Effects of Physiography and Fuel Characteristics on Fire Behavior

Thesis

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Abstract

Future predictions show dramatic increases in fire probability in the eastern U.S. where more frequent and human-caused fires exist compared to the west. Therefore, more attention needs to be given to understanding the factors of fire behavior and fire environment in eastern forests. However, quantification of future trends in fire activity is challenging owing to the lack of spatially complete and consistently derived data. The regional and spatial variability, complex and non-linear interactions between weather, vegetation, and human activity add more uncertainty to future fire behavior. In this study, we examined the potential effects of topographic variables and forest attributes on the fire environment at the fine scale in southeast Ohio. Ninety-four plots were established to quantify three factors of terrain: aspect, slope position, and slope steepness (^{o}). Fuel loads and fuel composition were analyzed to capture the interaction of terrain and fuel. Over the three topographic variables, aspects and slope position played a major role in the differences in forest structure and certain species abundance. This subsequently influenced the composition and characterization of the fuels. An ignition experiment was conducted under controlled laboratory conditions to determine how the differences in fuel composition, based on species, arising from different topographic positions can influence the potential differences in fire behavior. A linear correlation was found between fuel

load composition (oak vs. maple) and forest attributes. Significant differences in the flame temperature between oak and maple were discovered.

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Chapter 1 Review of the Literature

Wildland fire is a widespread and fundamental ecosystem process that can contribute to the carbon cycle and subsequently influence the climate system via CO_2 emissions (Bowman et al., 2009), and can sustain specific fire-dependent ecosystems (Allen et al., 2002). In recent decades, however, rapidly increasing fire activities have been observed due to a variety of factors, including fuel build-up, human activity, and climate change (Abatzoglou & Williams, 2016). The subsequent fire regime shift has caused an increase in fire occurrence and size, and fire seasons now show a continued increasing trend in length with observed warming and drying, including within non-forest vegetation types (Westerling, 2016). These fire regime changes will heighten fire severity and drive the changes in vegetation composition (Feurdean et al., 2020). For example, the predicted change in fire frequency and extent in the western U.S. is expected to transform the flora, fauna, and ecosystem processes in the Greater Yellowstone ecosystem and there are indications that similar changes will occur for other subalpine or boreal forests (Westerling et al., 2011).

Continuing changes in climate and fire regimes will increase the threat of larger and more frequent fires to fire-prone regions of the world (Dennison et al., 2014). Nonetheless, quantification of future trends in fire activity is challenging owing to the lack of spatially complete and consistently derived data (Dennison et al., 2014). The regional and spatial variability, complex and non-linear interactions between weather, vegetation, and human activity added more uncertainty to future fire severity and intensity (Flannigan et al., 2009). According to Parisien et al. (2011), fire regimes are mainly controlled by the flammability of fuels and weather in the boreal landscape. In south-eastern Australia, severe weather and drought associated with climate change is the primary factor of shifted fire regimes in dry forests, while topography and the vegetation community are the primary influence in mesic forests (L. Collins et al., 2019). Therefore, understanding how fire regimes vary with local conditions, particularly the spatial and temporal distributions of flammable fuels, climate, and human activity is critical to predicting future fire activity (Falk et al., 2011).

The Wildland Urban Interface (WUI) defined as the area where houses meet or intermingle with wildland vegetation (Kramer et al., 2018), is the area where wildfire poses the greatest risk to people and communities (Radeloff et al., 2018). The eastern US has a disproportional WUI area when compared to the western US. Approximately 60% of the US land mass occurs in the eastern US but it contains 83% of the WUI (Theobald & Romme, 2007). According to Theobald & Romme (2007), the eastern US has at least 6 times more WUI areas that are in the fire suppression-induced high severity of fire regime class compared to the western US, where fires were historically low intensity but recently displayed high intensity due to the century of fire exclusion. Furthermore, a previous study revealed that about 97% of all human-caused wildfires occur in the WUI (Mietkiewicz et al., 2020). In terms of area burned, the western US had 4 times more area burned by large human-caused fires (400-500 km^2, FPA-FOD dataset) compared to the eastern US; but the eastern US had 7 times more area burned by small human-caused fires (< 4 km^2, FPA-FOD dataset) and significantly more human-caused fires compared to the western US (Mietkiewicz et al., 2020). It is forecasted that by the end of the 21st century, the risk of extreme fire-weather conditions in eastern North America will more than double due to climate change (Touma et al., 2021). The more frequent fires combined with rapidly changing fire weather can set the future stage for more unexpected fire events in the eastern US. These hazardous conditions can result in reduced opportunities for prescribed burning in the southeastern US, which accounts for more than half of all prescribed burn in the US, and thus lead to significant risks of catastrophic fires due to the rapid build-up of fuels that prescribed fires would otherwise reduce (Kupfer et al., 2020).

In addition to climate and human activity, fuel characteristics vary between the eastern and western US. Two key differences in vegetative fuels between these two regions are the fuel chemistry and fuel moisture. Different species display differences in flammability, with some forests being more flammable than others (de Magalhães & Schwilk, 2012; Varner et al., 2021). In general, coniferous forests of the West tend to be more flammable than broadleaved forests of the East due to relatively lower ignition temperatures of extractives in coniferous foliage (Susott et al., 1990). According to Bianchi et al. (2019), the conifer species displayed lower live fuel moisture content compared to broadleaf species, making the conifers the more ignitable species. These differences will produce different fire behavior and fire risk between the eastern and western US. For example, forest stands mainly composed of broadleaved vegetation showed higher mortality rates than mixed or coniferous stands after fire due to differences in fire resistance (Dupire et al., 2019).

Since future predictions show dramatic increases in fire probability in the eastern U.S., where the greatest occurrence and expansion of the WUI exists, more attention needs to be given to understanding the factors of fire behavior and fire activity in eastern forests. The objective of this study is to determine how spatial variability, weather, and fuel characteristics in temperate hardwood forests influence fire behavior and fire activity.

Weather

Weather, fuels, and topography are known to be the principal factors that can influence fire behavior. Of the three factors, weather is generally considered the most dynamic and variable driver (Holsinger et al., 2016; Jolly et al., 2015). Some research has highlighted the role of weather and climate. For example, rainfall and temperature exert a major control on fire extent and occurrence (O'Donnell et al., 2011). Fire size appears to have a significant positive relationship with climate (Cansler & McKenzie, 2014). Collins et al. (2019) found that severe fire weather and drought can moderate the effect of topography, fuel, and vegetation. In gentle terrain, extreme weather can drive strong shifts in fire activity even when surface fuel loads are not high (Airey-Lauvaux et al., 2022). The climate-driven forest fire can still increase in the amount of area burned despite the fuel limitation (Abatzoglou et al., 2021). Cary et al., (2006) through the use of landscape fire models have determined that weather and climate can best explain the amount of burn area as compared to topographic and fuel pattern variables.

Weather variables such as air temperature, relative humidity, wind speed, and wind direction can influence wildfire activity directly and indirectly through the influence that weather has on fuel moisture (Finney, 2005). Higher temperatures and lower humidity correspond with lower fuel moisture and less energy required for pre-heating fuels, typically resulting in greater levels of fire damage (Thompson & Spies, 2009). During hot and dry periods, the low fuel moisture combined with higher windspeed resulted in an increase in fire intensity and the rate of spread, and thus increasing the probability of crown fire (Airey-Lauvaux et al., 2022). Thompson & Spies (2009) also found that when wind speeds were highest, there was a greater probability of widespread torching, crowning, and spotting fire. In addition, the upward global and regional warming trends were leading to the occurrence of high to extreme fire weather (Iglesias et al., 2022), which suggests that there is a greater chance for fires to grow rapidly, resulting in potentially large fires (B. M. Collins, 2014). Large fires can occur as both surface and crown fires, and typically small fires may become larger and cause greater damage under severe fire weather (Dimitrakopoulos et al., 2011).

Weather conditions can affect vegetation growth, fuel build-up, create mosaic microclimates and therefore affect fire behavior. Fire suppression policies and past management practices have led to denser forests in both the western and eastern US, causing alterations in the microclimate and fire regime (Bigelow & North, 2012; Hanberry et al., 2020). For example, air temperature and relative humidity are lower in mature forests compared to more open sites; this cooler and moister microclimate in closed forests displayed less flammability than in open woodlands (Barberá et al., 2023).

Different stand characterizations can produce different microclimates. For example, higher stand densities create lower wind speed and higher fuel moisture and thus reduces the probability of severe fire (Pinto & Fernandes, 2014). In forest fire risk modeling, microclimate combined with human factors can contribute more to the occurrence of fire than the use of large-scale climate variables (Saxena & Srivastava, 2007).

Since the beginning of the 20th century, the annual average temperature in Ohio has increased by more than 0.83 °C, which can cause an increase in the rate of soil and fuel moisture loss, and the intensity of future droughts (NOAA, 2022). There is no doubt that these trends will likely increase the future fire probability and fire intensity, as the current data has shown that the number of fires has doubled in the eastern US during the periods of 1984-1999 and 2005-2018 (Iglesias et al., 2022), and globally the length of fire seasons have increased 18.7% from 1979 to 2013 (Jolly et al., 2015). These potential changes in weather and climate and the changes witnessed in fire occurrence and behaviors suggest that fires in the future may not behave as in the past and present and thus acquisition of new data on wildland fire and factors that influence it becomes critical.

Topography

Topographic features (aspects, slope percentage, slope position, and elevation) have been identified as the most static environmental drivers of fire. It can affect fire behavior and fire spread through both direct and indirect factors (Thompson & Spies, 2009). For example, topographic variables can directly affect fire spread by acting as barriers, such as valley bottoms and ridge tops (Holsinger et al., 2016; Taylor & Skinner, 2003). Southerly aspects, which receives greater solar radiation compared to other aspects, can lead to drier conditions and smaller vegetation, and result in greater fire severity (Taylor & Skinner, 2003). Topographic variation can also modify fire behavior indirectly by modulating fuel moisture, fuel type, fuel arrangement, and wind intensities (Taylor & Skinner, 2003). Specifically, different topographic positions support different stand structures, vegetation compositions, and tree densities (Nero & Opoku, 2022), which subsequently causes different wind intensities and fuel conditions, ultimately affecting fire behavior. Furthermore, fuel flammability within a stand can be altered by aspect and slope due to the influence of the different solar irradiance on fuel moisture (Iniguez et al., 2008).

Kane et al. (2015) suggested that mountainous topography would create fine-scale environmental mosaics due to variations in aspect, slope, elevation, precipitation, and temperature, and that these different mosaics will have an influence on fire intensity, which has been confirmed by other researcher (Holden et al., 2009). North aspects tend to produce cooler fires than south-facing aspects due to north aspects receiving less direct sunlight (Iniguez et al., 2008). Schwemlein & Williams (2007) confirmed that for both fall and spring burns, the south-facing aspects produced the highest fire temperatures for slope positions, and significantly hotter than fires occurring on north-facing aspects. Slope positions and steepness can also influence fire temperatures, as more extreme fire severity tends to occur on upper slope positions (Lecina-Diaz et al., 2014). Slope steepness can cause varying solar irradiation depending on the slope angle with the sun even within similar aspects (Iniguez et al., 2008). Fire temperature differences between upper and lower slope positions are significant different regardless of the season of the burn (Schwemlein & Williams, 2007).

In steep and rugged landscapes, which consist many fire barriers (e.g., rock outcrops, steep ridges and stream channels), slope and aspect vary greatly within short distances, and can create different microclimates and fuel patterns within relatively small areas (Bigio et al., 2016). Previous studies had demonstrated that the variability of terrain can either amplify or mute the influence of weather or fuel on fire behavior. For example, rugged topography can reduce the influence that climate has on fire frequency and fire return interval by acting as fire barriers and creating isolated stand sites (Bigio et al., 2016). Airey-Lauvaux et al. (2022) through the use of the fire behavior model evaluated that flat slopes have a higher threshold for fuel accumulation compared to steep slopes and ridgetops, meaning that gentle slopes can reduce the influence of fuel to some extent. Specifically, as fuel increases in gentle slopes, little change will occur in fire line intensity and the occurrence of passive crown fire (Airey-Lauvaux et al., 2022). In addition, a steep and rugged landscape can pose more uncertainty regarding fire behavior. For instance, fire behavior can be very complex and dynamic when entering the bottom of the canyon, which can cause eruptive fires that are characterized by a sudden change in the rate of spread and therefore of energy release (Viegas & Simeoni, 2011). The steep slopes and canyons play the role of a constant and strong constraint to the fire, which is similar to the role of a strong and constant wind direction, and thus the dramatically modified fire always presents challenging situations (Rodrigues et al., 2019; Viegas & Simeoni, 2011). The complexity of terrain variables can influence fire-induced wind, with wind speed increasing in the upslope position of the terrain but decreasing in downslope positions (Eftekharian et al., 2019). These fire-induced winds will affect the fire's rate of spread.

The steep and rugged topography combined with the resulting microclimate changes increases the complex nature of fires and their behavior. It is therefore important to acquire more real fire data in its varying environment in order to achieve a greater understanding of the interplay of weather, fuel, and topography.

Fuel characteristics

When managing or controlling a fire, fire managers cannot change weather or topography, but fuels can be modified to keep the fire under control (Finney, 2005). Fuel characteristics and properties change under different weather conditions, topography, and ecosystem (vegetation type), creating variations in fuel moisture, fuel type, fuel shape and fuel loading, which subsequently determines fire behavior, such as fire rate of spread, flame length, and fire temperature (Curt et al., 2013; Holsinger et al., 2016; Matthews, 2014). Some of those specific fuel properties will be further discussed below.

<u>Fuel Arrangement</u>

Fuel arrangement is described as the spatial distribution of fuel particles and pieces, and it has always been recognized as a key driver of wildfire behavior (Atchley et al., 2021). Previous studies examined the influences of fuel arrangement and fuel pattern on fire intensity and rate of spread. Aggregated fuel patterns can result in higher fire intensity compared with homogenous or random fuel patterns (Hoffman et al., 2012). Fuel discontinuity associated with fuel density and heterogeneity can decrease fire spread and area burned on a fine scale (Atchley et al., 2021). The structural dynamics of certain species in shrublands can also be related to flammability by their ability to occupy more space and result in an increase in the level of fuel continuity (Baeza et al., 2006). The understory trees and shrubs can act as ladder fuels that help a surface fire to reach the crowns and generate a faster-moving and much more intense crown fire (Flannigan et al., 2016). However, fuel arrangement alone cannot explain fire behavior in some cases (Curt et al., 2013). It is important to understand the influence of fuel load, intrinsic factors of fuel, as well as fuel arrangement and their influence on fire behavior.

Fuel composition/chemistry

The composition of species in mixed stands had received intense interest due to their potential influences on fire behavior. Different species display differences in flammability, with some forests being more flammable than others (de Magalhães & Schwilk, 2012; Madrigal et al., 2009; van Wilgen et al., 1990). In general, coniferous forests tend to be more flammable than broadleaved forests as a result of relatively lower ignition temperatures of extractives in coniferous foliage (Susott et al., 1990). According to Cassandra (2012), the mixtures of two species of fuel showed non-additive effects on flammability; however, they found that some highly flammable species may have effects on fire dynamics out of proportion to their biomass. Different species can display differences in flammability. Ganteaume et al., (2009) found that species belonging to the genus *Pinus* displayed higher values of ignition frequency, rates of spread and combustion, while the genus *Quercus* required a longer time to reach ignition and displayed less flammability than a *Pinus* fuel bed. The differences between species can be explained by the differences in fuel chemistry in regard to the essential oils and terpenes contained in the fuel, which can enhance the heat of combustion (Ganteaume et al., 2009). Across the ecosystem, different species compositions can cause different fire intensities and increase the complexity of the fire. Understanding the heat of combustion variation among species and their chemistry traits can provide context for fire management and decision-making, especially under the circumstance of shifting forest species from pyrophytes to mesophytes (Varner et al., 2021).

