates suggest that 5 cm GLD for white oak may be reached within 20–40 years, whereas red oaks would reach this GLD within 15–20 years [41]. However, differences in site productivity and stand conditions would greatly influence these estimates.

Despite the apparent importance of a fire-free interval to ensure oak recruitment [39,40], there appears to be a sufficient amount of red and white oak recruits in the advance reproduction pool of frequently burned upland oak–hickory forests of the Arkansas Ozarks [22]. Importance values, which combine relative density and relative basal area, for the reproduction of red and white oak groups combined were around 40% for the repeated burning treatments of our study [22]. This allowed us to develop this study and highlights the inherent heterogeneity associated with prescribed burning, as 100% blackened areas are rarely achieved nor commonly desirable in burn plans. Moreover, the role of initial overstory stocking, stand development stage, and condition of reproduction pool should not be ignored when evaluating fire effects on oak reproduction [39]. Oak–hickory stands in this study were previously subjected to high-grading [22], thus indicating a positive role for low overstory stocking on oak recruitment outcomes in frequently burned oak–hickory stands [40]. This also suggests that, when adequate stocking of advance reproduction of sufficient size (>5 cm in GLD) remains available, frequent burning may continue to release oak from co-occurring mesophytic competitors [5].

4.2. Differential Oak Response

The white and red oak groups' survival probability did not significantly differ, despite higher odds for white oaks (Table 2; Figure 1). This disagrees with the hypothesized ranking of oak groups. White oak species generally have thicker barks, and their sprouts originate from lower portions below-ground than red oak species, hence the expectation that their survival would be higher than red oaks [39,42]. The members of the white oak group in this study were slightly larger, on average, in initial GLD (1 cm) than red oaks (Table 3), and for each given initial diameter and fire behavior metric, white and post oaks had higher survival than all other red oak species (Figure 1). Despite the relatively low sample size of tagged individual stems in this study, especially for black, blackjack, and southern red oaks, differential species responses and ranking were like those previously reported. Higher survival rates were reported for white and post oaks as compared to black and blackjack oaks in the Missouri Ozarks [16]; this agrees with the species ranking trends observed in this study. The ranking of white, post, and black oaks in terms of post-burn survival 10 years after repeated burning on an annual or quadrennial basis [17] is also consistent with the ranking obtained in this study. Observed GLDs in this study were also like that of References [16,17]. The low survival of southern red oak across all GLDs and high survival of white and post oaks, in descending order, in this study was also like that documented for the Missouri Ozarks [43]. The differential oak species' responses observed in this and other studies underscore the masking of fire effects that occurs when pooled species' responses are analyzed and reported [9].

4.3. Resprouting Response and Maple Control

In partial support of the hypothesis that red maples would have lower survival than oaks, the results show that red maple fire survival was lower than that for the white oak group, but it was not significantly different from that of the red oak group despite higher survival odds for red oak species (Table 2). The sensitivity of red maples to fire is well documented, highlighting their epigeal germination habit, lack of buried seed caches, aboveground sprout origin, and their thin smooth bark—especially as reproduction [2,39]. In contrast, oaks' life-history traits, such as their deep root systems, conservative growth strategy, below-ground sprout origin, and thicker bark, confer adaptations to fire-prone environments [2,39]. Frequent burning favors oak and selects against red maple [7,22], but post-burn maple sprouts may increase [12], remain competitive [9,10], or be in high density [8].

As expected, the red maple sprout density per clump was reduced three and twelve months after dormant season fires (Tables 3 and 4). Red maples had a higher number of sprouts than oaks before burning in these frequently burned stands (Table 3). This underscores the utility of fire and importance of repeated burning to keep mesophytic species in check in these systems. Despite the relatively lower pre-burn density of sprouts per clump for the white oak group, their numbers increased to match these of the red oak group one year after fire. This contrasts with results reported by Reference [12] but agrees with Reference [44], who reported a higher sprouting response for white and red oak groups as compared to red maple. The greater sprouting of oaks might be attributed to their ability to maintain higher and more stable root starch levels than red maples do [44].

