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Effects of Prescribed Fire on Planted Oak Growth and Survival in Restored Savannas

Allison Earl

Eastern Illinois University

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Abstract

Most oak savannas in the Midwestern United States have been lost to agriculture and habitat degradation. Because of their rarity and ability to support high plant and animal diversity, savannas are often a target for restoration. Oak savanna restoration frequently relies on direct planting of oak seedlings to establish the necessary tree canopy. Returning fire to the system is critical to the herbaceous component of the savanna, but managers risk damaging or killing trees if burning is introduced too soon. I studied growth and physiological responses of three oak species (*Quercus alba*, *Q. macrocarpa*, and *Q. velutina*) to prescribed fire to determine impacts on previously planted trees. This study utilized two restored oak savanna units that were planted in 1995 and 1998, each with burned and unburned areas. I tracked trees ranging from 0.9 to 29.8 cm in diameter to determine the size threshold above which top kill is unlikely, and documented differences in leaf structure and extension growth between burned and unburned portions of each area. There was no mortality observed and no trees larger than 4 cm diameter at breast height (dbh) were top killed by the fire. Fire responses in leaf mass per unit area and chlorophyll content were small and inconsistent across species and units. However, all oak species grew more in burned areas than trees in adjacent unburned areas. Therefore, the addition of low intensity prescribed fire to an oak savanna planting may increase the growth rate of planted trees with minimal risk of mortality.

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Thesis Director

Scott J. Meiners

Thesis Committee Member

Eric K. Bollinger

Thesis Committee Member

Robert E. Colombo

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Allison Earl

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Abstract

The majority of oak savannas in the Midwestern United States have been lost to agriculture and habitat degradation. Because of their rarity and their ability to support high plant and animal diversity, savannas are often a target for restoration. Oak savanna restoration frequently relies on direct planting of oak seedlings to establish the necessary tree canopy. Returning fire to the system is critical to the herbaceous component of the savanna, but managers risk damaging or killing trees if burning is introduced too soon. I studied growth and physiological responses of three oak species (*Quercus alba*, *Q. macrocarpa*, and *Q. velutina*) to prescribed fire to determine impacts on previously planted trees. This study utilized two restored oak savanna units that were planted in 1995 and 1998, each with burned and unburned areas. I tracked trees ranging from 0.9 to 29.8 cm in diameter to determine the size threshold above which top kill is unlikely, and documented differences in leaf structure and extension growth between burned and unburned portions of each area. There was no mortality observed and no trees larger than 4 cm diameter at breast height (dbh) were top killed by the fire. Fire responses in leaf mass per unit area and chlorophyll content were small and inconsistent across species and units. However, all oak species grew more in burned areas than trees in adjacent unburned areas. Therefore, the addition of low intensity prescribed fire to an oak savanna planting may increase the growth rate of planted trees with minimal risk of mortality.

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Introduction

Temperate savannas, which occupy only 0.02% of their historical range in the Midwestern United States (Nuzzo 1986), are among the most at-risk biomes because of their high rate of conversion to other land uses and low rate of protection (Hoekstra et al. 2005). Though tree diversity in savannas is low, dominated by one to a few oak (*Quercus*) species (Dey & Kabrick 2015), the interaction between spatially heterogeneous habitats and intermediate disturbance frequency results in high herbaceous plant species richness (Peterson & Reich 2008; Dey & Kabrick 2015). Savannas also support a high wildlife diversity and many species of conservation concern, including birds, bats, and the endangered Karner blue butterfly (*Lycaeides melissa samuelis*, Dey & Kabrick 2015). Fire, the main disturbance in oak savannas, contributes to the heterogeneity of the landscape because it does not occur evenly, leaving a mosaic of burned and unburned patches (Hutchinson et al. 2008). Loss of oak savannas to agriculture and fire suppression has contributed to the homogenization of the landscape, increasing susceptibility to invasive species, disease outbreaks, and climate change (Dey & Kabrick 2015).

Historically, oak savannas in the Midwestern United States were maintained by anthropogenic burning (Hutchinson et al. 2012). Oaks, with their thick bark, efficient wound compartmentalization, deep root collar buds, and high sprouting capacity, are well-suited to withstand periodic burning (Smith & Sutherland 1999; Brose & Van Lear 2004; Hutchinson et al. 2012). In the absence of burning, fire-sensitive shrubs and trees can become established in savannas, eventually generating a closed-canopy forest (Peterson & Reich 2001; Haney et al. 2008; Hutchinson et al. 2008). Though there can be an initial increase in oak recruitment after fire suppression (Abrams 1992), shade-tolerant species such as maples (*Acer* spp.) become the stronger competitors as the canopy closes, displacing oaks (Hutchinson et al. 2008, 2012). After fire suppression and canopy closure, oaks generally have poor regeneration even with canopy gaps (Hutchinson et al. 2008).

Burning may have several direct and indirect impacts on oaks. There can be damage from the fire that directly impairs stem function (Smith & Sutherland 2005). Trees that resprout after a burn have higher photosynthetic rates than unburned plants (Fleck et al. 1996, 1998). Resprouts may also have a smaller leaf area index on a larger root system and, therefore, less water limitation to photosynthesis (Fleck et al. 1998; Rieske 2002). Furthermore, nitrogen mineralization rates increase following prescribed fire, which can lead to a burst of plant growth (Dijkstra et al. 2006) and altered leaf chemistry (Kay et al. 2007). The ultimate utility of reintroducing a fire regime into a savanna restoration will be determined by the balance between negative and positive effects of burning on both oaks and herbaceous flora.

Because oak savanna restoration is a slow process and has only recently become a common restoration target, there is relatively little literature available on the practice. The methods used to restore or create an oak savanna depend on the starting conditions. In degraded savannas that have experienced canopy closure, a common technique is to thin the stand and reintroduce fire (Packard & Mutel 2005). The other approach, most often used when starting with abandoned agricultural land, is to plant trees into a grassland. The benefits of this technique are planted tree seedlings may grow faster than those that naturally recruit (Lorimer et al. 1994) and the ability to control tree species composition. However, this method is slower and less well studied, as most of the oak savanna restoration literature documents thinning practices (e.g., Brudvig et al. 2011; Lettow et al. 2014; Abella et al. 2020).