Fuel moisture

The estimation of the moisture content of fuels is a critical variable in fire risk assessment (Aguado et al., 2007). The water content of fuels can reduce the probability of ignition and moderate fire intensity (A. P. Dimitrakopoulos & Box, 2001). Fuel moisture is a dynamic parameter that can change quickly with the change of weather and the surrounding environment. Ray et al., (2005) found that fuel moisture can be influenced by canopy height and leaf area index, because a taller and denser canopy results in slower drying after the precipitation. Changes in topography can also lead to different fuel moisture due to sunlight availability (Matthews, 2014). The dynamic traits of fuel moisture made it a critical factor to consider.

Fuel load

Fuel load and fire weather are the major drivers of the impact that climate change will have on fire danger, since the warming weather and potential increases in annual fine fuel load (Clarke et al., 2016). With the increased fuel load, fire line intensity and the probability of passive crown fire will increase (Airey-Lauvaux et al., 2022). Even though the terrain can limit the effects of fuel accumulation on fire behavior, however, at high surface fuel load, high severity fire and passive crown fire can become widespread and occur on all topographic positions (Airey-Lauvaux et al., 2022). Besides, fuel loads can be reduced by fire, then gradually rebuild through time (Nolan et al., 2022; Penman & York, 2010). This changeable fuel load and fuel accumulation significantly increase the uncertainty of the potential of large forest fires (Nolan et al., 2022).

Conclusion

Continuing changes in climate and fire regimes will increase the threat of larger and more frequent fires to fire-prone regions, especially in the eastern U.S., where the greatest occurrence and expansion of the WUI exists. However, predicting future trends in fire activity is challenging due to incomplete and inconsistent data.

The steep and rugged topography combined with the resulting microclimate changes increases the complexity of vegetation composition. The varied vegetation type among landscape positions can produce different fuel characteristics and create variations in fuel composition and fuel loadings, which subsequently determine fire behavior, such as fire rate of spread, flame length, and fire temperatures.

Overall, the potential changes in weather, topography, and fuel can influence fire behavior greatly. The warming trends in climate and shifted forests due to fire suppression policies all suggest that fires in the future may not behave as in the past and present. It is important to acquire updated fire data in varying environments in order to achieve a greater understanding of the interplay of weather, fuel, and topography in temperate hardwood forests.

Chapter 2 Effects of Forest Attributes on Fire Environment and Fire Behavior

Introduction

The fire environment is described as the factors that can change or influence the ignition, behavior, and extent of fires (McCaw, 2018). It can be represented by the three parameters of fuel, weather, and topography (Countryman, 1966). Fire behavior that is modified by fuel is typically influenced by fuel bed continuity and heterogeneity, which can be characterized by the fuel vegetation composition, fuel type, fuel structure, biomass, and fuel moisture (Loudermilk et al., 2012). Forest litter is the main resource that contributes to the fuel bed. Litter production as well as fuel dynamics are dependent on the forest vegetation structure, seasons, and landscape positions (Capellesso et al., 2016). Understanding how fuel varies along landscape position and forest structure is important to predict the fire environment and subsequent fire behavior.

Fuel conditions are controlled by different factors spatially and temporally. South aspects that often receive more direct sunlight result in lower fuel moisture and therefore become more combustible compared to other aspects. It had been confirmed that fire intensity on the south aspects have displayed higher temperatures than the north-facing aspect (Schwemlein & Williams, n.d.). In addition to abiotic topographic factors, differences in fuel conditions and fire behavior can also be explained by distinctive vegetation among landscape positions (Keane et al., 2004). The stand conditions can alter microclimate and fuel moisture (J. M. Kane, 2021) and the structural development of forest vegetation over time and space often determines important fuel characteristics such as fuel type and fuel load (Keane et al., 2004). For example, shallow south-facing and steep north-facing slopes support ponderosa pine forest and mixed-conifer forest, respectively, in southern Arizona (Iniguez et al., 2008). In southern Ohio, mesophytic species mainly distribute on northeastern aspects, and xerophytic species mainly distribute on drier and more exposed positions such as south-facing aspects (Rubino & McCarthy, 2003). These different forest vegetation create different fuel compositions and therefore different fire behavior (Iniguez et al., 2008). A better fine scale understanding of the role of vegetation conditions and topography and their interactions on fuel composition is critical for fire behavior estimation, especially in areas that comprised of steep slopes that can contribute to complex fire behavior.

Besides, forest structure and vegetation composition can influence fuel conditions by modifying the microclimate. Shrublands or more open sites have higher air temperatures and lower fuel moisture compared to dense forests (Tanskanen et al., 2006). Forests with a thinning midstory and understory vegetation tend to have greater fire intensity due to the dry fuel and high wind speed that is created from the more open conditions (Banerjee et al., 2020). In addition to microclimate, fuel condition is highly related to overstory and understory vegetation. Above-ground biomass and basal area are major factors that are correlated with fine fuel loads (Nolan et al., 2022). Dense stands with closed canopy tend to have higher foliage biomass and therefore higher litter production in the forest floor (Bahru & Ding, 2020). Moreover, even though the microclimate that is caused by different stand condition can explain the differences of fuel moisture between different stand type; however, under a similar microclimate and forest type, the variability of fuel moisture can mainly be explained by vegetation composition, with some species being more sensitive to the environment (Barberá et al., 2023). For example, McDaniel et al., (2021) found that oak species gained less moisture initially than non-oaks (winged elm and hickory) and lost moisture more quickly by comparing single-species fuel bed. The complex interaction between microclimate and vegetation can increase the complexity of fuel condition and thus the complexity of fire prediction.

The fire-dependent ecosystems in the eastern US have shifted in structure and species composition from more open-canopied upland oak forest to closed-canopy forest occupied by shade-tolerant or other opportunistic species due to fire exclusion (Hanberry et al., 2020). Even though oak still maintains dominance in the overstory layer, the abundance of mesophytic species such as red maple (*Acer rubrum* L.), sugar maple (*A. saccharum* Marshall), and American beech (*Fagus grandifolia* Ehrh.) in the midstory and understory are poised to replace oak (Fei et al., 2011; Fei & Steiner, 2007). The non-oak species composition often leads to lower fire intensity due to their canopy, bark, and leaf litter, which tends to alter the fuel bed condition (Babl et al., 2020).

The objective of this study was to characterize the relationship between forest attributes and topography with the fire environment. Accessing the effect of the forest overstory and understory attributes (canopy closure, average DBH, forest density, species) and topography features (aspect, slope, slope percent) on fuel conditions (fuel load, fuel composition). Specifically, to (1) compare the variation of forest parameters and fuel conditions among landscape positions, (2) determine the influence of topography factors on forest structure and fuel condition, and (3) determine the relationship between forest parameters and fuel condition. The results of this study will provide fire managers with a better prediction of fire behavior based on the characterization of the fire environment.

Methods

Study area

The study area is located at Zaleski State Forest (82°25’W, 39°18’N), in Vinton County, Ohio. This area lies on the unglaciated Appalachian Plateau, which consists of steep hills and valleys and is the most rugged area in the state. The forest is dominated by oak species including white oak (*Quercus. alba* L.), red oak (*Quercus. rubra* L.), and black oak (*Quercus. velutina* Lam.), with the subcanopy/understory comprised of red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrhart) and black gum (*Nyssa sylvatica* Marsh.).

Field sampling and measurement

An area of 58 hectares located within Zaleski State Forest, referred to as Morgan Hollow, was selected for this study. The field sampling and measurements were conducted from June to August 2022.

A total of 94 circular 0.04 ha sample plots were established, approximately 60 meters apart from each other (depending on the accessibility and forest edge) and distributed evenly in a gridwork across the study site that has opposing / opposite aspects to capture the influence of aspects on the fire environment (Fig. 2.1). The aspects (N= 315°- 45°, E = 45°- 135°, S= 135°- 225°, W=225°- 315°) and slope degree were measured and recorded at each plot center. The slope position was recorded by visual estimate as upper, middle, and lower position. The forest canopy closure (%) was measured with a GRS Densitometer.

Within each sample plot, trees greater than 10cm DBH were considered a part of the overstory and measured and recorded by species. A smaller circular 0.01ha plot that was circumscribed about the same plot center was established to measure the understory, recording trees > 1.4m in height and < 10cm DBH. The percentage of herb and shrub coverage was visually estimated and recorded respectively, and the height of the tallest shrub was measured in each 0.01 ha plot.

The volume of 100-hour and 1000-hour fuels were determined using a modified method used by Tao and Williams (2010). Two transects with each length of 30m, were established through the plot center at 90 degrees to each other, in a north-south, east-west direction. The diameter of each log that fell within the 100-hour (2.5 – 7.6 cm diameter) and 1000-hour (7.7 – 20.3 cm diameter) time lag fuel size class were measured with calipers at the midpoint of the log and recorded. The volume of logs recorded in each time lag fuel class were determined by the following:

$$\text{Volume } (m^3/ha) = \pi^2 * [(d1^2 + d2^2 \ldots\ldots dn^2)/8L]$$

Where d1, d2, dn = the mid-diameter (cm) of each of the n pieces intersecting the transect, and L = the total length of both transects (total 60 m).

In the month of October after the leaf fell, one 30cm x 30cm subplot was randomly established at 0.5 meters from each plot center. The depth of forest litter to the mineral soil was measured within this plot, and all forest litter contained within this subplot was collected down to the mineral soil, including all forest fuel classified in the 1-hour (<0.6 cm diameter) and 10-hour (0.7 – 2.5 cm diameter) fuel class (leaf litter, grasses, twigs, and woody vegetation). Fuel samples were bagged and labeled for further analysis in the laboratory.

Laboratory method

Fuel samples were stored in paper bags and oven-dried at 70℃ for 48 hours until they maintain a constant weight. Samples were then separated based on genus (oak, maple, and others) and weighed to the nearest 0.1g to determine the proportional biomass by species composition.

Statistical analysis

One-way analysis of variance (ANOVA) followed by Duncan's multiple range test (significance level $\propto = 0.05$) was performed to compare the means of forest variables among landscape positions. Correlation and regression analyses were conducted to determine the relationship between forest variables and fire environment (aerial fuel and surface fuel) and how the relationship changes among landscape positions. Oak and maple data were analyzed separately via ANOVA and Pearson’s correlation coefficient. A significant correlation was assumed when $r > 0.30$ and $p < 0.05$. All statistical analyses were performed in R, version 4.2.2 (R Core Team, 2022).

Results

Forest attributes were variable between landscape positions, especially in the understory and ground layer. For example, the number of trees and basal area per hectare of the understory exhibited standard deviations that were close to the mean values (Table. 2.1).

Aspect

In the overstory layer, there were no significant differences in canopy closure among aspects, but the south-facing aspect had a slightly lower canopy closure than the other three aspects. Similarly, average DBH and basal area displayed no significant differences among different aspects; however, trees per hectare (tree >10cm dbh) was significantly higher on the north aspect compared to the west aspect (Fig.2.2). In the understory layer, the average DBH and trees per hectare (trees > 1.4m height, <10cm DBH) had no significant differences among aspects, but the basal area on east and north aspects are significantly higher than south and west aspects (Fig. 2.3). In the ground layer, the west aspects had the lowest herb coverage but the highest shrub height and woody plant coverage. This is in contrast with the north aspects which had the lowest wood coverage and shrub height (Fig. 2.3). The 1-hour and 10-hour fuel, 100-hour fuel volume, and litter depth did not show high variation among aspects, but the 1000-hour fuels volume displayed a significantly higher value on the west aspect than south aspects (Fig. 2.4).

Slope position

Slope position was divided into three categories, upper, middle, and lower slope position. In the overstory layer, the average DBH and trees/ha displayed no significant differences between different slope positions; however, lower slope positions displayed a significantly higher canopy closure value compared to upper slope positions, and upper positions displayed a significant higher basal area than lower slope positions (Fig.2.5). In the understory layer, the average DBH and trees/ha do not display significant differences among slope position, but the basal area at middle slope positions showed a significant higher value compared to upper slope positions (Fig. 2.6). In the ground layer, the lower slope positions displayed the lowest herb coverage and significantly lower than middle positions. Woody plant coverage and maximum shrub height of lower slope positions was significantly lower than both middle and upper slope positions. However, no significant differences existed in herb and woody plant coverage and maximum shrub height between middle and upper slop positions (Fig. 2.6). The fuel conditions did not significant differences across the different slope positions, with each slope position have the similar fuel load (1-hour & 10-hour, 100-hour, and 1000-hour fuels) and fuel depth (Fig.2.7).

Slope steepness

Slope steepness was divided into four categories, steep (slope >40°), mid-steep (30° < slope <40°), mid-gentle (20° < slope <30°), and gentle (slope <20°). In the overstory, canopy closure was significantly lower at the gentle slope compared to the other three slope categories, the average DBH is significantly higher at the mid-steep slope compared to the steep slope. The number of trees/ha and basal area have no significant differences among all slope steepness categories (Fig.2.8).

The understory attributes were similar across the different slope steepness categories, with no significant differences among each category (Fig.2.9). In the ground layer, the gentle slopes had the highest woody plant coverage and shrub height, and was significantly higher than steep slopes. There were no significant differences in herb coverage among all slope steepness categories (Fig.2.9). The fuel condition did not show significant variation across the different slope steepness categories, with each category have a similar fuel load (1-hour & 10-hour, 100-hour, and 1000-hour fuels) and fuel depth (Fig. 2.10).

Linking forest attributes to surface fuel

The surface fuel conditions here refer to the amount of 1-hour & 10-hour fuels (kg/ha), 100-hour and 1000-hour fuel volumes (m^3/ha), herb and woody plant coverage (%), and the maximum shrub height (m).

In the overstory attributes, we found that, overall, herb coverage was negatively correlated with mean DBH (r=-0.36), basal area (r=-0.33), and crown closure (r=-0.27), but positively correlated with trees/ha (r=0.24) (Table 2.2). When examining the understory attributes (Table 2.2), herb coverage was positively correlated with the number of trees (r=0.39), and basal area (r=0.37).

Examination of the relationship of overstory attributes with the woody vegetation coverage finds that it was negatively correlated with canopy closure (r=-0.54), and the number of trees/ha (r=-0.40), but positively correlated with the mean DBH (r=0.48). The woody vegetation coverage was negatively correlated with mean DBH (r=-0.52) and basal area (r=-0.29) of the understory, but positively correlated with the trees/ha (r=0.23) in the understory (Table 2.2).

The maximum height of shrubs was negatively correlated with canopy closure (r=-0.45) and trees/ha (r=-0.49) in the overstory, but positively correlated with the overstory mean DBH (r=0.43). In the understory, maximum shrub height was negatively correlated with the mean DBH (r=-0.61), but positively correlated with the number of trees in the understory (r= 0.35) (Table 2.2).

In the overstory attributes, the 100-hour fuel volume was negatively correlated to the average DBH (r=-0.21), but positively correlated with trees/ha (r=0.27). There are no significant correlations between 100-hour fuel and understory attributes (Table 2.2). The 1000-hour fuel did not show significant correlations with either understory or overstory attributes (Table 2.2).

For fuel depth, there were negative correlations with canopy closure (r=-0.27), and positive correlations with mean DBH (r=0.23) in overstory (Table 2.2). The fuel depth was negatively correlated with basal area of understory (r=-0.22). Regarding 1-hour and 10-hour fuels, there are positive correlations with mean DBH (r=0.40) and basal area (r=0.21), but negatively correlations with trees/ha (r=-0.24) in overstory. The 1-hour and 10-hour fuels did not show significant correlations with understory (Table 2.2).

Correlations vs. Aspects

We found strong correlation between forest attributes and fuel condition with the data for all aspects combined; however, the forest attributes varied among aspects, while fuel condition did not show significant differences among aspects. Different aspects might play some roles in these correlations. Thus, we examined the correlation by aspects to examine how aspects influence the relationship between forest attributes and fuel condition.