Clearly, additional monitoring of individuals tagged in this study would be required before the competitive status of topkilled red maple can be determined. Such monitoring in this and other studies at long-term scales would aid in clarifying the utility of fire in controlling maple and other mesophytic species.

4.4. Fire Behavior and Fuel Effects

Before burning, the loadings of fuel components were relatively uniform among burn units. In this study, pre-burn fuel loadings were estimates from frequently burned stands, burned four times since 2005. Litter and woody 1-hour pre-burn loadings were 30%–40% of that reported by Reference [45] for the Missouri Ozarks and were generally lower than the parameters for standard fuel Model 9 (Hardwood Litter) [46]. The pre-burn loading for 10-hour fuel was like that reported by Reference [45], however. Lower fuel loads may be the result of lower overstory density, as stands in this study were previously subjected to high grading [22].

The four dormant season burns conducted in this study varied in fireline intensity, flame length, and heat per unit area (Table 1). Burn Units 17 and 19 had higher fireline intensities, flame lengths, and heat per unit area compared to the remaining units. The observed high and uniform consumption of litter among units was expected, as hardwood litter is the fire-carrying fuel [46]. Lower duff consumption for Unit 6 and higher consumption in Units 17 and 19 were associated with differences in duff moisture. Variability in fire behavior was associated with differences in weather and burn-day conditions, but explicit testing of weather and burn day is not feasible with a limited dataset of four experimental burns. Variable fire behavior among burn units was equally, if not more so, matched with heterogeneity in fire behavior within each unit. This resulted in non-significant differences in time-integrated temperatures above 60 °C for both ground-level and 30 cm aboveground thermocouples (Table 5). Thermocouple time-integrated temperatures above 60 °C were negatively related to soil and duff moistures but positively correlated to duff load consumption, highlighting that the magnitude and residence time of fire-induced heating registered at the tip of thermocouples included surface heating from smoldering combustion associated with the trailing end of the flaming front or following the passage of the front, as well as lag times in probe responses to change in air temperature following front passage, especially in our case, where relatively thick thermocouples were used [28,29].

The effect of variable fire behavior within and among burn units was captured in survival response three months post-burning (Figure 2). The magnitude and duration of fire-induced heating captured by thermocouples were significant explanatory variables in the survival model, along with litter depth. Integrated temperatures around 10,000 °C s^{-1} were associated with survival probabilities of 60% for the white oak group; 40% for the red oak group, with the exception of the southern red oak (20%); and 10% for red maple (Figure 2). Burns like those in Unit 6 had a mean-time-integrated temperature above 60 °C for 30 cm aboveground thermocouples around this 10,000 °C s^{-1} threshold and might be used as a guideline for burn plans in similar systems (Table 5). Although direct control over fire-induced heating may not be possible, manipulation of some of the factors affecting it may allow indirect control in favoring oaks over red maple. For example, repeated burning would result in the maintenance of low fuel levels and thus potentially lower fire-induced heating and fireline intensities such as those witnessed for Burn Unit 6 (Table 1).

5. Conclusions

These findings show that a GLD threshold of 5 cm or greater provides oaks, especially the white oak group, with high survival (>60%) in upland sites with frequent low-severity fire, while red maples experience higher topkill rates. Frequent fires may continue to topkill the maples while maintaining oak dominance in the reproduction pool, thus providing higher recruitment potential into the overstory. These findings highlight the importance of the adequate stocking of advance reproduction in fire reintroduction and silvicultural plans, and they provide resource managers with a practical way of determining the length of fire-free period in upland oak–hickory systems. For burn plans in these systems, burns with fire behavior that is very low to low may provide greater control in favoring oaks and selecting against red maple, especially if GLD thresholds are considered.