One challenge of planting oaks into new sites is that young oaks are more susceptible to fire than older trees. Death of the aboveground stem, followed by resprouting (top kill), is common for trees less than 12.7 cm in basal diameter (Dey & Fan 2009). If prescribed burning is done too frequently, resprouts may deplete root reserves and die (Brose et al. 2006). Larger trees are more likely to survive because they have thicker insulating bark (Harmon 1984), providing better protection to essential plant tissues (Spalt & Reifsnyder 1962; Keyser et al. 2018). In degraded savannas with a history of fire exclusion, 4 fires/decade were needed to stabilize the shrub layer and prevent dominance by non-oak species (Haney et al. 2008). In planted savannas, to protect young trees yet still maintain savanna structure, mechanical control (e.g., mowing) in place of prescribed fire may be needed for several years after planting (Packard & Mutel 2005). Alternatively, dry vegetation around the base of young trees can be removed or wetted prior to a prescribed fire (Packard & Mutel 2005), but this is impractical at large scales. Abella et al. (2020) found the benefits of savanna restoration were quickly lost if management practices became infrequent and allowed competitive woody species to displace open-habitat species. While mowing mimics some effects of prescribed fire, it is not a perfect substitute because it results in reduced species richness (Rooney & Leach 2010). Prescribed fire is also the more cost-efficient option in most cases (Packard & Mutel 2005). Despite the complications associated with oak savanna creation, the large number of oak savannas converted to agriculture necessitates that some restorations must start from scratch.

This study looked at planted oak growth and survival after prescribed fires in oak savanna restorations in northern Illinois. Responses of planted oaks were tracked to address the following research questions: 1) Is there a threshold of tree diameter above which risk of top kill from prescribed fire is low? 2) Does prescribed fire generate differences in leaf physiology? and 3) Does prescribed fire alter oak growth?

Methods

Study Site

Research took place at the Richardson Wildlife Foundation in West Brooklyn, IL (41°42’ N, 89°11’ W). Two management units planted to oak savanna and scheduled for prescribed burns were selected for study (Figure 1). Oak species planted in the units include *Quercus alba* (white oak), *Q. macrocarpa* (bur oak), and *Q. velutina* (black oak). *Quercus rubra* (red oak) and *Q. palustris* (pin oak) were also planted, but were not included because these are less common upland savanna species (Abrams 1992). Unit 1 is approximately 6 ha and was planted to oaks in 1995. It received its first prescribed burn in 2019. Unit 2 is about 4 ha, was planted in 1998, and had never been burned. Both units were formerly in row crop rotations and then seeded to cool season pasture grasses. Oaks were planted within a year of the grasses using bare root stock with an initial distance of 2.7 m between trees. Winter interseeding of native grasses and forbs occurred in 2012 for Unit 1 and 2010 and 2016 for Unit 2. Unit 2 also received mowing and herbicide treatments between 2000-2010 to control *Cirsium arvense* (Canada thistle). A firebreak was mown through each unit and one section of each was burned 17 March 2022, producing burned and unburned areas in each.

Experimental Design

Prior to the burn, up to 40 trees each of three savanna oak species (*Quercus alba* [white oak], *Q. macrocarpa* [bur oak], and *Q. velutina* [black oak]) were marked in each half of the units (Table 1). Locations of the trees were recorded using a GPSMAP 66s (Garmin Ltd., Olathe, KS, USA). Due to differences in seedling availability at planting, trees were not distributed evenly across the units, resulting in varying sample sizes. Trees were selected to represent a range of sizes and understory cover density in an attempt to capture a gradient of fire severity and potential tree responses.

For all trees sampled, the diameter at breast height (dbh) and 2021 extension growth of four lateral branches of each tree were measured to reflect pre-burn performance. The morning of the burn, a 5500FW Fire Weather Meter Pro (Kestrel Instruments, Boothwyn, PA, USA) was placed adjacent to one of the units to monitor the weather conditions throughout the day. In addition, pyrometers were placed 0.5 meter from the north side of the base of each tree in the burned subunits to measure the surface temperature during the fire (Cole et al. 1992; Wally et al. 2006). An additional 22 pyrometers were placed in Unit 1 and 10 pyrometers in Unit 2 in open areas away from trees. The pyrometers were constructed by painting copper tags with 11 lacquers (OMEGALAQ Liquid Temperature Indicating Lacquers, Omega Engineering Inc., Norwalk, CT, USA), which liquify at different temperatures (149 – 399°C, Wally et al. 2006). The maximum temperature of the fire at the location of the pyrometer is between the last lacquer that changed appearance and the first that did not. The lower temperature value was recorded. If no lacquer changed appearance, a value of 20°C was recorded to represent the ambient air temperature. A second copper tag was stapled on top of the painted tag to prevent char and soot accumulation (Wally et al. 2006).

Five days after the burn, the scorch height and the percent of the surface area scorched on the bole of each tree were measured (Regan & Agee 2004). Scorch height was measured from the ground to the highest point on the bole where char was evident (Keyser et al. 2018). The percent of the bole scorched to the maximum scorch height was visually estimated. Scorch height and stem size have been shown to be correlated with stem mortality of deciduous, broadleaved species (Rebain et al. 2010; Keyser et al. 2018). These measures, in combination with the pyrometer data, assess the intensity of the burn at the scale of each tree (Wally et al. 2006; Keyser et al. 2018), which can be related to tree mortality (Loomis 1973). This is important because fire behavior is complex, and unlikely to uniformly impact a management unit (Cole et al. 1992).

The units were visited twice during the 2022 growing season. In the last week of June, two leaves were collected from each tree and their chlorophyll content was measured (CL-01 Chlorophyll Content Meter, Hansatech Instruments Ltd, Pentney, King's Lynn, Norfolk, UK) in the field. The leaves were packed in whirl-pac bags with a moist paper towel and kept refrigerated until their surface area was measured (LI-3100 Area Meter, LI-COR Biosciences, Lincoln, NE, USA). The leaves were dried at 60°C for at least four days, and their biomass measured. These data were used to calculate leaf mass per unit area (LMA), a measure of the leaf's dry-mass investment per unit of area (Wright et al. 2004) related to plant growth and resource acquisition strategies (Poorter et al. 2009). Any trees that had been top killed but resprouted were noted. In the second week of August, lateral extension growth of four branches of each tree was measured for the 2022 growing season to compare with pre-burn data.