On east-facing aspects, the herbaceous cover was negatively correlated (r=-0.61) with the mean overstory DBH but positively correlated (r=0.548) with the number of overstory trees/ha (Table 2.3). The woody plant cover, maximum shrub height, volume of 1000-hour fuels, and fuel depth were all negatively correlated (r = -0.65, -0.55, -0.45, -0.74, respectively) with canopy closure (Table 2.3). Woody plant cover and maximum shrub height were both positively correlated (r = 0.47 and 0.46, respectively) with the mean DBH of the overstory. The 1-hour and 10-hour fuel loads were positively correlated (r = 0.61) and negatively correlated (r = -0.51) with the mean DBH of the overstory and the number of overstory trees/ha, respectively.

Within the understory on east-facing slopes, the woody plant cover was negatively correlated with the mean DBH (r = -0.51) and the basal area (r = -0.43) (Table 2.3). The maximum shrub height was negatively correlated (r = -0.76) with the mean DBH.

On the north-facing aspects, the herb coverage was negatively correlated with the basal area of overstory (r=-0.46) (Table. 2.4**)**. The woody coverage and maximum shrub height both negatively correlated with trees/ha of overstory (r=-0.48, -0.46, respectively). In the understory, the herb coverage was positively correlated with basal area (r=0.69). Besides, the herb coverage, woody coverage, and maximum shrub height were all positively correlated with trees/ha of understory (r=0.65, 0.46, 0.48, respectively). The 100-hour fuel volume was positively correlated with mean DBH of understory (r=0.46). However, there were no significant correlation between forest attributes with 1000-hour fuel volume, fuel depth and 1- and 10-hour fuel load (Table. 2.4**)**.

On the south-facing aspect, the woody coverage and maximum shrub height were both negatively correlated with the canopy closure (r=-0.47 and -0.43), and trees/ha (r=-0.57 and -0.66) in overstory, but both were positively correlated with the mean DBH of overstory (r=0.65 and 0.64). The volume of 1000-hour fuel was negatively correlated with trees/ha of overstory (r=-0.43) (Table. 2.5). Within the understory, both the woody coverage and maximum shrub height were negatively correlated with the average DBH (r=-0.57 and -0.58), but positively correlated with trees/ha (r=0.72 and 0.70). The volume of 1000-hour fuel was positively correlated with trees/ha of understory (r=0.49) (Table. 2.5).

On the west-facing aspect, the herb coverage, woody coverage, and maximum shrub height were negatively correlated with canopy closure (r=-0.67, -0.55, -0.58, respectively). The herb coverage was negatively correlated with trees/ha of overstory (r=-0.46). the woody coverage was positively correlated with mean DBH (r=0.44) in overstory (Table. 2.6). Besides, both fuel depth and 1- and 10-hour fuel load were positively correlated with the mean DBH of overstory (r=0.41 and 0.60). When examining the understory attributes, the herb coverage was positively correlated with trees/ha (r=0.68). the woody coverage and maximum shrub height were both negatively correlated with the mean DBH (r=-0.55 and -0.67). There were no significant correlations between understory attributes with the volume of 100-hour and 1000- hour fuel, fuel depth, and 1- and 10-hour fuel load (Table 2.6).

Oak and maple

Oak forests are an important ecosystem in the eastern U.S. due to its economic and habitat values. It is a fire dependent ecosystem that requires the use of fire to maintain its presence in the landscape. In the absence of fire, red maple, a fire-intolerant species, has become a major competitor and threat to oak and has been overtaking oak ecosystems in the absence of fire. Therefore, these two species were evaluated to determine their contributions to the potential fuel load, which may have a potential influence on fire behavior when fire – prescribed or wild – passes through these systems.

The composition of the overstory was dominated by oak species, which accounted for 54.0% and 34.3% of the basal area and trees/ha, respectively. Maple species, primarily red maple, which is one of the main competitors of oak comprised 8.8% and 17.3% of the basal area and trees/ha, respectively, in the overstory. The understory displayed a reversal in these species dominance as oak only made up 3.6% of the basal area, compared to 16.6% for maple. A similar trend was found in the number of understory trees/ha, as oak accounted for 4.4% while red maple accounted for 12.1%.

Oak and Maple vs. Aspect

Fuel load in this description of results refers to the leaf litter (kg/ha). Oak fuel load was significantly higher on south and west aspects compared to east and north aspects (Fig 2.11) both in terms of fuel weight (kg/ha, graph A) and percent of total fuel load (graph B). The data revealed that, the number of oak trees per hectare and basal area are likewise significantly higher on south and west aspects compared to east and north aspects (Fig 2.12, A and B). However, the mean DBH of the overstory was not significantly different across all aspects (Fig 2.12, C). When examining the understory layer, the trees/ha, basal area, and average DBH of oak were not significantly different among all aspects (Fig. 2.12, D - F).

Maple fuel load (kg/ha) displayed no significant differences among aspects (Fig. 2.13, A), but maple fuel loading as a percentage of total fuel load is significantly higher on the west aspects compared to east and south aspects (Fig 2.13. B). In the overstory layer, there were no significant differences among aspects for the number of maple trees/ha and basal area, but maple DBH was significantly higher on north-facing aspects (Fig 2.14, C). In understory layer, the number of maple trees/ha, basal area, and average DBH were not significantly different among all aspects (Fig. 2.14, D – F). However, the number of maple trees as a percent of the total tree population in the overstory are significantly higher on west-facing aspects compared to east aspects (Fig. 2.15A), and in the understory the percentage of maple trees/ha are significantly higher on south aspects (Fig 2.15, C).

<u>Oak and Maple vs. Slope position</u>

Oak fuel load and the percentage oak of the total fuel load was significantly higher at the upper slope position than lower and middle positions (Fig 2.16). In the overstory layer, the number of oak trees/ha was significantly different across three slope positions, with lower positions having the lowest number, and upper positions having the highest number. Oak basal area was significantly higher in the upper slope positions, while there is no differences among slope positions for the understory oak attributes (Fig 2.17). The percentage of oak stems/ha and basal area percentage in the overstory was significantly different among slope positions, with the percentage increasing from lower to upper position (Fig 2.18). The percentage of oak stems/ha in the understory are significantly lower at the lower position (Fig 2.18).

The maple fuel load and the percent maple of the total fuel load was significantly higher at lower slope positions compared to middle slope positions, but similar to upper positions (Fig 2.19). In the overstory layer, maple attributes had no significant differences between different slope position (Fig 2.20). In the understory layer, maple basal area and average DBH are significantly higher at the lower position (Fig 2.20). Maple tree percentage was higher at upper position, and basal area percentage are higher at lower position in understory (Fig 2.21).

Oak and Maple vs. Slope Steepness

There were no significant differences among the different slope steepness categories for the oak fuel load and the percent of the total fuel load that oak was comprised of (Fig 2.22). The average DBH of oak was significantly lower on gentle slopes in overstory (Fig 2.23). The gentle slopes had the highest oak trees/ha in both the overstory and understory layer (Fig 2.23). Oak tree percentage in overstory layer had the highest value on gentle slope, the other percentage that oak comprised of the total species composition was not significantly different among all slope categories (Fig 2.24).

Maple fuel load and the percent the maple fuel load comprised of the total fuel load was not significantly different among all slope categories (Fig 2.25). Maple stems/ha was high on the steep slope category in the overstory layer, but lower in the understory layer (Fig 2.26), and maple percentage based on species composition followed the same pattern (Fig 2.27).

Correlation between oak and maple attributes and fuel

All overstory variables (trees/ha, basal area, mean DBH) were strongly correlated with the fuel loading for both oak and maple (Tables 2.7 and 2.8). Of those, basal area was the most significant factor to predict the fuel load, which produced an R value of 0.725 and 0.540 for oak and maple, respectively (Figs. 2.28 and 2.29). No significant correlations were found between the oak fuel load and percent with the understory variables (Table 2.7). However, the maple fuel load and the maple fuel percent were significantly correlated with the basal area and mean DBH of the understory (Table 2.8).

Discussion

The findings of this study demonstrate that topographic variables exert considerable influences on species distributions and abundances and the environment in which litter beds develop and fires occur (Dickinson et al., 2016; Méndez-Toribio et al., 2016). Iverson et al. (1997) found that oaks were abundant and obtained higher basal areas on drier and nutrient-poor sites. This finding is consistent with our results that oaks dominate on south and west-facing aspects, especially on upper slope positions, where there is more exposure to solar radiation and drier and hotter conditions than in other positions. On the other hand, maples had high distribution variability and tended to be more general in their tolerances. Species abundance and composition, in turn, can influence fuel bed composition, causing different fire intensities (Varner et al., 2021).

We divided topographic variables into three categories (aspects, slope positions, and slope steepness) to evaluate the forest attributes and fuel composition variation. We found in our study that forest attributes and fuel (total fuel and divided oak and maple fuel) did not vary significantly among slope degree categories, concluding that slope steepness plays a minor role in the forest structure and fuel conditions compared with aspects and slope positions.

Aspect

A previous study found that fine scale variation in microclimate arising from topographic positions in mountainous landscapes can change the influence of fire interval and subsequent tree establishment (Hoecker et al., 2020). Linking microclimate created by forest structure with fuel bed generated by species composition revealed the potential differences in fire probability among topographic positions. The south-facing aspect had a slightly lower canopy closure (77%), with lower tree density, which allowed more sunlight to access the ground and resulted in a dry and hot environment. The lower tree density also allowed higher wind speed and accelerated the drying of fuel. Regarding surface fuel, south-facing aspects had greater proportion of oak leaves, which can generate higher fire intensity and showed more flammability than non-oak species (McDaniel et al., 2021). Our study confirmed this and is presented later in chapter 3. The higher shrub height and wood coverage can serve as ladder fuels, which increased the probability of crown fire under extreme weather (Bradstock et al., 2010). Schwemlain and Williams (2007) found that south and west-facing slopes produced the hottest fires compared to other aspects, both in spring and fall time of the year. All those factors combined displayed the greater potential of fire and higher level of fire damage on south-facing aspects (Taylor & Skinner, 2003), especially in the upper slope position.

Overall, even though there were no differences in the fuel load among all aspects, southern aspects had the highest oak component in the fuel loading. This, combined with the lower crown closure and lower stand density, suggests that under normal conditions we should expect the most intense fires on the south-facing slopes. Besides, the south-facing slopes had the lowest volume of 1000-hour fuels, which means the rate of spread can potentially be higher. The presence of these fuels can slow the fire's rate of spread as it can act as an impediment to surface fire movement (Kolaks et al., 2003).

Contrasted with south-facing aspects, the north-facing aspect were expected to have the lowest fire risks. According to our data, northern aspects had the highest canopy closure (87%), with a high tree density. This closed forest created a shading and moist microclimate with less sunlight and less wind speed which can reduce the rate of litter drying (Ma et al., 2010). Additionally, the high proportion of maple fuel can also dampen the litter bed flammability by increasing fuel moisture, since maple fuel exhibits greater moisture gain and a slower drying rate which can extend its influence into the mixed litter beds (J. M. Kane et al., 2021). The woody plants and shrubs can serve as ladder fuels during the fire, while the low woody plant coverage and maximum shrub height on the northern aspects suggested that there was less chance to produce crown fire on the north-facing aspects.

Eastern and western aspects were considered to have the intermediate potential of fire. However, compared with eastern aspects, west aspects tend to have a slightly higher potential to produce intense fire. Even though east and west had similar canopy closure, the west had lower tree density than east, which can generate higher wind speed and accelerate the drying of fuel. Furthermore, the percentage of oak fuel are significantly higher on west slopes than east slopes, allowing west slopes the ability to be more readily to carry a fire (J. M. Kane et al., 2021) due to the different flammability of oak and maple fuel (Varner et al., 2021). Therefore, a higher fire intensity was expected on the western aspects compared with eastern aspects.

Slope position

Our results suggest that the upper slope positions produced the highest level of potential fire, where it had the lowest canopy closure and more open to sunlight. Besides, the high level of surface fuel (herb and woody plant) and oak fuel load also indicate the potential higher fire intensity in upper slope positions. This agrees with a study by Schwemlein and Williams (2007) which found the hottest fire temperatures in upper slope positions in oak forests, regardless of the time of year. The high coverage of herb and wood vegetation enhance the continuity of fuel and facilitates an increment in the fire spread velocity (Brooks et al., 2004). In addition, the high percentage of oak fuels made the upper position more flammable than other positions (McDaniel et al., 2021). Contrary to the upper position, the lower positions were considered the lowest level of fire intensity, with a more closed forest canopy, wetter and cooler microclimate, and less oak fuel proportions. The fire potential on middle slope position might be more dependent on aspects. Thus, the high intensity should be expected on the upper slope positions among all aspects, especially the south-facing aspects; in contrast, the lowest intense fire would likely occur on the lower position, especially on the north-facing aspects.

<u>Correlations</u>

Establishing robust linkages between forest structure and surface fuel loads can be problematic because forest structure and surface fuels can vary at different spatial scales (Keane et al., 2012). Our results analyzed the correlations between forest attributes and fuel conditions and found that different topographic variations would mute or amplify the correlations. Over the 94 sample plots, fuel load displayed a positive correlation with the average DBH of overstory (r=0.4), which was consistent with a previous study that canopy fuel load can be predicted using diameter at breast height (Kucuk et al., 2007). This correlation was amplified on the east and west aspects but was muted on the north and south aspects.

Our results demonstrated that the relationship between forest attributes and fuel condition can vary among different landscape positions; however, there were still many gaps related to how and why the relationship varied. Therefore, more research needs to be conducted to examine the variable relationship between forest attributes and fuel condition since it is critical for the prediction of fuel variation and therefore fire behavior among different landscape positions.

<u>Oak and maple</u>

Our data showed that oak still maintained dominance in the overstory with an average percentage of 34.3% for the number of trees and 54.0% for the basal area of all sample plots. Maple, a mesophytic species, is often highly abundant as a result of fire suppression policies in the U.S during the past century that kept fire out of many fire-dependent forests, such as oak forests (Nowacki & Abrams, 2008). Over the 94 sample plots, the contribution of maple to the total number of trees was 17.3%, and to the basal area was 8.8% in the overstory. Combined, oak and maple accounted for 51.6% of the total stems per hectare and 62.8% of the basal area in the overstory. The abundance and high proportion of oak and maple therefore made significant contributions to the fuel load. Within the 94 plots, the average percentage of oak fuel was 27.6% and maple fuel was 6.2%. Furthermore, we found the linear regression between basal area and fuel load at the species level, which means the basal area is the most significant predictor for fuel load of single species. These relationships may enhance our understanding of fuel composition and fuel load prediction, with the bigger basal area trees produce more litter fuel, and therefore combined with the different heat release by different species can help fire managers better predict fire behavior.

Conclusion

This study demonstrated that topographic variables play an important role in species distributions and abundances, especially for oak and maple. The different distribution of vegetation species can subsequently affect the fuel bed conditions and fire behavior. By dividing topographic variables into three categories, we found that slope steepness plays a minor role in the forest structure and fuel conditions compared to aspects and slope positions. Among different landscape locations, the most intense fires are expected on south-facing slopes, especially on upper slope positions due to lower crown closure, lower stand density, and a higher proportion of oak fuel. In contrast, the north-facing aspect is expected to have the lowest fire intensity due to high canopy closure and tree density, and the high proportion of maple fuel. Additionally, by establishing linkages between forest attributes and surface fuel conditions, we demonstrated that the relationship between forest attributes and fuel conditions can vary among different landscape positions; however, there still exist gaps related to how and why the relationship varied. These findings can provide fire managers with a better prediction of fire behavior based on the different characterization of the fire environment by landscape positions.