Author Contributions: Conceptualization, M.B.; methodology, M.B.; validation, M.B. and B.P; formal analysis, M.B. and B.P.; investigation, B.P. and M.B.; resources, M.B. and R.F.; data curation, M.B.; writing—original draft preparation, B.P., M.B., R.F., and M.P.; writing—review and editing, M.B.; visualization, M.B. and B.P.; supervision, M.B.; project administration, M.B.; funding acquisition, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding with support, in part, by the McIntire-Stennis Cooperative Forestry Research Program as awarded to the Arkansas Forest Resources Center.

Data Availability Statement: All data generated or analyzed during this study are included in this published article. Access to datasets used and/or analyzed beyond what is presented in the article is available from the corresponding author on reasonable request.

Acknowledgments: Thanks to the Arkansas Forestry Division, especially Dennis Spear and his prescribed burn crew for conducting and supervising the burns. This project was assisted by Dalton Weatherly, Billy Sanders, Phillip Duncan, and Alan Jones of the University of Arkansas at Monticello.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Dyer, J.M. Revisiting the Deciduous Forests of Eastern North America. *Bioscience* **2006**, *56*, 341–352. [CrossRef]
2. Abrams, M.D. Fire and the development of Oak Forests. *Bioscience* **1992**, *42*, 346–353. [CrossRef]
3. Nowacki, G.J.; Abrams, M.D. The Demise of Fire and " Mesophication " of Forests in the Eastern United States. *Bioscience* **2008**, *58*, 123–138. [CrossRef]
4. Brose, P.H.; Dey, D.C.; Waldrop, T.A. *The Fire—Oak Literature of Eastern North America: Synthesis and Guidelines*; United States Department Of Agriculture: Washington, DC, USA, 2014.
5. Brose, P.H.; Dey, D.C.; Phillips, R.J.; Waldrop, T.A. A meta-analysis of the fire-oak hypothesis: Does prescribed burning promote oak reproduction in Eastern North America? *For. Sci.* **2013**, *59*, 322–334. [CrossRef]
6. Guyette, R.P.; Spetich, M.A. Fire history of oak-pine forests in the Lower Boston Mountains, Arkansas, USA. *For. Ecol. Manag.* **2003**, *180*, 463–474. [CrossRef]
7. Signell, S.A.; Abrams, M.D.; Hovis, J.C.; Henry, S.W. Impact of multiple fires on stand structure and tree regeneration in central Appalachian oak forests. *For. Ecol. Manag.* **2005**, *218*, 146–158. [CrossRef]
8. Keyser, T.L.; Arthur, M.; Loftis, D.L. Repeated burning alters the structure and composition of hardwood regeneration in oak-dominated forests of eastern Kentucky, USA. *For. Ecol. Manag.* **2017**, *393*, 1–11. [CrossRef]
9. Alexander, H.D.; Arthur, M.A.; Loftis, D.L.; Green, S.R. Survival and growth of upland oak and co-occurring competitor seedlings following single and repeated prescribed fires. *For. Ecol. Manag.* **2008**, *256*, 1021–1030. [CrossRef]
10. Green, S.R.; Arthur, M.A.; Blankenship, B.A. Oak and red maple seedling survival and growth following periodic prescribed fire on xeric ridgetops on the Cumberland Plateau. *For. Ecol. Manag.* **2010**, *259*, 2256–2266. [CrossRef]
11. Arthur, M.A.; Alexander, H.D.; Dey, D.C.; Schweitzer, C.J.; Loftis, D.L. Refining the Oak – Fire Hypothesis for Management of Oak-Dominated Forests of the Eastern United States. *J. For.* **2012**, *5*, 257–266. [CrossRef]
12. Blankenship, B.A.; Arthur, M.A. Stand structure over 9 years in burned and fire-excluded oak stands on the Cumberland Plateau, Kentucky. *For. Ecol. Manag.* **2006**, *225*, 134–145. [CrossRef]
13. Pyne, S.J.; Andrews, P.L.; Laven, R. *Introduction to Wildland Fire*, 2nd ed. revised; Wiley: Hoboken, NJ, USA, 1996.
14. Van Wagner, C.E.; Methven, I.R. Discussion: Two recent articles on fire ecology. *Can. J. For. Res.* **1978**, *8*, 491–492. [CrossRef]
15. Brose, P.H.; Schuler, T.M.; Ward, J.S. Responses of Oak and Other Hardwood Regeneration to Prescribed Fire: What We Know As Of 2005. In *Proceedings of the Fire in Eastern Oak Forests: Delivering Science to Land Managers*; Dickinson, M.B., Ed.; U.S. Department of Agriculture, Forest Service, Northern Research Station: Newton Square, PA, USA, 2005; pp. 123–135.
16. Dey, D.C.; Hartman, G. Returning fire to Ozark Highland forest ecosystems: Effects on advance regeneration. *For. Ecol. Manag.* **2005**, *217*, 37–53. [CrossRef]
17. Fan, Z.; Ma, Z.; Dey, D.C.; Roberts, S.D. Response of advance reproduction of oaks and associated species to repeated prescribed fires in upland oak-hickory forests, Missouri. *For. Ecol. Manag.* **2012**, *266*, 160–169. [CrossRef]
18. Rothermel, R.C.; Deeming, J.E. Measuring and interpreting fire behavior for correlation with fire effects. *Gen. Tech. Rep.* **1980**, *INT-93*, 6.
19. Butler, B.W.; Dickinson, M.B. Tree injury and mortality in fires: Developing process-based models. *Fire Ecol.* **2010**. [CrossRef]
20. Stephan, K.; Miller, M.; Dickinson, M.B. First-order fire effects on herbs and shrubs: Present knowledge and process modeling needs. *Fire Ecol.* **2010**, *6*, 95–114. [CrossRef]