Data analyses

Pyrometer data showed little variation in surface temperatures and was not included as a factor in analyses. To assess the probability of top kill, a multiple logistic regression was run, using species, dbh, scorch height, and scorch percent as predictors. Extension growth values for each tree were averaged and the 2021 average subtracted from the 2022 average to get the absolute change in growth for each tree. Preliminary analyses used dbh as a covariate for each species but was not significant and was dropped from all analyses. Responses to the burn for change in growth, LMA, and average chlorophyll content were analyzed with three-way factorial ANOVAs that included unit, area (burned vs unburned), and species (*Q. alba*, *Q. macrocarpa*, or *Q. velutina*). Top killed trees were excluded from these analyses. Linear regression was used to test whether scorch height or percent was related to change in growth, LMA, or chlorophyll content. All analyses were conducted with R version 4.1.2 (R Core Team 2021).

Results

Pre-burn Summary

Although, initial sizes and extension growth within species and units/treatments did not vary dramatically, the average dbh of the *Q. macrocarpa* trees in the unburned area of Unit 1 was significantly larger and had greater growth than the burned area (Table 2, Figure 2, Figure 3). Overall, marked trees ranged from 0.9 to 29.8 cm in diameter. Units differed in dbh for *Q. macrocarpa* and for dbh and extension growth for *Q. velutina*.

Prescribed Burn Conditions

Firing operations for Unit 1 occurred between 1300 and 1530. The average air temperature during the burn was 19.6°C, average relative humidity was 45.5%, and average wind speed was 1.2 m/s. The average minimum surface temperature at marked trees was 333°C (95% CI, 322-344°C) compared to a slightly higher average of 351°C in open areas. The average scorch height and scorch percent were 68.0 cm (95% CI, 58.7-77.3 cm) and 32.6% (95% CI, 28.2-37.0%), respectively. Unit 2 was burned immediately after Unit 1 and finished at 1730. During the second burn, average air temperature was 18.1°C, average relative humidity was 40.8%, and average wind speed was 1.2 m/s. The average minimum surface temperature at the marked trees was 330°C (95% CI, 319-342°C) and in open areas, the average minimum surface temperature was higher at 365°C. The average scorch height and scorch percent were 35.0 cm (95% CI, 30.3-39.7 cm) and 34.7% (95% CI, 28.6-40.7%). No basal scarring was noted in either unit.

Mortality

There was no mortality caused by fire in the marked trees, but 14 trees (4 *Q. alba*, 4 *Q. macrocarpa*, and 6 *Q. velutina*) were top killed in Unit 1 and five trees (4 *Q. alba* and 1 *Q. macrocarpa*) were top killed in Unit 2. The largest top killed tree was a 4 cm *Q. macrocarpa* and in total, 40% of the trees 4 cm dbh or less in the burned areas were top killed. No trees were top killed in the unburned areas. In a logistic regression, increasing tree diameter reduced the probability of being top killed (coefficient = -2.15, P = 0.0002, Figure 4). Greater scorch height increased the probability of being top killed (coefficient = 0.03, P = 0.014), but the percentage of the trunk scorched was unrelated (coefficient = 0.01, P = 0.579). *Quercus velutina* trees had a higher probability of top kill (coefficient = 2.99, P = 0.017) than *Q. alba* and *Q. macrocarpa*, which did not differ (coefficient = 0.38, P = 0.716).

Leaf Characteristics

Trees in Unit 1 had lower LMA than trees in Unit 2, and trees in unburned areas generally had a greater LMA than trees in burned areas, although this varied across units (Table 3, Figure 5). The LMA of trees in Unit 1 did not respond to burning, whereas trees in Unit 2 had greater LMA in the unburned area. Leaf mass per unit area was unrelated to local burn intensity as measured by scorch height ($F_{1, 186\ df} = 0.005$, $R^2 < 0.0001$, $p = 0.946$) and scorch percent ($F_{1, 186\ df} = 0.169$, $R^2 = 0.0009$, $p = 0.681$).

Burning altered leaf chlorophyll content (Table 3, Fig 6), but this varied dramatically across units and species. Trees in the burned area of Unit 1 had a lower chlorophyll content than trees in the unburned area, whereas tress in the burned area of Unit 2 had a slightly higher chlorophyll content. There was also a significant interaction between area and species. Chlorophyll content was higher in the unburned areas for *Q. alba* and *Q. macrocarpa* in unit 1, but lower for *Q. velutina* in unit 2. Average chlorophyll content was weakly and negatively related to scorch height ($F_{1, 186\ df} = 8.02$, $R^2 = 0.041$, $p = 0.005$) but there was no relationship with the percentage of the trunk scorched ($F_{1, 186\ df} = 1.31$, $R^2 = 0.007$, $p = 0.254$).

Growth

Growth varied dramatically between burned and unburned areas, but this again varied with unit (Table 3, Figure 7). Trees in Unit 1 (second burn) had a greater increase in extension growth with burning than trees in Unit 2 (first burn). In contrast, trees in unburned areas of both units had about equal extension growth (i.e., no change in growth) in 2022 and 2021. Neither scorch height ($F_{1, 187\ df} = 3.526$, $R^2 = 0.019$, $p = 0.062$) nor scorch percent ($F_{1, 187\ df} = 3.568$, $R^2 = 0.019$, $p = 0.060$) was significantly related to change in extension growth.

Discussion

Oak mortality in response to fire was not an issue in this site as none of the surveyed trees died. Furthermore, top kill was uncommon and only occurred in the smallest trees. However, mortality may occur several growing seasons after a fire (Brose et al. 2006), so my data may underestimate stem mortality. There were also some non-lethal effects of the fire noted in the field, particularly in Unit 1. The fire partially or completely killed lower branches on some trees. This was more common in the northern part of the unit, where trees were denser, and may be related to the higher scorch height observed in Unit 1 or the 2019 burn.

In the growing season after the fire, risk of being top killed was similar for *Q. alba* and *Q. macrocarpa*, but higher for *Q. velutina*; differences among species were minor. Regardless of species, in restorations with small trees, conducting a low intensity, dormant season burn in a restored savanna after the trees are greater than 5 cm dbh should greatly reduce the risk of top kill. This tree size is smaller than suggested by Arthur et al. (2012), who found top kill common in trees 10-20 cm dbh in oak-dominated forests. Our threshold of 5 cm dbh is in line with Hruska & Ebinger (1995), who concluded trees in a restored savanna should be greater than 3 m tall to escape top kill, relating to a basal diameter of 2.4-4.25 cm. Depending on local site conditions, lowering the size threshold should allow the implementation of prescribed fire earlier than the 20 to 30 year age suggested by Dey & Kabrick (2015).