Table 2.1 Observed values for forest variables at the Morgan Hollow study site located in Zaleski State Forest, Ohio (n = 94).

Forest Variable	Min	Max	Average	SD	CV%
Overstory					
Closure (%)	5.00	98.00	82.65	19.44	23.52
Average DBH (cm)	11.57	47.58	22.78	5.86	25.71
Tree number /ha	150	1700	628.19	326.83	52.03
Basal area (m^2/ha)	1.86	61.11	29.75	11.29	37.95
Understory					
Average DBH (cm)	0.35	7.48	2.55	1.59	62.60
Tree number /ha	300	16400	3181.91	2919.05	91.74
Basal area (m^2/ha)	0.01	10.79	2.32	2.15	92.99
Ground					
Herb coverage %	2.00	89.50	30.91	27.65	89.46
Wood coverage %	5.25	89.75	38.23	25.80	67.48
Max shrub height(m)	0.25	1.38	0.89	0.30	33.34
Large fuel					
100-hr fuel m^3/ha	0.31	11.14	4.85	2.37	48.85
1000-hr fuel m^3/ha	0.00	48.34	15.96	10.80	67.70
Fuel characteristic					
Fuel depth (cm)	6.00	25.00	11.54	2.51	21.72
1-&10-hr Fuel (kg/ha)	31.01	219.57	67.20	29.33	43.64

Table 2.2 Overall Pearson's correlation coefficient between forest attributes and fuel conditions at the Morgan Hollow study site.

r	Herb %	Wood %	Shrub height(m)	100fuel m^3/ha	1000fuel m^3/ha	Fuel depth (cm)	1-&10-hr Fuel (kg/ha)
Overstory							
Closure %	-0.272**	-0.540***	-0.453***	0.102	-0.092	-0.268**	-0.005
Average DBH (cm)	-0.355***	0.480***	0.431***	-0.205*	0.048	0.228*	0.400***
Tree number/ha	0.236*	-0.397***	-0.486***	0.269**	-0.126	0.008	-0.243*
Basal area (m^2/ha)	-0.327**	0.035	-0.026	-0.022	0.023	0.194	0.205*
Understory							
Average DBH (cm)	0.109	-0.521***	-0.608***	0.198	-0.119	-0.060	-0.069
Tree number/ha	0.389***	0.227*	0.352***	-0.145	0.194	-0.115	-0.147
Basal area (m^2/ha)	0.372***	-0.285**	-0.202	0.136	0.119	-0.215*	-0.172

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 2.3 Pearson's correlation coefficient between forest attributes and fuel condition on east-facing aspects at the Morgan Hollow study site.

r	Herb %	Wood %	Shrub height(m)	100fuel m^3/ha	1000fuel m^3/ha	Fuel depth (cm)	1-&10-hr Fuel (kg/ha)
Overstory							
Closure %	-0.245	-0.649**	-0.549**	-0.097	-0.448*	-0.737***	0.041
Average DBH (cm)	-0.611**	0.471*	0.456*	-0.154	0.215	0.197	0.612**
Tree number/ha	0.548**	-0.237	-0.386	0.388	-0.145	-0.047	-0.509*
Basal area (m^2/ha)	-0.261	0.230	0.214	-0.100	0.074	0.188	0.183
Understory							
Average DBH (cm)	0.268	-0.513*	-0.761***	0.060	-0.254	-0.150	-0.234
Tree number/ha	0.094	-0.086	0.169	-0.215	0.244	-0.041	-0.111
Basal area (m^2/ha)	0.201	-0.425*	-0.415	-0.044	0.070	-0.229	-0.126

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 2.4 Pearson's correlation coefficient between forest attributes and fuel condition on north-facing aspects at the Morgan Hollow study site.

r	Herb %	Wood %	Shrub height(m)	100fuel m^3/ha	1000fuel m^3/ha	Fuel depth (cm)	1-&10-hr Fuel (kg/ha)
Overstory							
Closure %	-0.038	-0.414	-0.276	-0.012	0.019	0.003	-0.328
Average DBH (cm)	-0.392	0.233	0.188	-0.321	-0.156	0.231	0.212
Tree number/ha	-0.040	-0.475*	-0.458*	0.123	-0.213	0.177	-0.094
Basal area (m^2/ha)	-0.460*	-0.233	-0.261	-0.162	-0.201	0.279	0.098
Understory							
Average DBH (cm)	0.146	-0.297	-0.402	0.463*	-0.021	-0.141	-0.259
Tree number/ha	0.645**	0.459*	0.482*	0.022	0.355	-0.307	-0.147
Basal area (m^2/ha)	0.688***	0.217	0.203	0.305	0.306	-0.341	-0.275

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 2.5 Pearson's correlation coefficient between forest attributes and fuel condition on south-facing aspects at the Morgan Hollow study site.

r	Herb %	Wood %	Shrub height(m)	100fuel m^3/ha	1000fuel m^3/ha	Fuel depth (cm)	1-&10-hr Fuel (kg/ha)
Overstory							
Closure %	-0.297	-0.471*	-0.430*	0.087	-0.375	-0.069	0.144
Average DBH (cm)	-0.231	0.647***	0.641***	-0.071	0.391	0.224	0.182
Tree number/ha	0.327	-0.567**	-0.662***	0.386	-0.427*	-0.042	-0.184
Basal area (m^2/ha)	-0.395	0.025	0.018	0.283	0.114	0.172	0.330
Understory							
Average DBH (cm)	0.015	-0.573**	-0.579**	0.062	-0.367	0.065	0.325
Tree number/ha	0.360	0.724***	0.703***	-0.066	0.484*	0.142	-0.116
Basal area (m^2/ha)	0.381	-0.296	-0.181	0.207	-0.086	-0.022	0.001

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 2.6 Pearson's correlation coefficient between forest attributes and fuel condition on west-facing aspects at the Morgan Hollow study site.

r	Herb %	Wood %	Shrub height(m)	100fuel m^3/ha	1000fuel m^3/ha	Fuel depth (cm)	1-&10-hr Fuel (kg/ha)
Overstory							
Closure %	-0.670***	-0.552**	-0.576**	0.364	0.195	0.006	-0.016
Average DBH (cm)	0.158	0.441*	0.355	-0.318	-0.178	0.411*	0.604**
Tree number/ha	-0.458*	-0.214	-0.278	0.302	0.315	-0.067	-0.212
Basal area (m^2/ha)	-0.236	0.117	0.040	0.035	0.195	0.250	0.292
Understory							
Average DBH (cm)	-0.317	-0.545**	-0.667***	0.333	0.222	0.022	-0.165
Tree number/ha	0.678***	0.272	0.374	-0.268	-0.107	-0.353	-0.213
Basal area (m^2/ha)	0.224	-0.384	-0.279	0.299	0.044	-0.378	-0.298

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 2.7 Pearson's correlation coefficient between oak fuel and oak variables at the Morgan Hollow study site.

r	Overstory			Understory		
	Tree number/ha	Basal area (m^2/ha)	DBH (cm)	Tree number/ha	Basal area (m^2/ha)	DBH (cm)
Fuel load (kg/ha)	0.476***	0.725***	0.356***	0.082	-0.166	-0.130
Fuel %	0.538***	0.681***	0.333**	0.100	-0.182	-0.161

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

Table 2.8 Pearson's correlation coefficient between maple fuel and maple variables at the Morgan Hollow study site.

r	Overstory			Understory		
	Tree number/ha	Basal area (m^2/ha)	DBH (cm)	Tree number/ha	Basal area (m^2/ha)	DBH (cm)
Fuel load (kg/ha)	0.516***	0.540***	0.279**	0.080	0.368***	0.394***
Fuel %	0.487***	0.493***	0.236*	0.081	0.352***	0.353***

***Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level

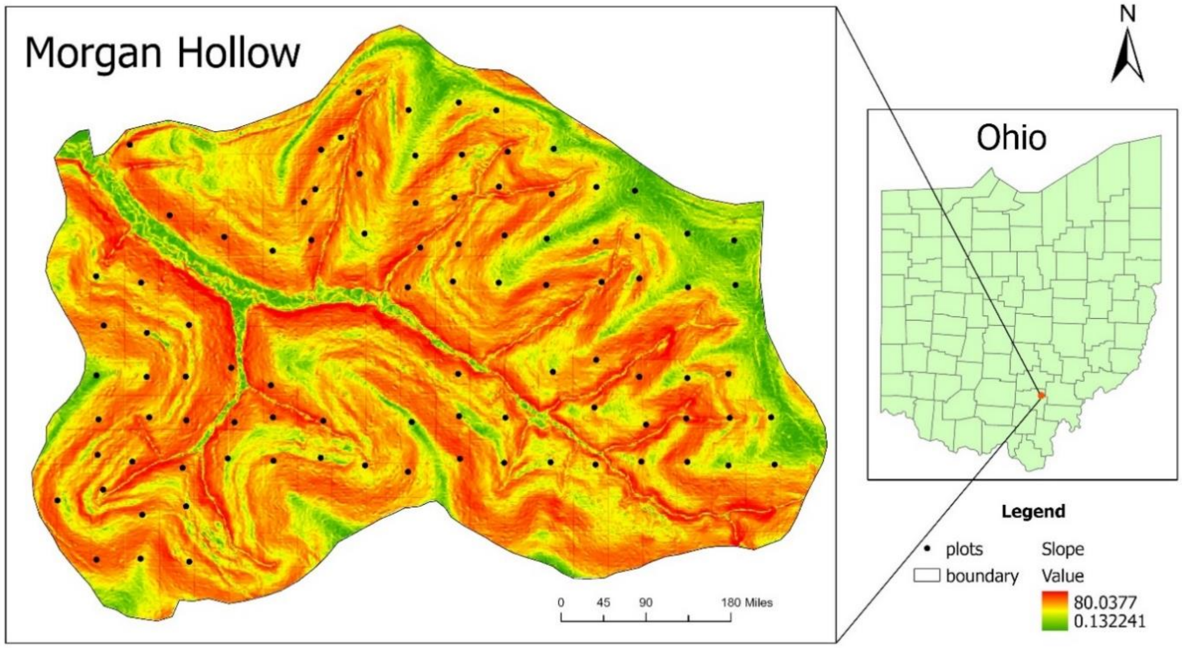

Figure 2.1 Study area (Morgan Hollow) located in Zaleski State Forest, southern Ohio, displaying slope steepness in degrees. The black dots indicate the location of the 94 sample plots, with approximately 60 meters apart from each other (depending on the accessibility and forest edge) and distributed evenly in a gridwork across the study site that has opposing / opposite aspects to capture the influence of aspects on the fire environment.

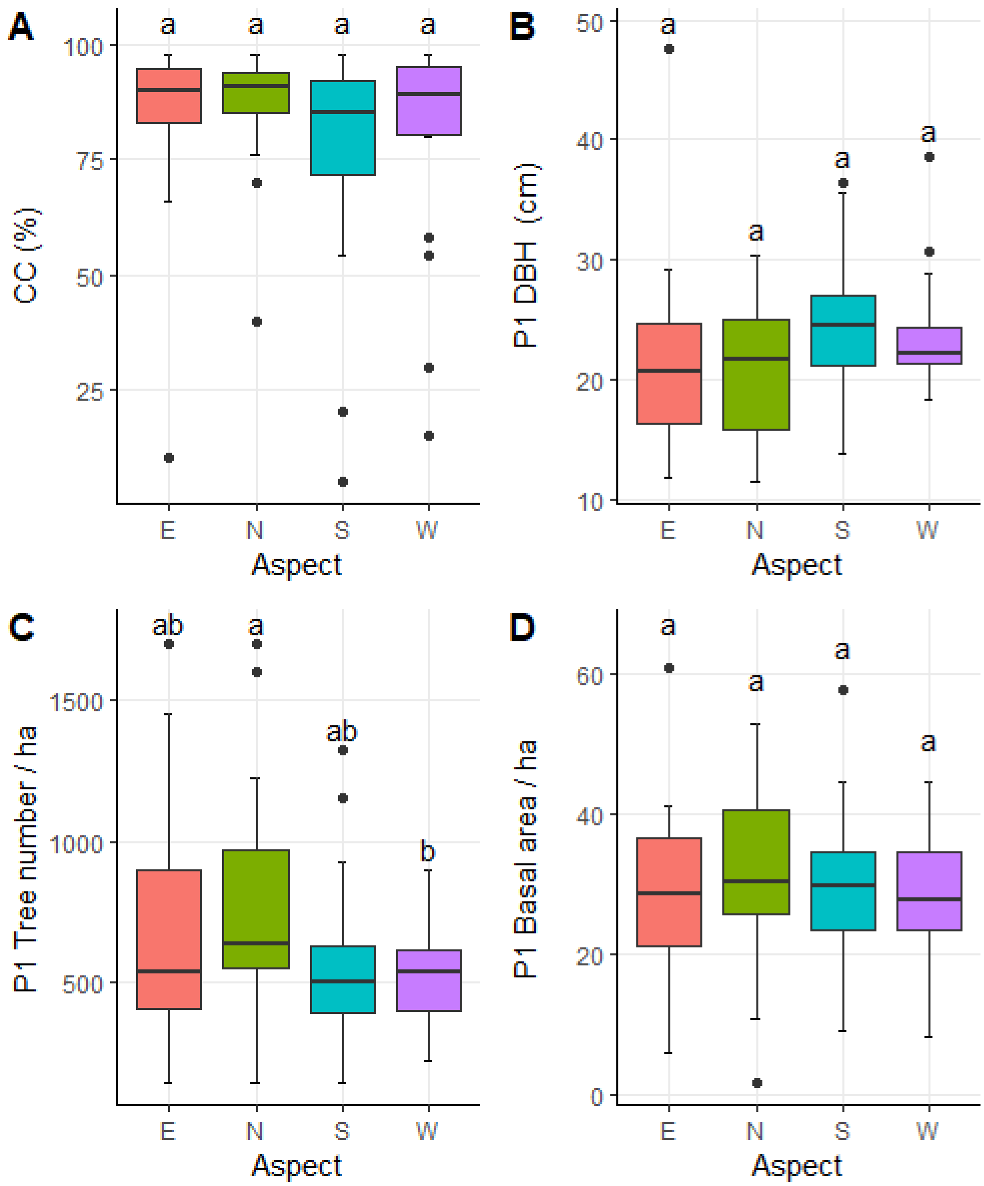

Figure 2.2 The relationship of overstory attributes – canopy closure % (graph A), average DBH (cm) (graph B), number of trees per hectare (graph C), and basal area (m^2/ha) (graph D) with aspect (N= 315°-45°, E = 45°-135°, S= 135°-225°, W=225°-315°). Boxes with different letters are significantly different (P < 0.05) according to the post-hoc Duncan's multiple range test.