21. Lutes, D.C.; Keane, R.E.; Reinhardt, E. FOFEM 6.0 User Guide. 2012; p. 65. Available online: https://www.frames.gov/catalog/12443 (accessed on 3 November 2022).
22. Bataineh, M.M.; Pelkki, M. Rehabilitation of cutover pak-hickory stands using prescribed burning and herbicide application: Decadal responses of vegetation. In *Proceedings of the 19th Biennial Southern Silvicultural Research Conference. e-Gen. Tech. Rep. SRS-234*; Kirschman, J.E., Johnsen, K., Eds.; USDA Forest Service, Southern Research Station: Asheville, NC, USA, 2018; pp. 347–354.
23. Harper, M.D.; Haley, G.J.; Phillips, W.W. *Soil Survey of Washington County, Arkansas*; United States Department of Agriculture: Washington, DC, USA, 1969.
24. Morris, T.W. Initial Effects of Prescribed Fire and Herbicide Treatments in Upland Oak Forests of the Arkansas Ozarks. Ph.D. Thesis, University of Arkansas at Monticello, Monticello, AR, USA, 2007.
25. Gingrich, S. Measuring and Evaluating Stocking and Stand Density in Upland Hardwood Forests in the Central States. *For. Sci.* **1967**, *13*, 38–53. [CrossRef]
26. Hiers, J.K.; O'Brien, J.J.; Mitchell, R.J.; Grego, J.M.; Loudermilk, E.L. The wildland fuel cell concept: An approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. *Int. J. Wildl. Fire* **2009**, *18*, 315–325. [CrossRef]
27. Walker, J.D.; Stocks, B.J. Thermocouple errors in forest fire research. *Fire Technol.* **1968**, *4*, 59–62. [CrossRef]
28. Kennard, D.K.; Outcalt, K.W.; Jones, D.; O'Brien, J.J. Comparing Techniques for Estimating Flame Temperature of Prescribed Fires. *Fire Ecol.* **2005**, *1*, 75–84. [CrossRef]
29. Bova, A.S.; Dickinson, M.B. Beyond "fire temperatures": Calibrating thermocouple probes and modeling their response to surface fires in hardwood fuels. *Can. J. For. Res.* **2008**, *38*, 1008–1020. [CrossRef]
30. McGranahan, D.A. An inconvenient truth about temperature–time data from thermocouples. *Plant Ecol.* **2020**, *221*, 1091–1104. [CrossRef]
31. Brown, J.K. *Handbook for Inventorying Downed Woody Material*; Gen. Tech. Rep. INT-16; U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1974.
32. Byram, G.M. Combustion of forest fuels. In *Forest Fire Control and Use*; Davis, K.P., Ed.; McCgraw-Hill Book Company: New York, NY, USA, 1959; pp. 61–89.
33. Moreno, J.M.; Oechel, W.C. A simple method for estimating fire intensity after a burn in California chaparral. *Acta Oecologica* **1989**, *10*, 57–68.