The effects of the prescribed burns on leaf physiological characteristics were less clear as changes induced by fire were generally small and inconsistent across units. The fire appeared to cause a decrease in LMA in Unit 2, but not Unit 1. This contrasts with studies conducted in forests, in which burned white and red oak seedlings had a significantly higher LMA than unburned seedlings (Gilbert et al. 2003; Alexander & Arthur 2009). Perhaps this is because the seedlings in these studies experienced an increase in light availability after the burn, which is associated with increased LMA (Ellsworth & Reich 1993). Low LMA is associated with higher foliar nutrient concentrations (Wright et al. 2004), so an increase in nutrient availability after the burn may have contributed to the lower LMA in Unit 2, which had received its first burn. LMA is also a plastic trait that changes with size and age, leading to different conclusions between seedlings and saplings (Husk & Warton 2007).

Leaf chlorophyll content was even more confounded, with burn treatment only being significant when interacting with unit or species. Because chlorophyll content and leaf N content are positively related (Percival et al. 2008), I would expect to see an increase in chlorophyll content with the increase in available N as a result of the fires. Instead, *Q. macrocarpa*, which had the most consistent sample size across units and burn areas, reacted to the burn in opposite directions in the different units. Overall, mean chlorophyll content in the unburned areas was 13% higher in Unit 1, but 9% lower in Unit 2. This magnitude of change is similar to measurements of *Q. rubra* across light treatments (Rebbeck et al. 2012), but because the differences I detected were not consistent between units, the prescribed burns likely had minimal impact on photosynthetic processes.

The absolute change in extension growth had a clear response to the burn treatment. In both units, trees grew more in the burned areas than in the unburned areas, whereas growth in unburned portions of both units was largely unchanged. Although small differences in extension growth between the units and treatment areas existed prior to the burn, differences became much stronger after the burn. For example, in 2021 (pre-burn), *Q. macrocarpa* in the burned area of Unit 1 grew on average 17% more than in the unburned area, but in 2022, grew 66% more. An increased growth rate may speed recruitment into the overstory (Brudvig et al. 2011). The response of Unit 2 was smaller than Unit 1. There could be a stronger impact on growth after a second burn, but this cannot be fully tested with my data. Because the increase in growth was larger in Unit 1, where there was no difference in LMA and a decrease in chlorophyll content in the burned area, the increase in growth was not a direct result of changes in photosynthetic processes. It is unknown whether the differences in growth will persist for more than one season. Increases in height growth of oak seedlings in a pine-oak forest persisted for three growing seasons post-fire (Gilbert et al. 2003). Yet, increases in plant available soil N as a result of fire disappear after one year (Wan et al. 2001), so the increase in growth of these larger trees may be similarly short-lived.

Overall, the trees in this study responded positively to the prescribed burn. Because there was no mortality and only the smallest trees were top killed, it may be feasible to use dormant season prescribed fire as a tool to increase the growth of planted trees, especially once they exceed 5 cm dbh. Increased growth in burned areas suggests that fire will improve oak growth in the short term, speeding the development of a more mature savanna canopy. Most importantly, the introduction of fire into developing savanna restorations will reduce the cover of aggressive shrubs which are often responsible for the degradation of remnant savannas (Peterson & Reich 2001; Haney et al. 2008; Brudvig et al. 2011). Fires should also allow the expansion of the diverse and heterogeneous forb understory characteristic of savannas, often the initial motivation behind savanna restoration.

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Table 1. Number of trees tracked in the burned and unburned areas of the two study units at Richardson Wildlife Foundation.

	Unit 1		Unit 2	
Species	Burned	Unburned	Burned	Unburned
Q. alba	40	4	40	40
Q. macrocarpa	39	40	40	40
Q. velutina	40	40	9	7

Table 2. Influence of study site (Unit 1 vs. Unit 2) and treatment areas (burning) on average initial sizes and pre-burn (2021) extension growth of the trees included in the study, separated by species. Significant model terms indicated in bold.

	Dbh			Extension growth		
Factor	F	P	R^2	F	P	R^2
Q. alba						
Unit	2.76	0.0993	0.043	1.40	0.2383	0.015
Burn Treatment	2.57	0.1117		0.06	0.8084	
Unit × Burn	<0.01	0.9883		0.35	0.5581	
Error						
Q. macrocarpa						
Unit	43.12	**<0.0001**	0.292	1.98	0.1619	0.039
Burn Treatment	13.36	**0.0004**		4.27	**0.0405**	
Unit × Burn	7.51	**0.0069**		0.10	0.7534	
Error						
Q. velutina						
Unit	12.28	**0.0007**	0.137	9.80	**0.0023**	0.129
Burn Treatment	2.34	0.1296		0.59	0.4436	
Unit × Burn	0.03	0.8719		3.19	0.0774	
Error						

Table 3. Influence of unit (Unit 1 vs. Unit 2), burn treatmeant (burned vs. unburned), and species (*Q. alba*, *Q. macrocarpa*, or *Q. velutina*) on the responses of LMA, chlorophyll content, and absolute change in growth. Significant model terms indicated in bold.