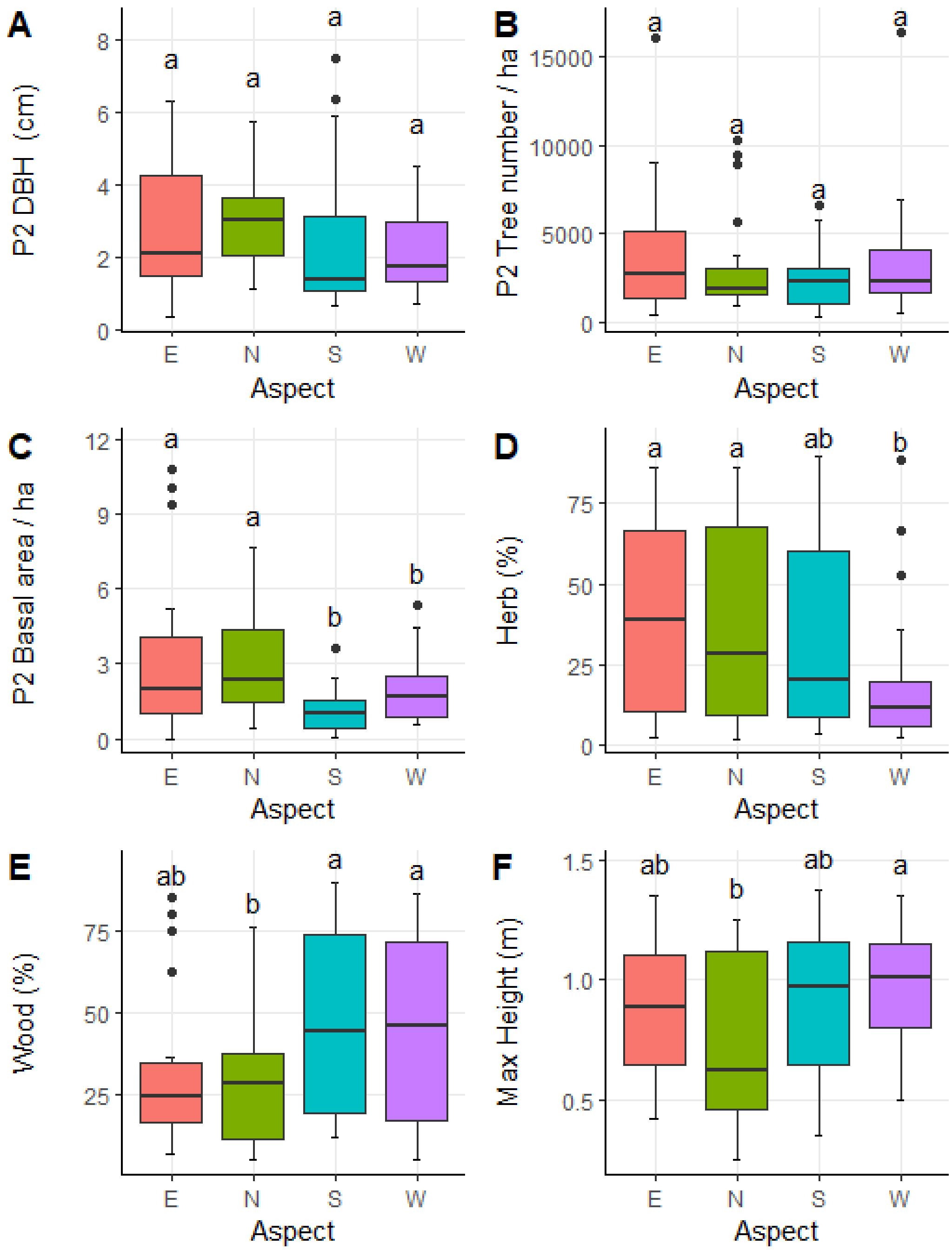

Figure 2.3 The relationship of understory attributes – average DBH (cm) (graph A), number of trees per hectare (graph B), and basal area (m^2/ha) (graph C) with aspects. The relationship of ground layer attributes-herb coverage (graph D), woody plant coverage (graph E), and maximum shrub height (m) (graph F) with aspect.

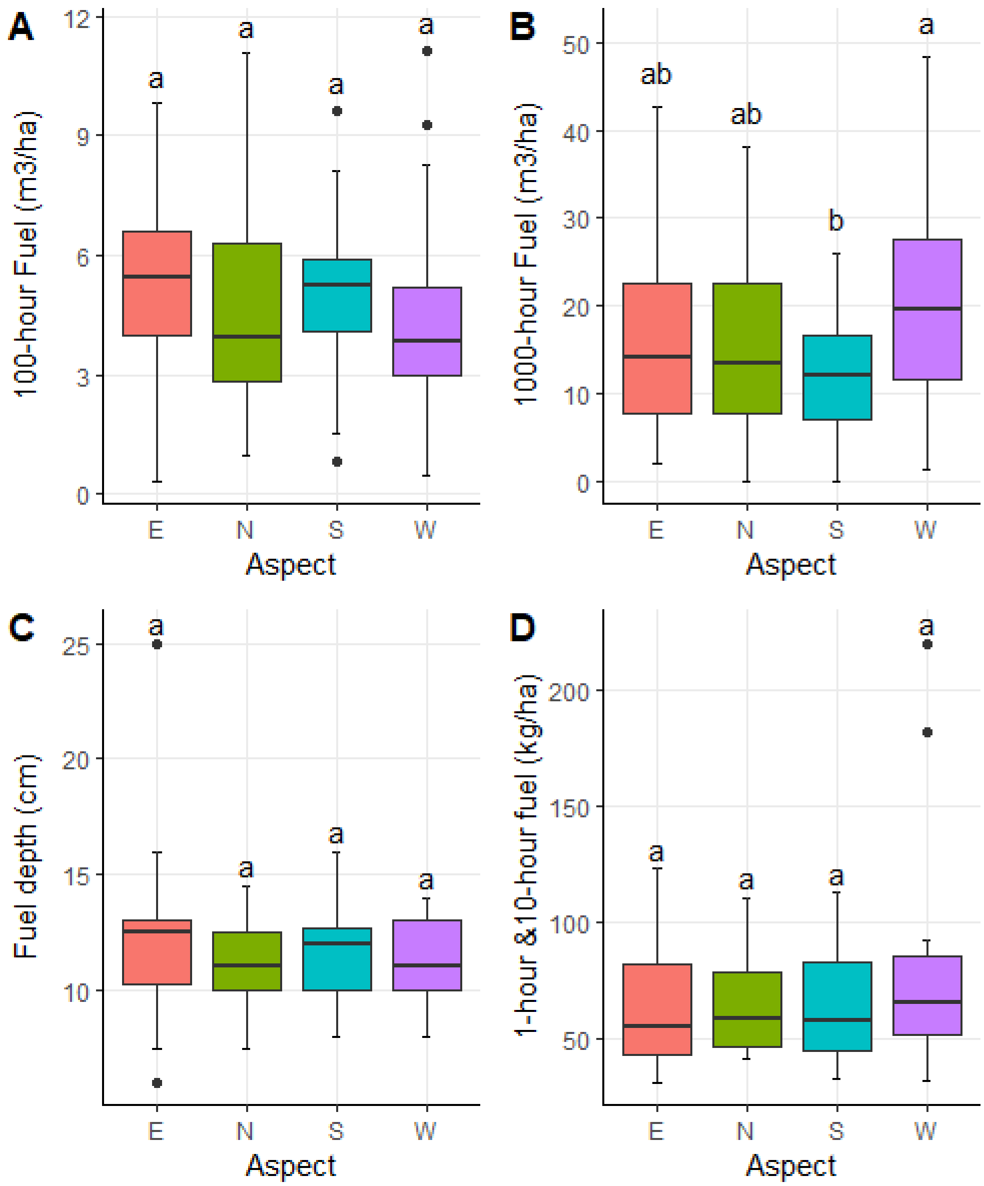

Figure 2.4 The relationship of fuel attributes – 100-hour fuel volume (m^3/ha) (graph A), 1000-hour fuel volume (m^3/ha) (graph B), fuel depth (cm) (graph C), and 1- & 10-hour fuel load (kg/ha) (graph D) with aspect.

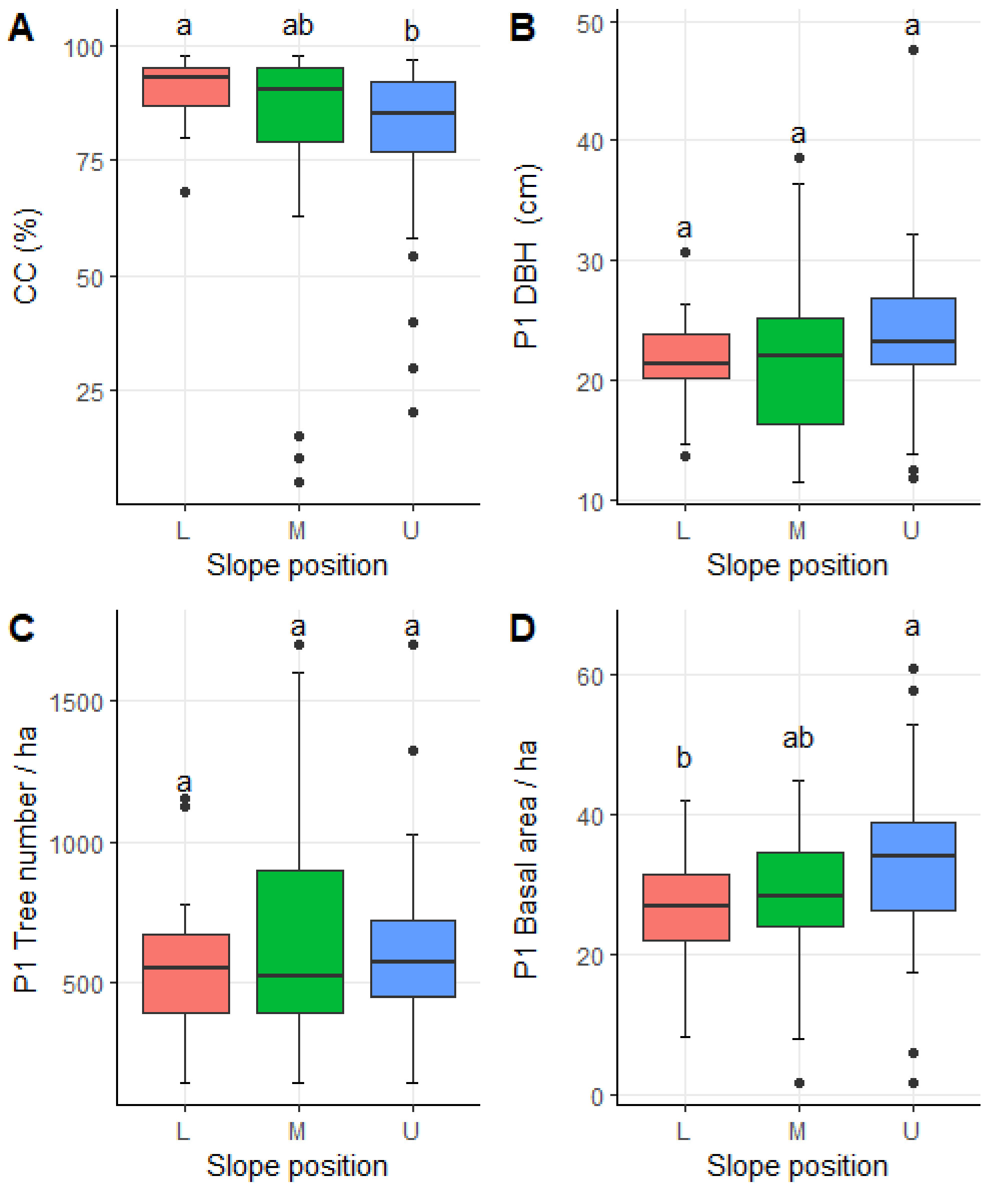

Figure 2.5 The relationship of overstory attributes – canopy closure % (graph A), average DBH (cm) (graph B), number of trees per hectare (graph C), and basal area (m^2/ha) (graph D) with slope position (L = lower position, M = middle position, U = upper position). Boxes with different letters are significantly different ($P < 0.05$) according to the post-hoc Duncan's multiple range test.

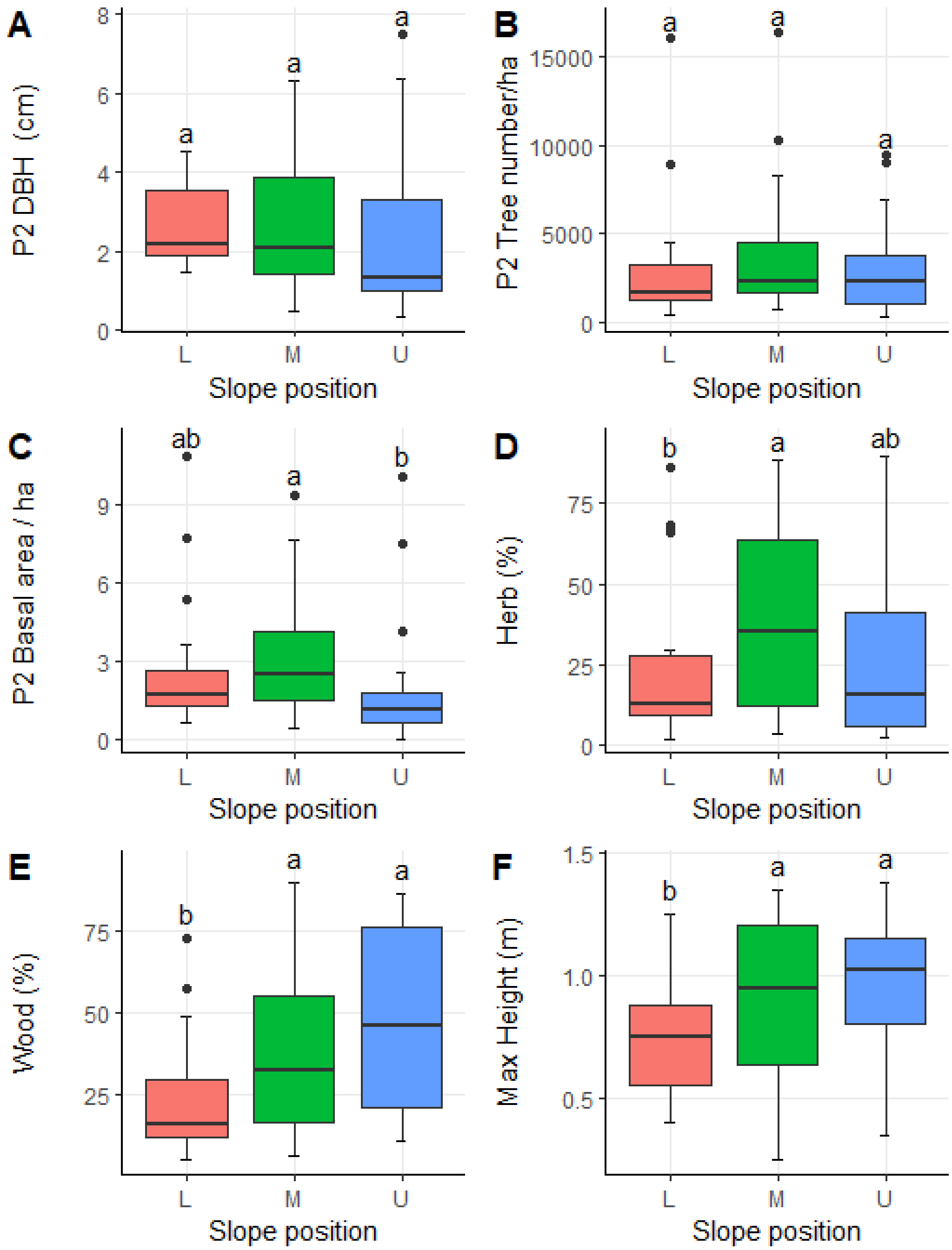

Figure 2.6 The relationship of understory attributes– average DBH (cm) (graph A), number of trees per hectare (graph B), and basal area (m^2/ha) (graph C) with aspects. The relationship of ground layer attributes-herb coverage (graph D), woody plant coverage (graph E), and maximum shrub height (m) (graph F) with slope position.