34. Wally, A.L.; Menges, E.S.; Weekley, C.W. Comparison of three devices for estimating fire temperatures in ecological studies. *Appl. Veg. Sci.* **2006**, *9*, 97. [CrossRef]
35. Zuur, A.F.; Ieno, E.N.; Walker, N.J.; Saveliev, A.A.; Smith, G.M. Zero-Truncated and Zero-Inflated Models for Count Data. In *Mixed Effects Models and Extensions In Ecology with R*; Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., Eds.; Springe: New York, NY, USA, 2009; pp. 261–293. ISBN 978-0-387-87458-6.
36. Team R. *R Development Core Team R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2013.
37. Alexander, M.E. Calculating and interpreting forest fire intensities. *Can. J. Bot.* **1982**, *60*, 2185. [CrossRef]
38. Scott, J.H.; Burgan, R.E. *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model*; Gen. Tech. Rep. RMRS-GTR-153; US Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2005; pp. 1–80.
39. Brose, P.H. Development of prescribed fire as a silvicultural tool for the upland oak forests of the Eastern United States. *J. For.* **2014**, *112*, 525–533. [CrossRef]
40. Knapp, B.O.; Hullinger, M.A.; Kabrick, J.M. Effects of fire frequency on long-term development of an oak-hickory forest in Missouri, U.S.A. *For. Ecol. Manag.* **2017**, *387*, 19–29. [CrossRef]
41. Johnson, P.S.; Shifley, S.R.; Rogers, R. *The Ecology and Silviculture of Oaks*, 2nd ed.; CABI Publishing: New York, NY, USA, 2009; ISBN 0851995705.
42. Hengst, G.E.; Dawson, J.O. Bark properties and fire resistance of selected tree species from the central hardwood region of North America. *Can. J. For. Res.* **1994**, *24*, 688–696. [CrossRef]
43. Paulsell, L.K. *Effects of Burning of Ozark Hardwood Timberlands*; University of Missouri, College of Agriculture, Agricultural Experiment Station: Columbia, MO, USA, 1957; Volume 640.
44. Huddle, J.A.; Pallardy, S.G. Effect of fire on survival and growth of Acer rubrum and Quercus seedlings. *For. Ecol. Manag.* **1999**, *118*, 49–56. [CrossRef]
45. Hartman, G.W. Changes in fuel loading as the result of repeated prescribed fires within the Ozark forests of Missouri. In *Proceedings of the 14th Central Hardwood Forest Conference-GTR NE-316*; Yaussy, D.A., Hix, D.M., Goebel, P.C., Long, R.P., Eds.; U.S. Department of Agriculture, Forest Service, Northeastern Research Station: Newton Square, PA, USA, 2004; pp. 162–167.
46. Anderson, H.E. *Aids to Determining Fuel Models for Estimating Fire Behavior*; General Technical Report INT-122; U.S. Department of Agriculture, Forest Service: Ogden, UT, USA, 1982.