Factor	df	MS	F	P	R^2
LMA					
Unit	1	66.24	24.76	**<0.0001**	0.154
Burn Treatment	1	30.18	11.28	**0.0009**	
Species	2	0.64	0.24	0.7869	
Unit × Burn	1	40.10	14.99	**0.0001**	
Unit × Species	2	4.52	1.69	0.1861	
Burn × Species	2	8.00	2.99	0.0516	
Unit × Burn × Species	2	3.23	1.21	0.2999	
Error	347	2.68			
Chlorophyll content					
Unit	1	61.07	6.53	**0.0110**	0.113
Burn Treatment	1	7.86	0.84	0.3600	
Species	2	69.82	7.46	**0.0007**	
Unit × Burn	1	123.47	13.20	**0.0003**	
Unit × Species	2	2.63	0.28	0.7555	
Burn × Species	2	36.21	3.87	**0.0218**	
Unit × Burn × Species	2	0.90	0.10	0.9082	
Error	347	9.36			
Absolute change in growth					
Unit	1	629.09	8.44	**0.0039**	0.125
Burn Treatment	1	1814.57	24.34	**<0.0001**	
Species	2	35.26	0.47	0.6236	
Unit × Burn	1	468.53	6.28	**0.0126**	
Unit × Species	2	172.01	2.31	0.1011	
Burn × Species	2	60.86	0.82	0.4429	
Unit × Burn × Species	2	122.82	1.65	0.1941	
Error	348	74.56			

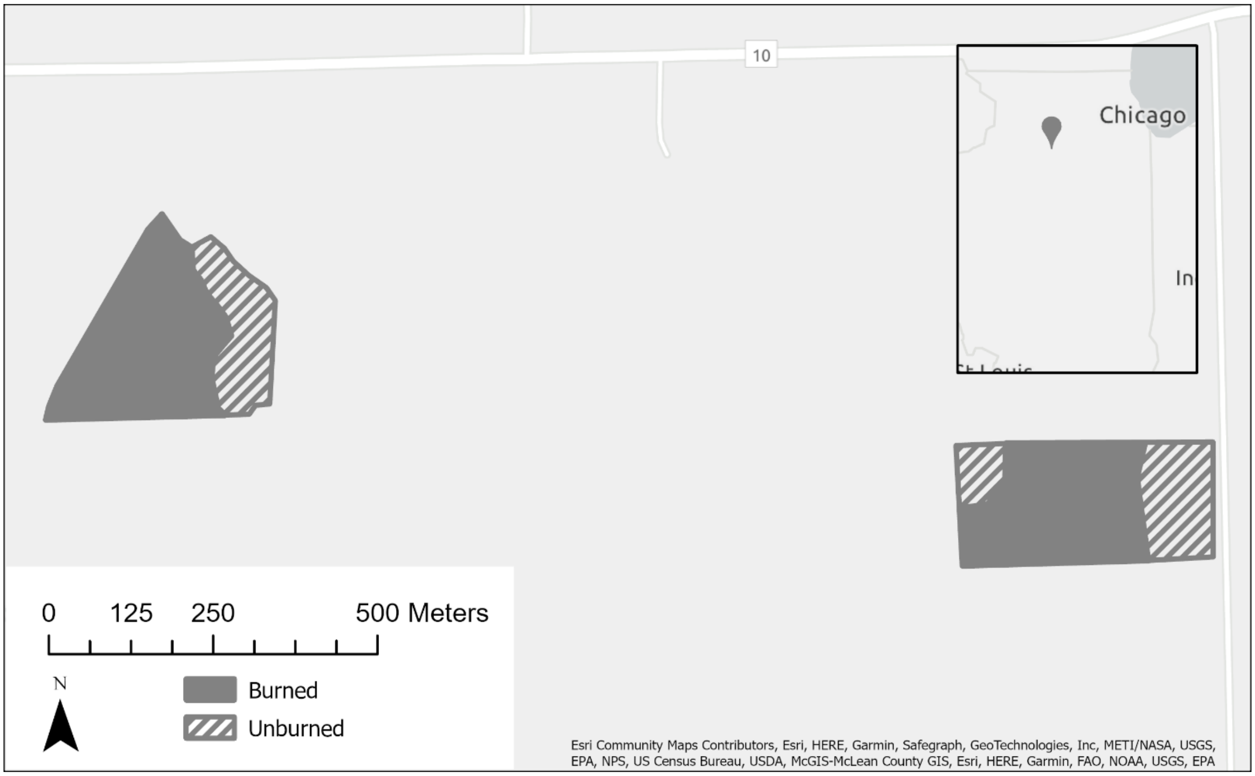

Figure 1. Map showing the location of Richardson Wildlife Foundation within Illinois (inset) and the locations of the study sites. Unit 1 is to the west of Unit 2. Burned areas are show in solid grey and unburned areas in hatched grey.