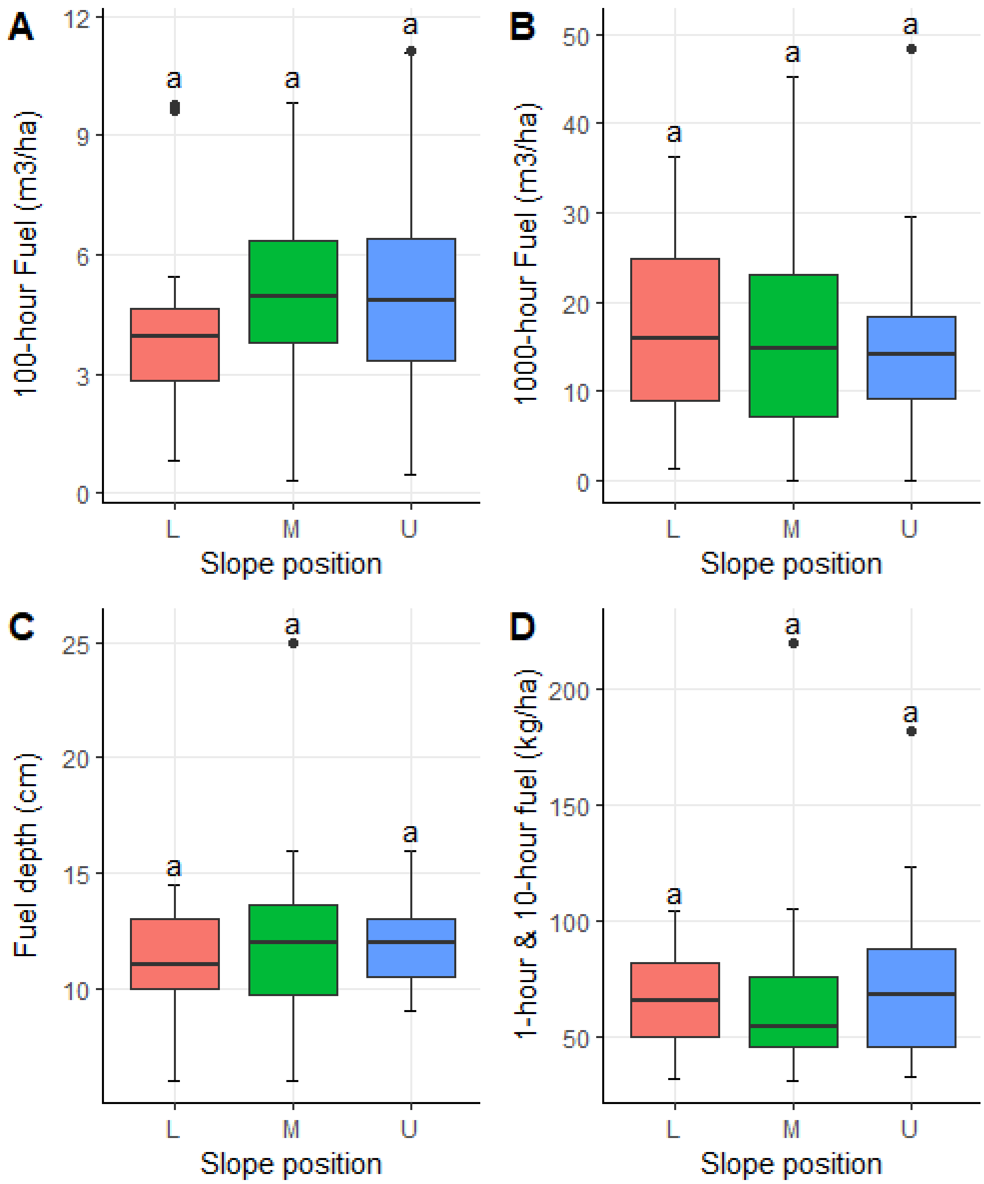

Figure 2.7 The relationship of fuel attributes – 100-hour fuel volume (m^3/ha) (graph A), 1000-hour fuel volume (m^3/ha) (graph B), fuel depth (cm) (graph C), and 1- & 10-hour fuel load (kg/ha) (graph D) with slope position.

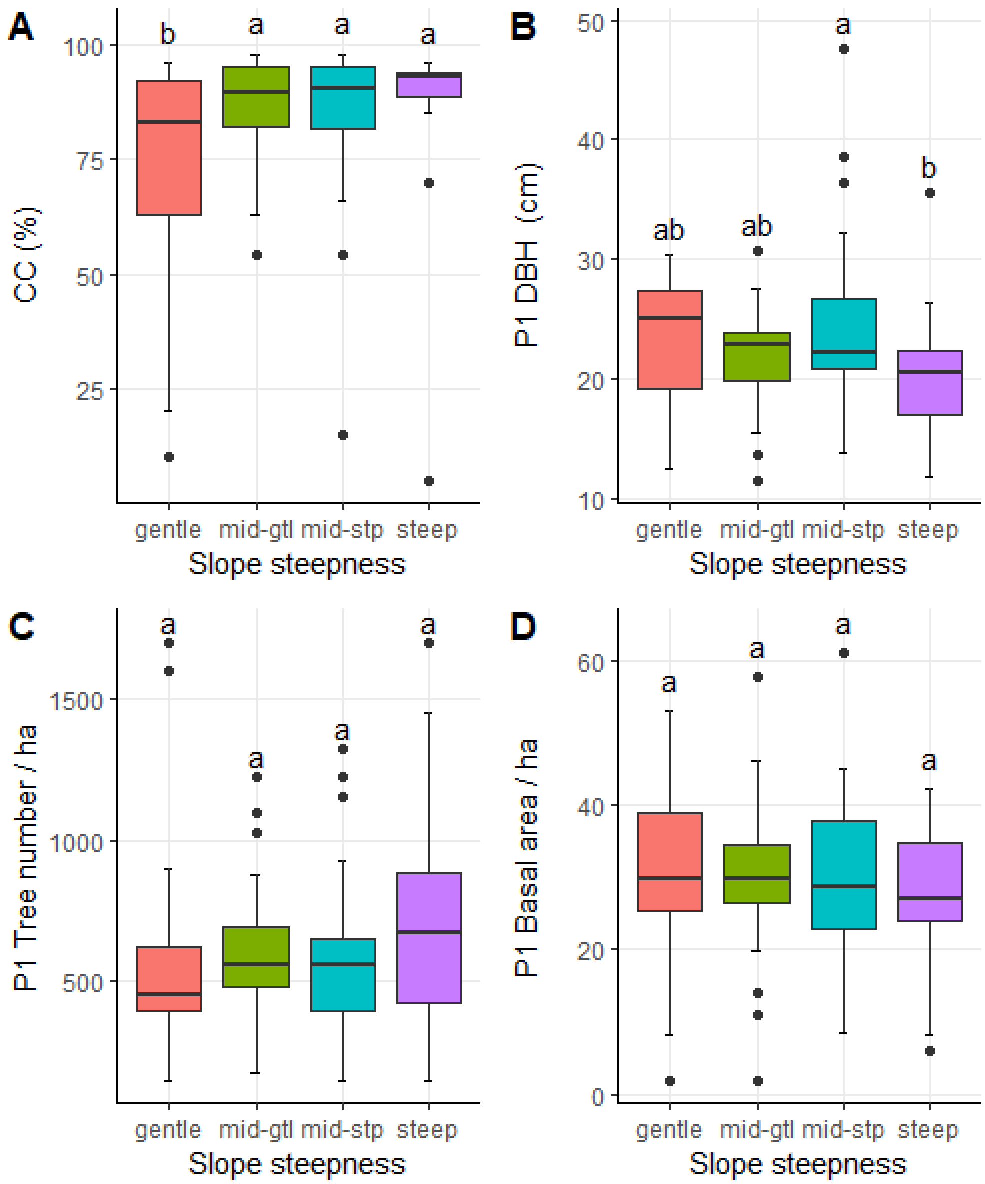

Figure 2.8 The relationship of overstory attributes – canopy closure % (graph A), average DBH (cm) (graph B), number of trees per hectare (graph C), and basal area (m^2/ha) (graph D) with slope steepness (gentle = slope <20°, mid-gentle = 20° < slope <30°, mid-steep = 30° < slope <40°, steep = slope >40°). Boxes with different letters are significantly different (P < 0.05) according to the post-hoc Duncan's multiple range test.

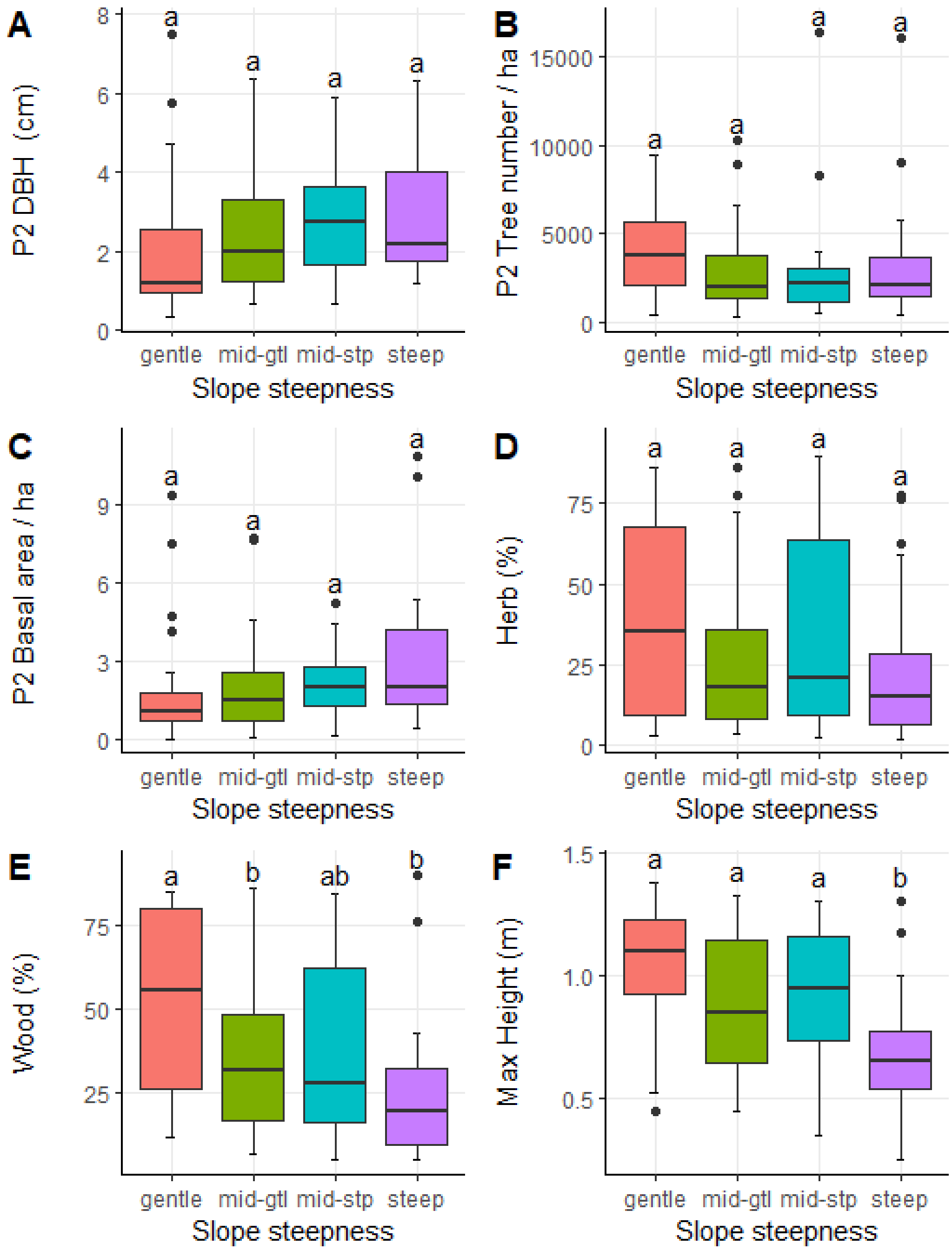

Figure 2.9 The relationship of understory attributes– average DBH (cm) (graph A), number of trees per hectare (graph B), and basal area (m^2/ha) (graph C) with aspects. The relationship of ground layer attributes-herb coverage (graph D), woody plant coverage (graph E), and maximum shrub height (m) (graph F) with slope steepness.

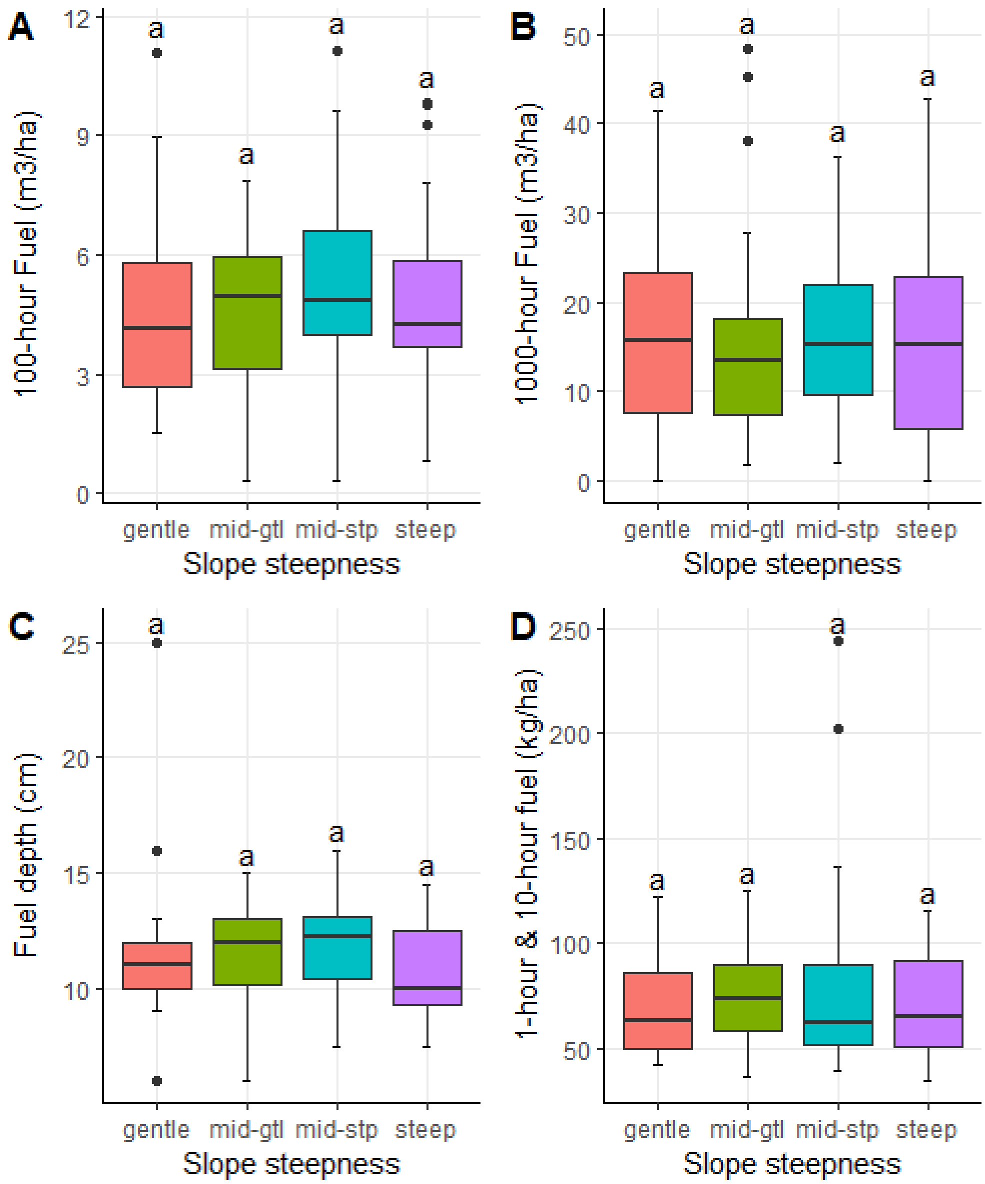

Figure 2.10 The relationship of fuel attributes – 100-hour fuel volume (m^3/ha) (graph A), 1000-hour fuel volume (m^3/ha) (graph B), fuel depth (cm) (graph C), and 1- & 10-hour fuel load (kg/ha) (graph D) with slope steepness.

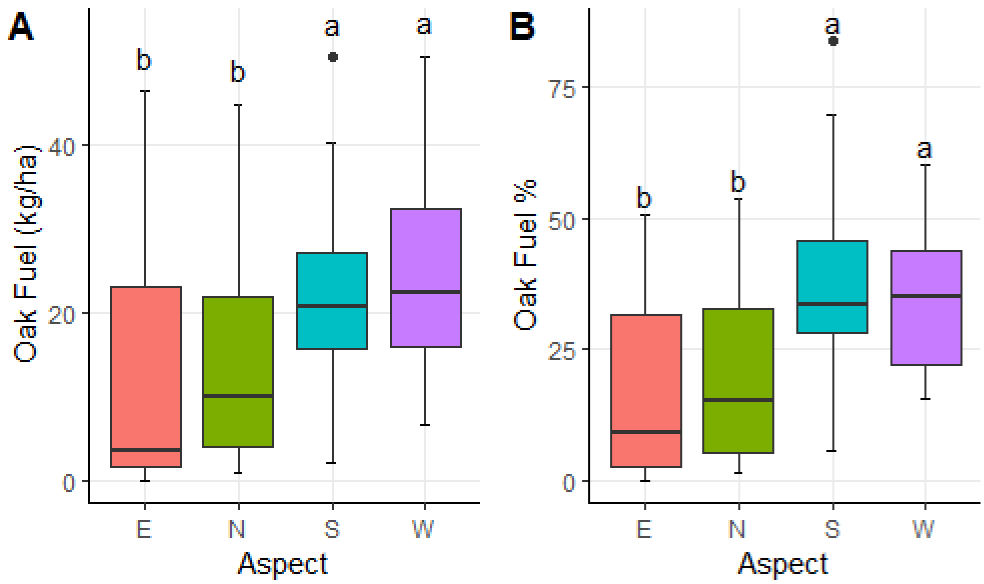

Figure 2.11 Oak fuel load (kg/ha) by aspect (A), and oak fuel loading as a percentage of total fuel load by aspect (B) (N= 315°-45°, E = 45°-135°, S= 135°-225°, W=225°-315°). Boxes with different letters are significantly different ($P < 0.05$) according to the post-hoc Duncan's multiple range test.

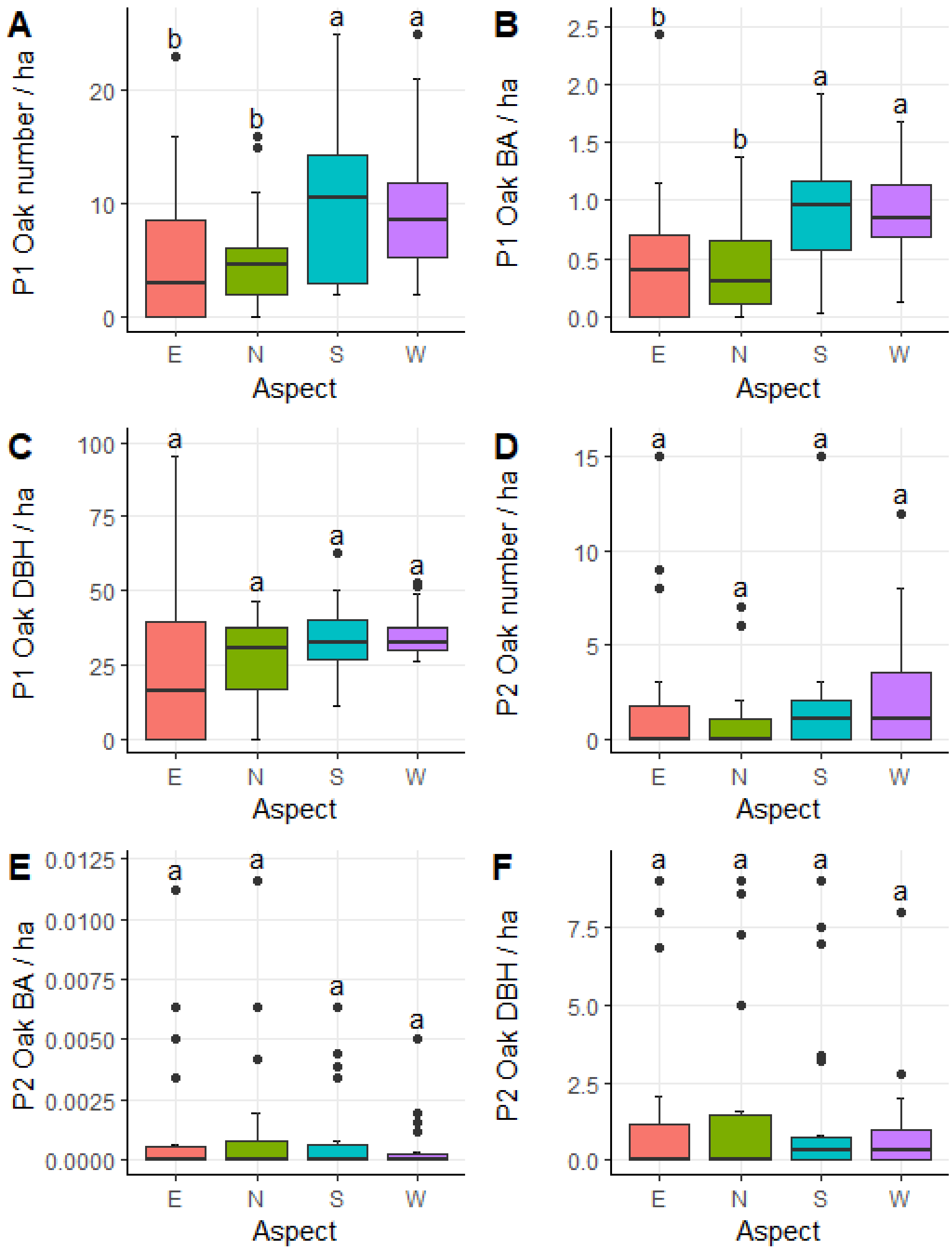

Figure 2.12 The relationship of the attributes of the oak component in the overstory (graphs A – C) and understory (graphs D – F) with aspect. BA = basal area.

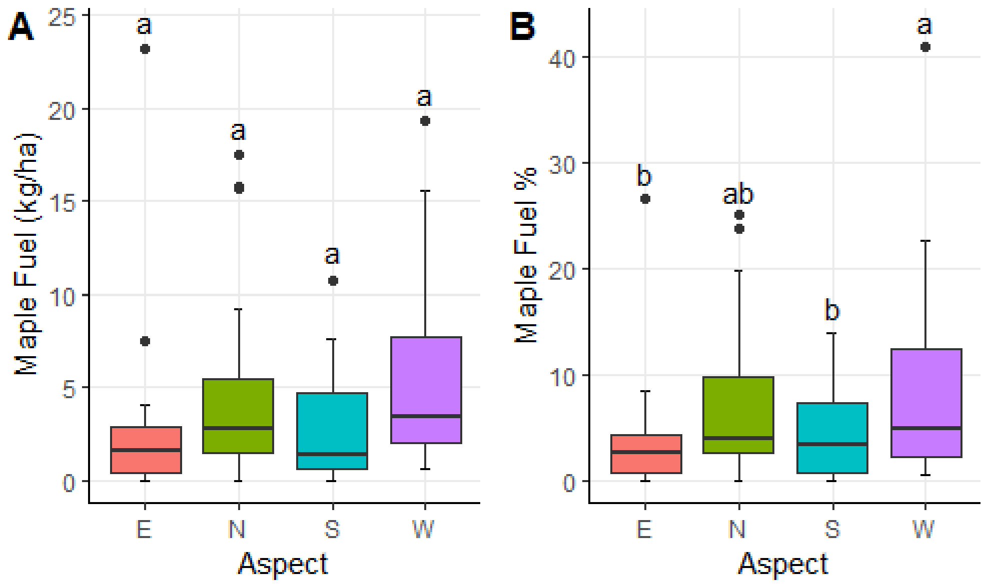

Figure 2.13 Maple fuel load (kg/ha) by aspect (A), and maple fuel loading as a percentage of total fuel load by aspect (B).

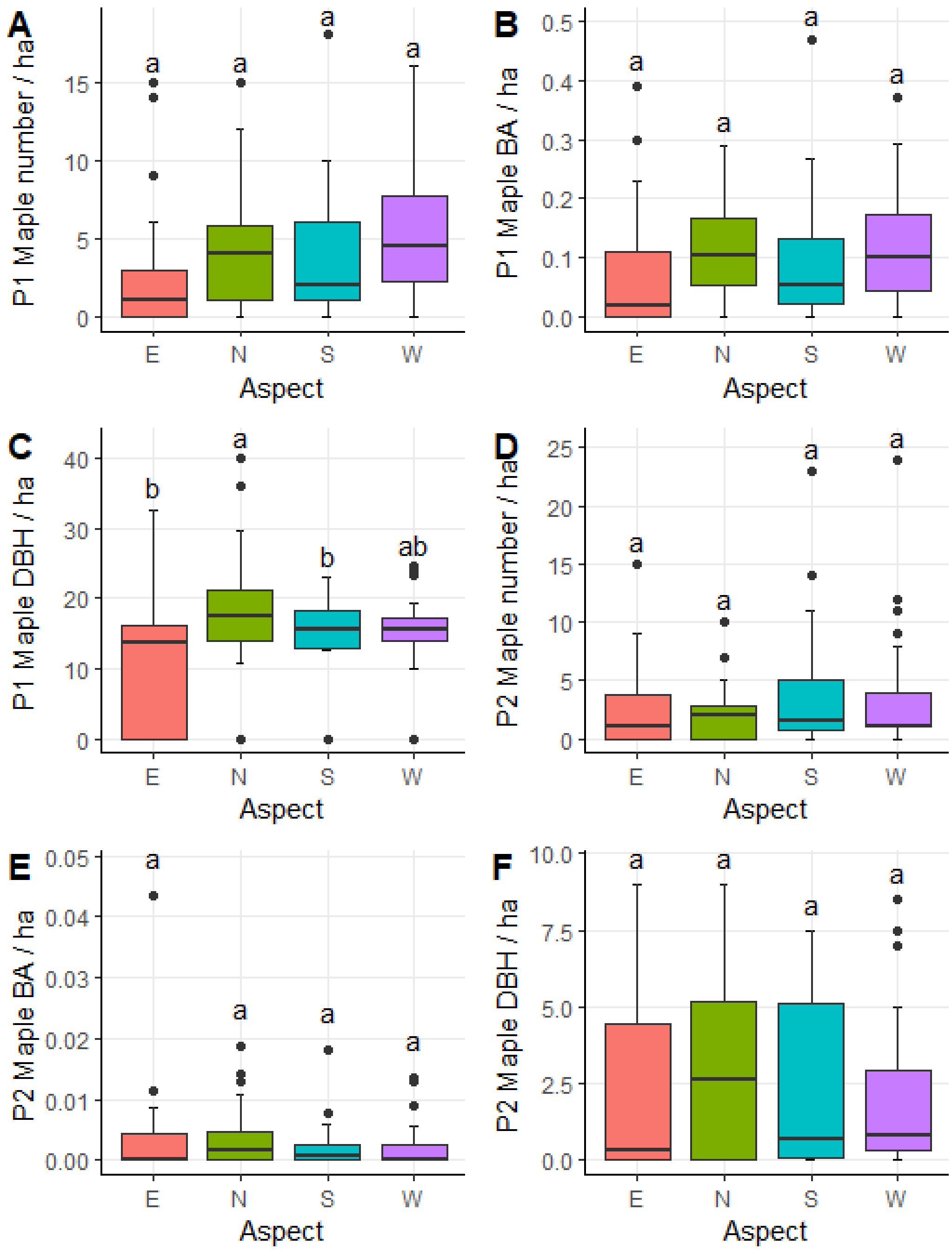

Figure 2.14 The relationship of the attributes of the maple component in the overstory (graphs A – C) and understory (graphs D – F) with aspect. BA = basal area.

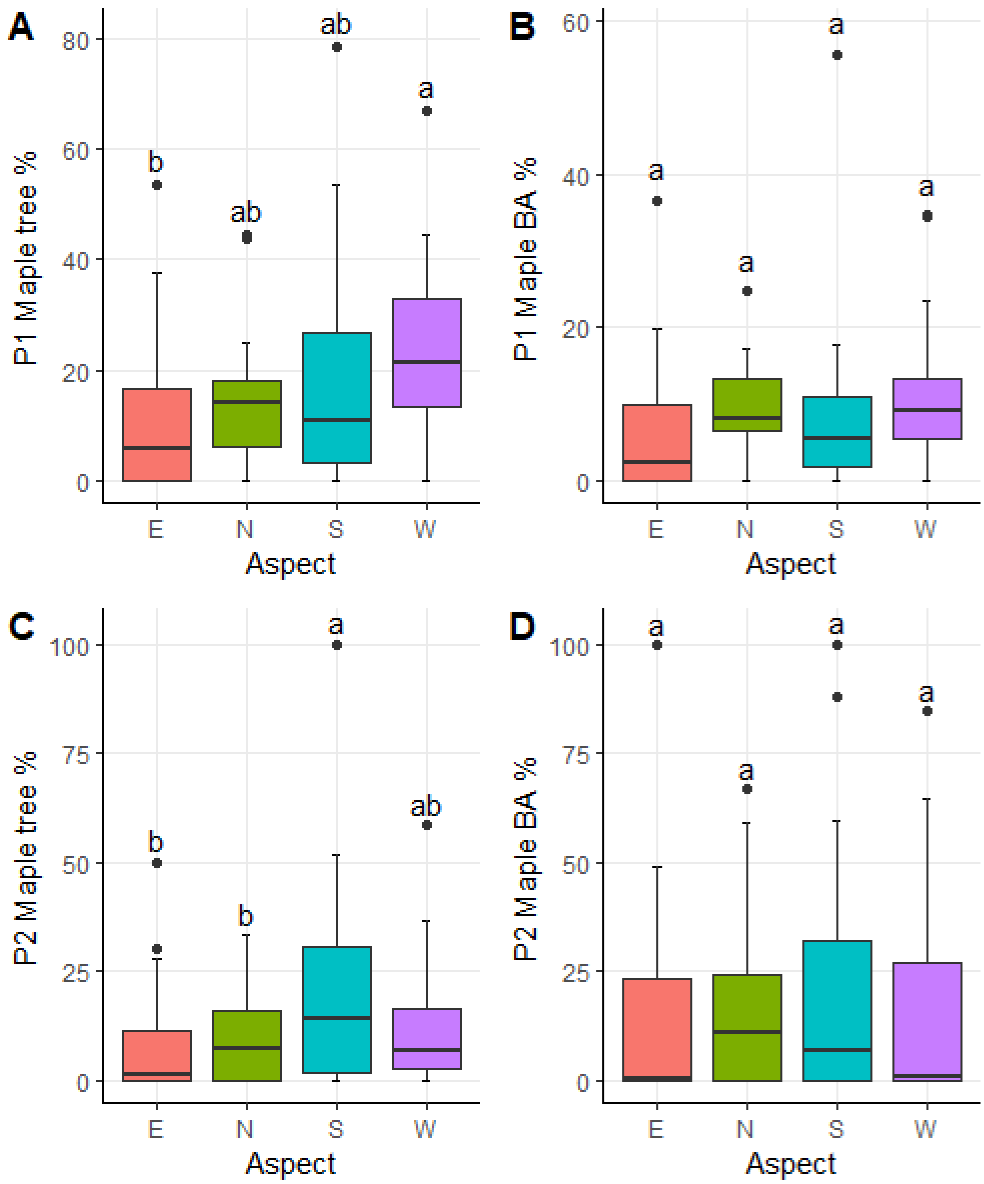

Figure 2.15 The trees/ha and basal area of maple as a percent of the forest composition by aspect for the overstory (graphs A, B) and the understory (graphs C, D).