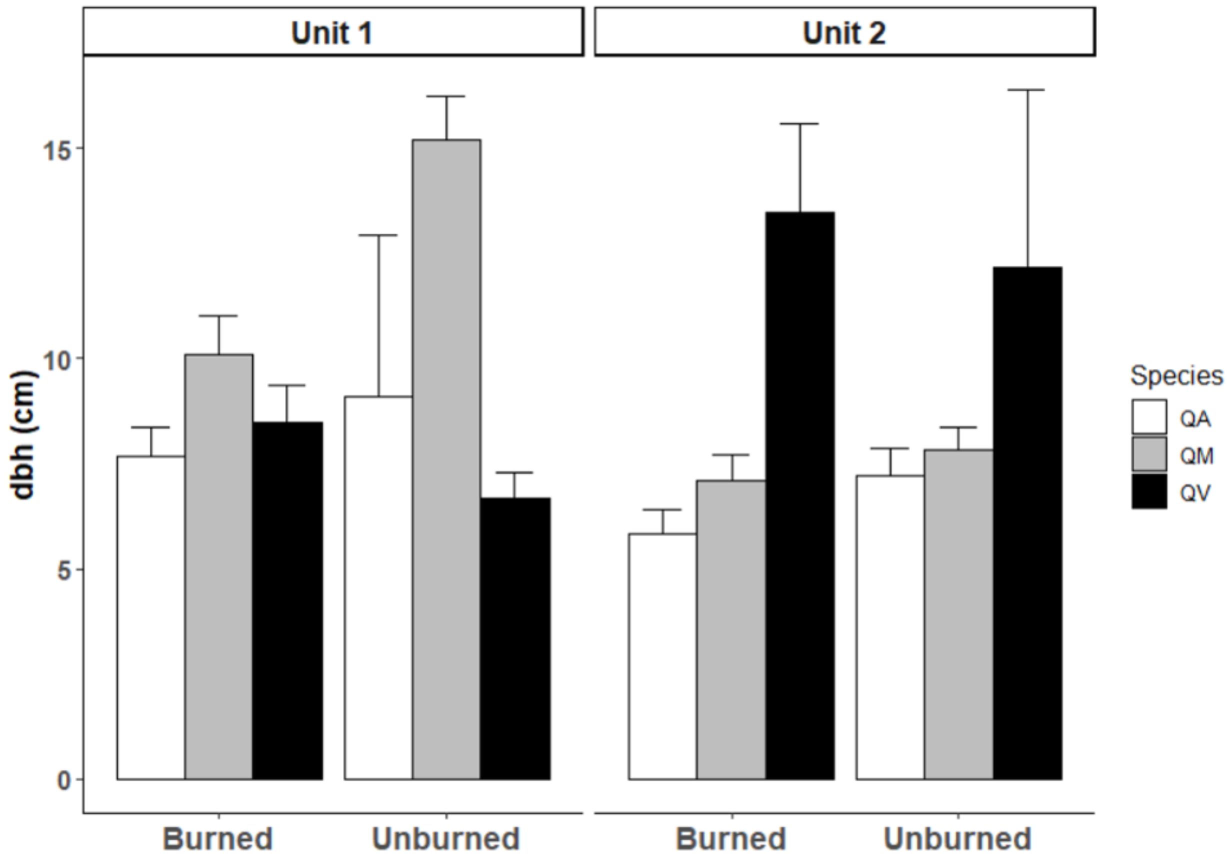

Figure 2. Variation in tree size of each trees species in each unit and burn treatment prior to the experiment. Error bars represent one SEM.

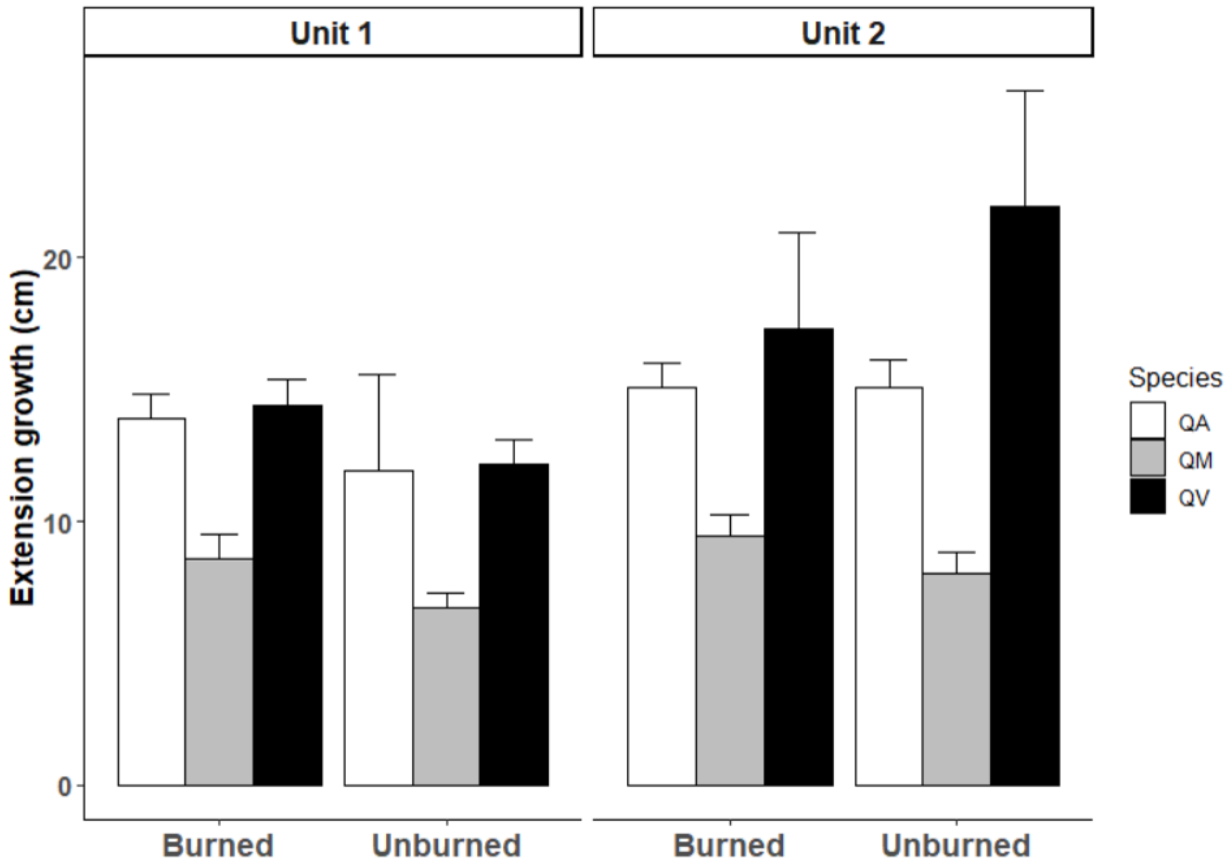

Figure 3. Variation in extension growth of each tree species in each unit and burn treatment prior to the experimental burn. Error bars represent one SEM.

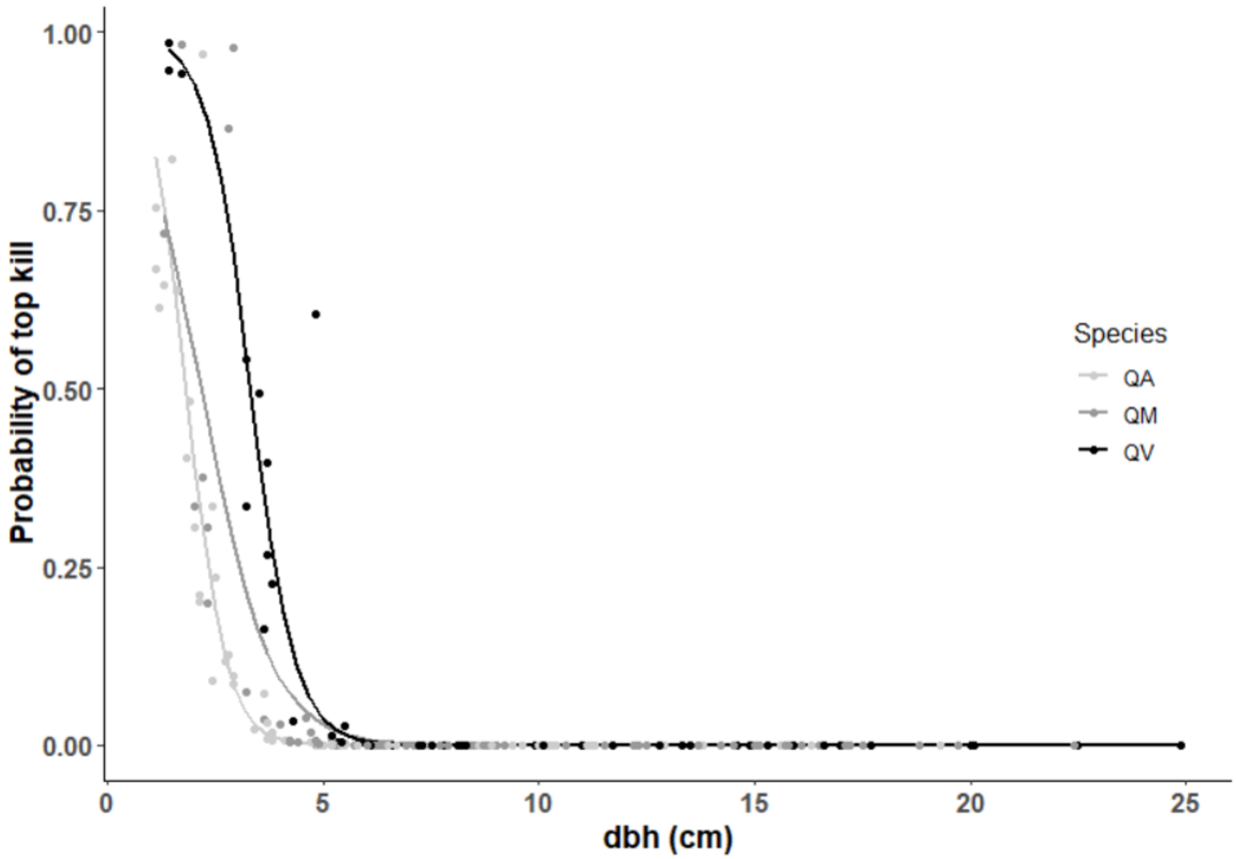

Figure 4. Probability of being top killed by fire as a function of initial tree size for the three *Quercus* species. Predictions from a logistic regression that included dbh, species, and scorch height as predictors.

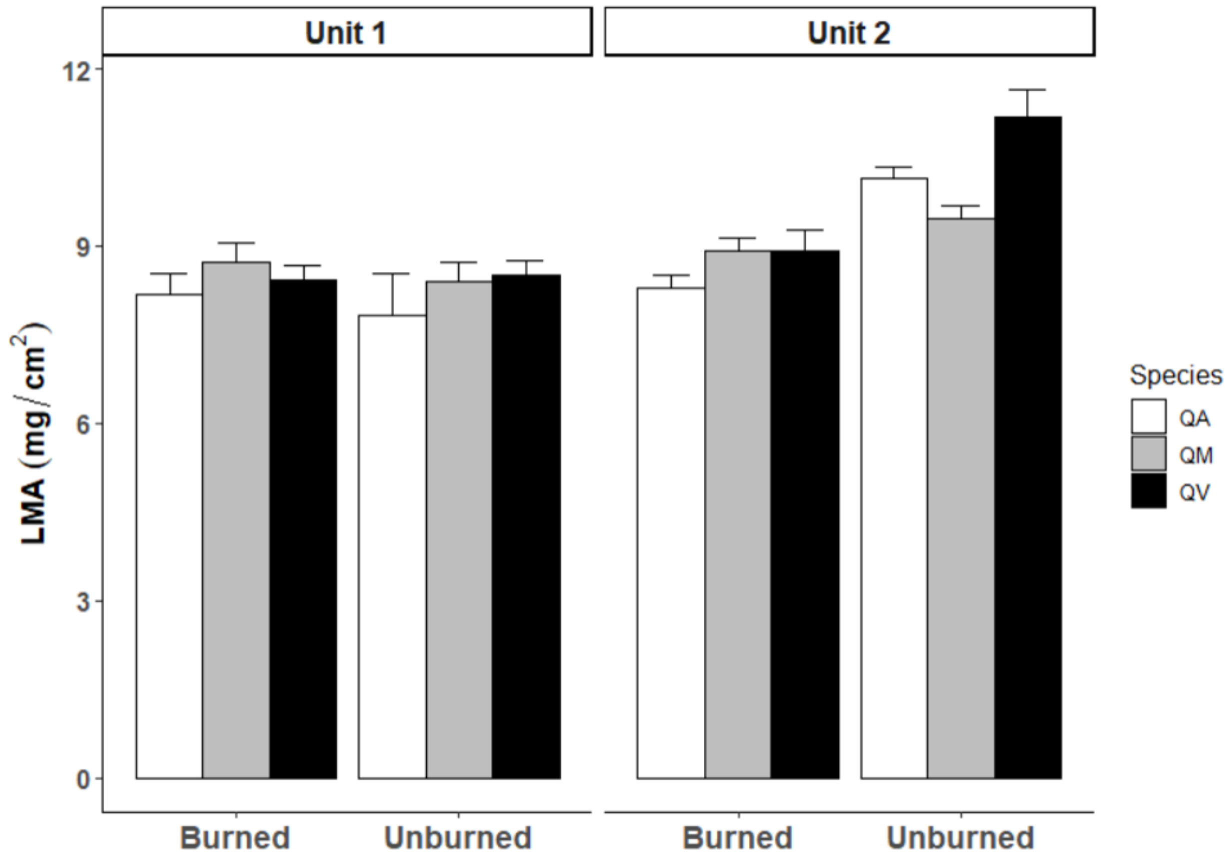

Figure 5. Influence of burn treatment, unit, and species on leaf mass per unit area. Excludes top killed individuals. Error bars represent one SEM.

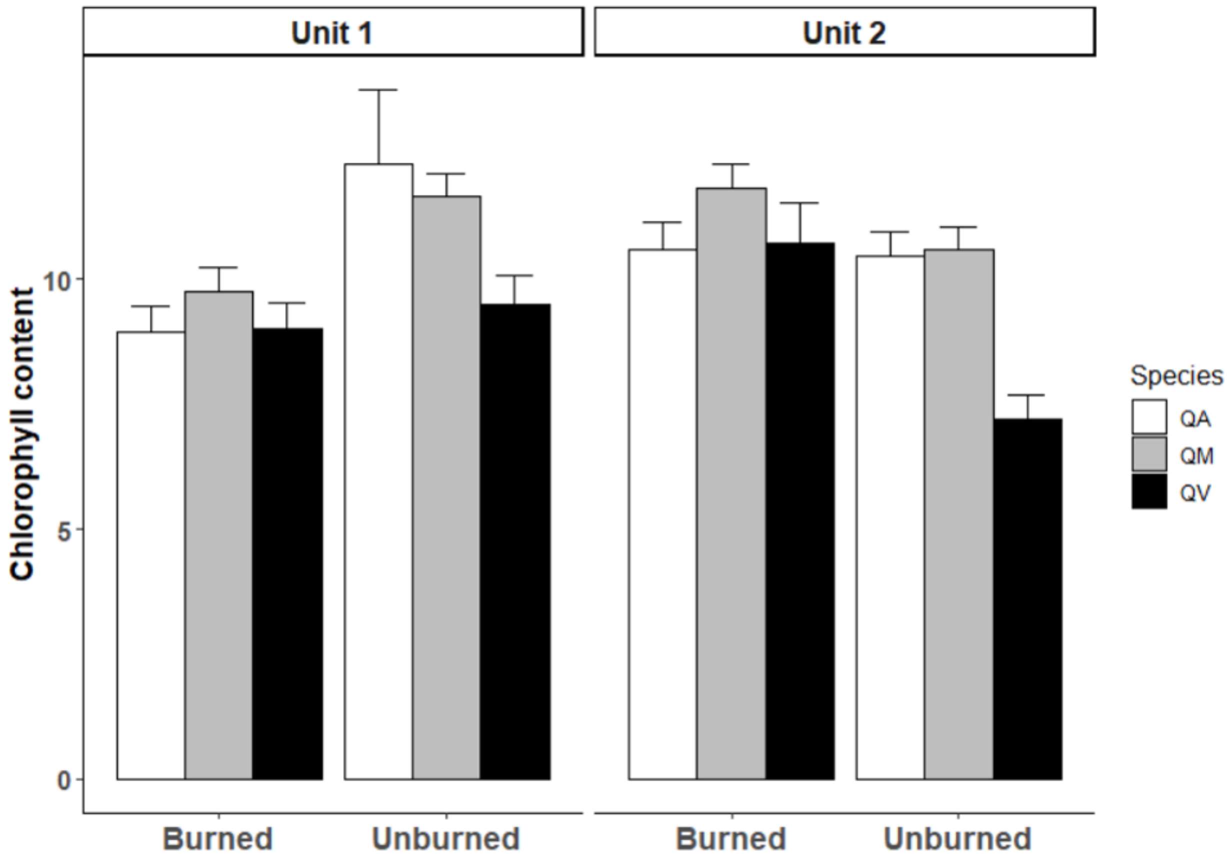

Figure 6. Response of chlorophyll content to burn treatment, separated by unit and species. Chlorophyll content units are relative. Excludes top killed individuals. Error bars represent one SEM.

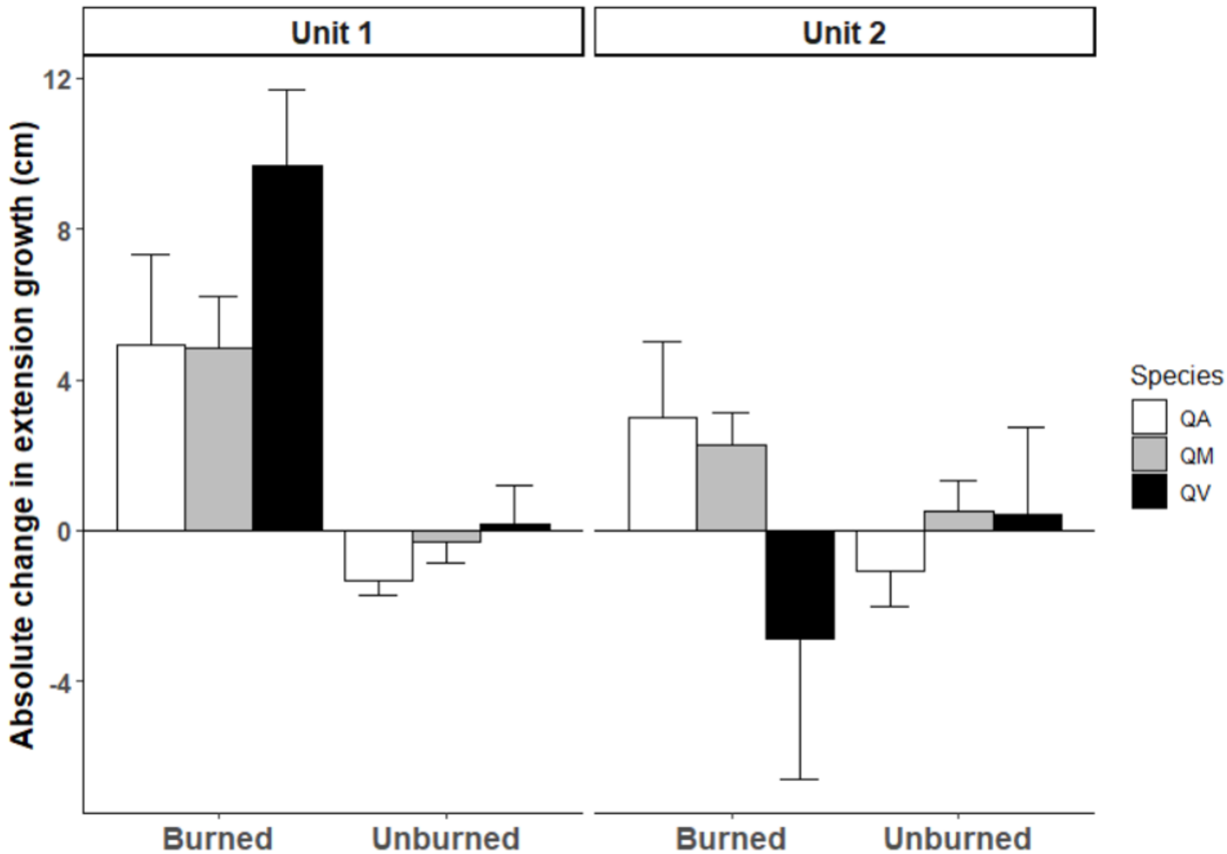

Figure 7. Response of absolute change in extension growth (2021 to 2022) to burn treatment, unit, and species. Excludes top killed individuals. Error bars represent one SEM.