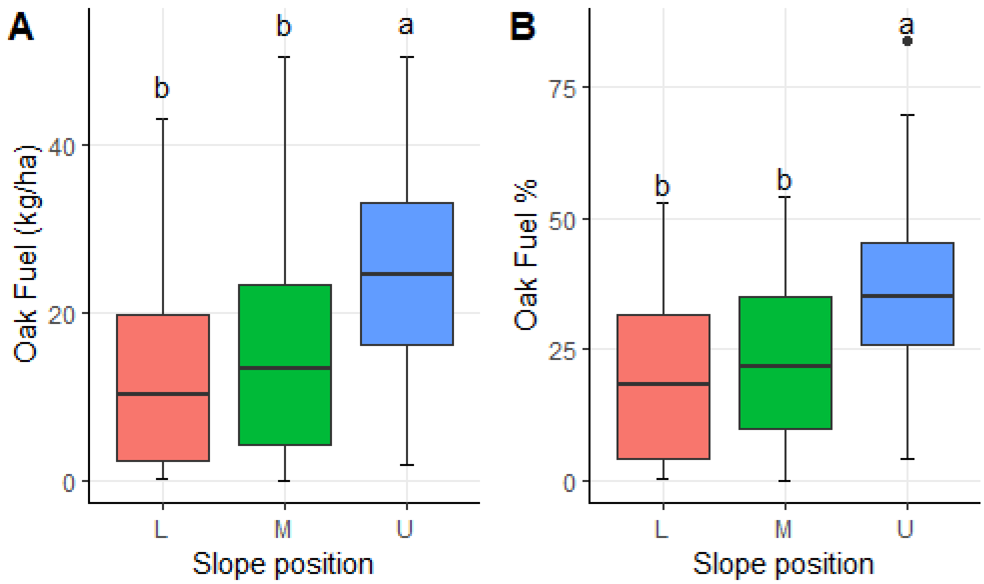

Figure 2.16 Oak fuel load (kg/ha) by slope position (A), and oak fuel loading as a percentage of total fuel load by slope position (B) (L = lower position, M = middle position, U = upper position). Boxes with different letters are significantly different (P < 0.05) according to the post-hoc Duncan's multiple range test.

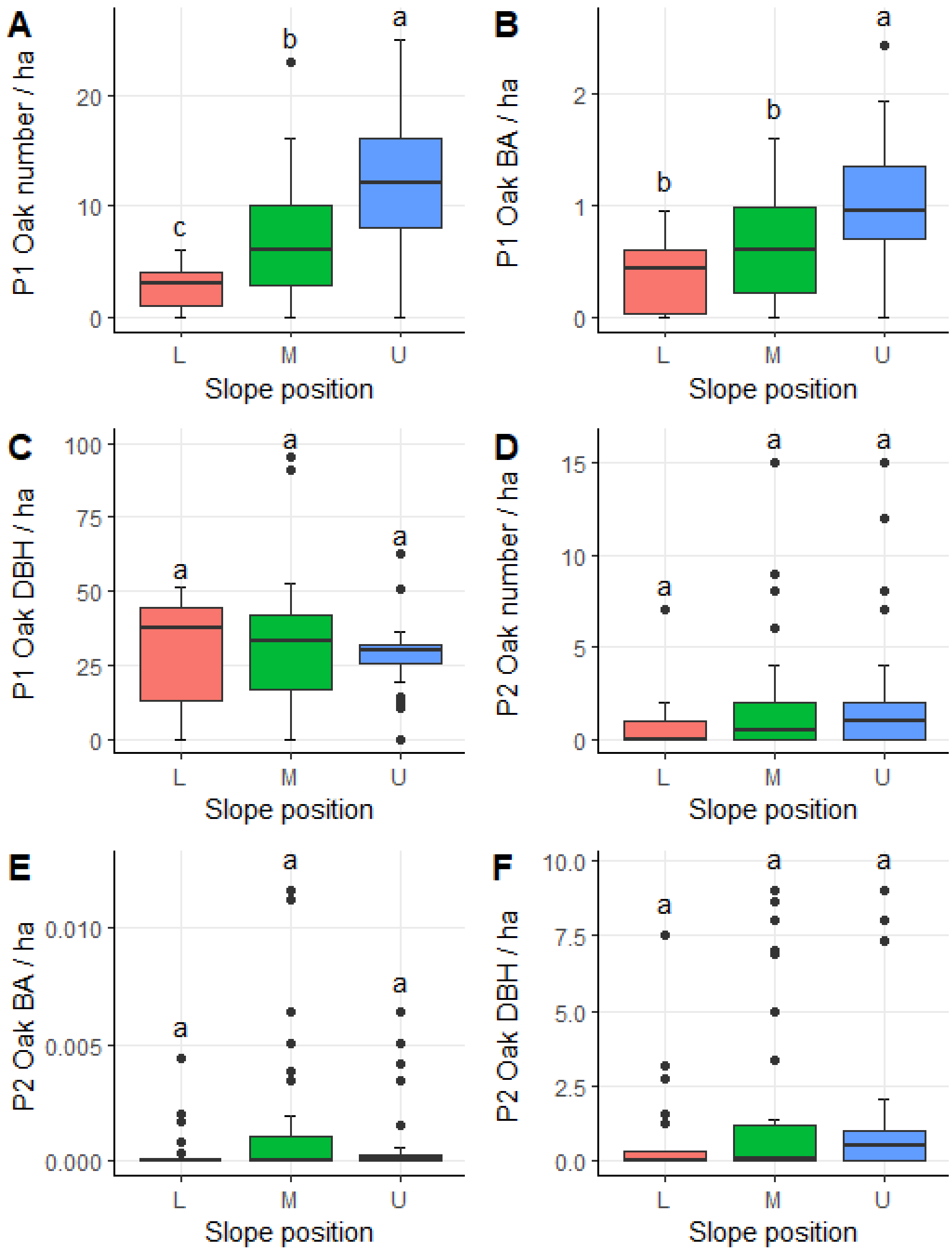

Figure 2.17 The relationship of the attributes of the oak component in the overstory (graphs A – C) and understory (graphs D – F) with slope position.

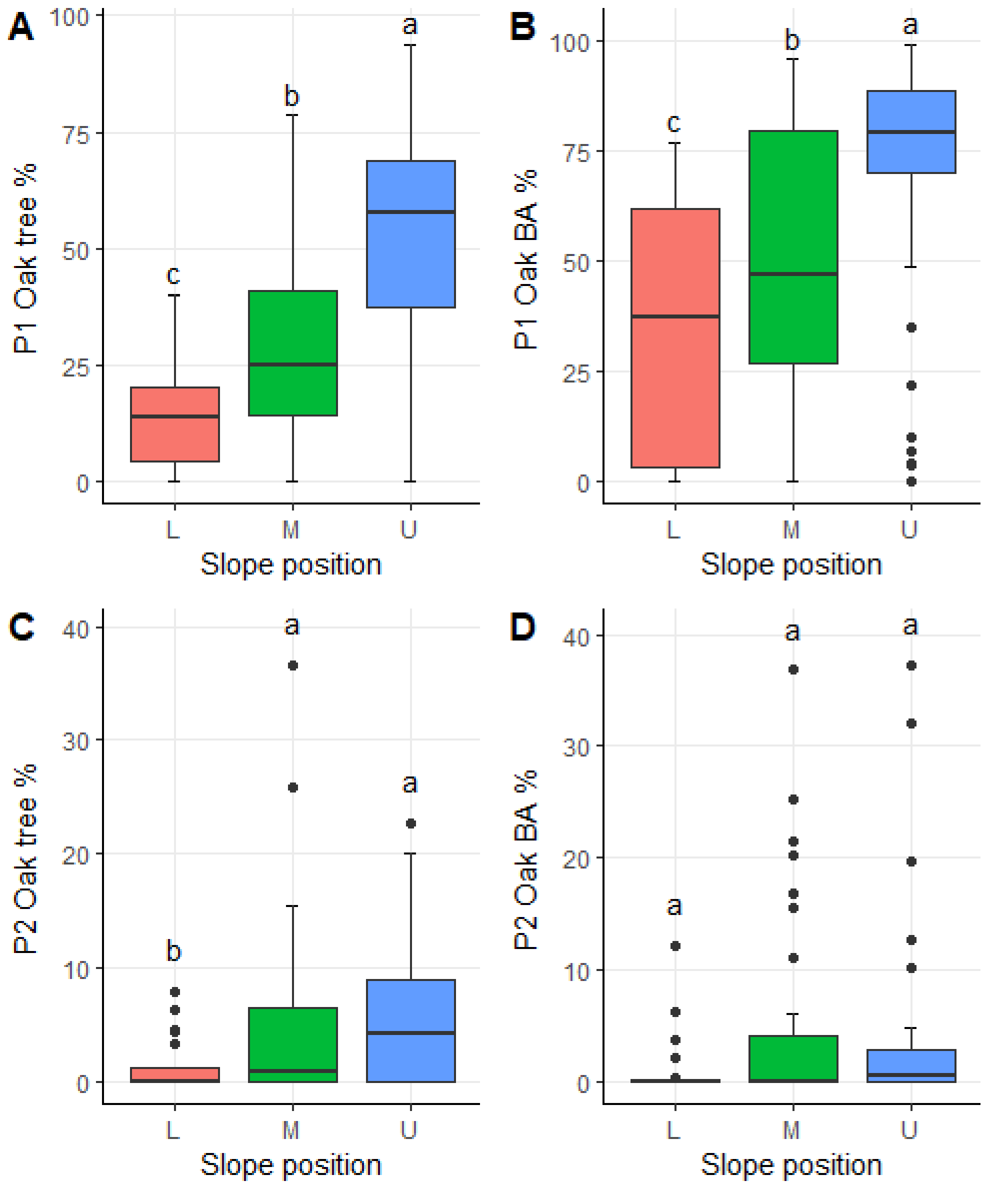

Figure 2.18 The trees/ha and basal area of oak as a percent of the forest composition by slope position for the overstory (graphs A, B) and the understory (graphs C, D).

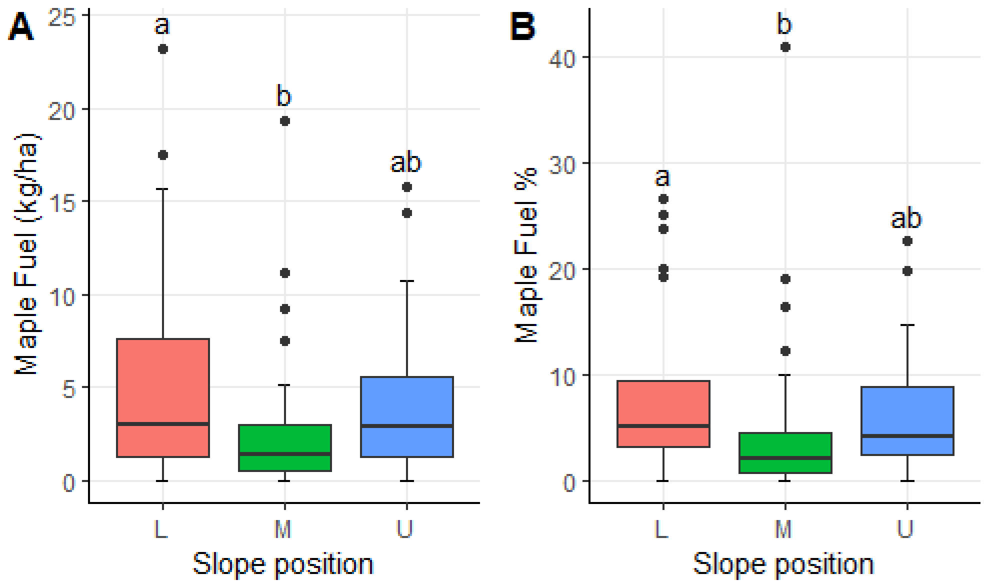

Figure 2.19 Maple fuel load (kg/ha) by slope position (A), and maple fuel loading as a percentage of total fuel load by slope position (B).

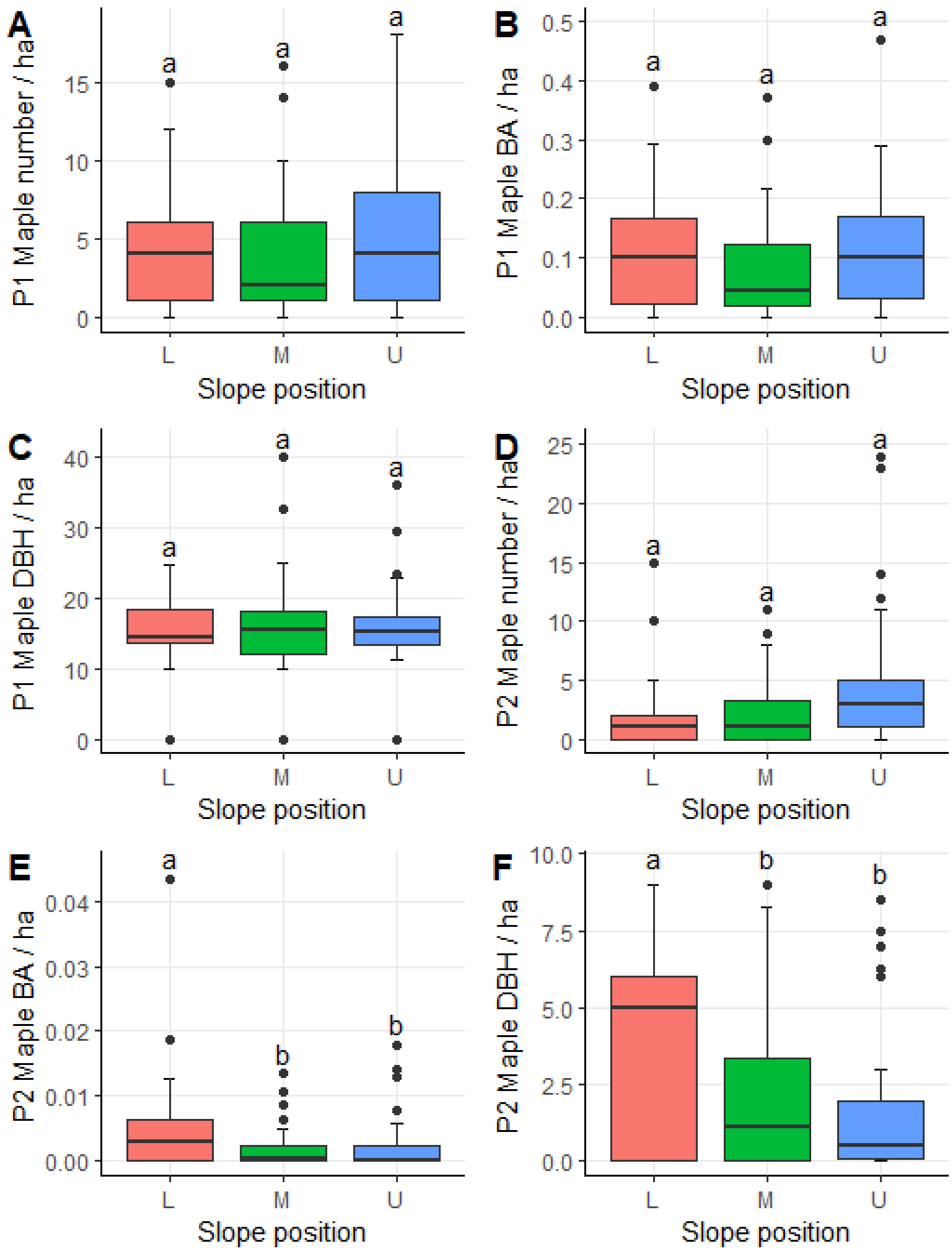

Figure 2.20 The relationship of the attributes of the maple component in the overstory (graphs A – C) and understory (graphs D – F) with slope position.

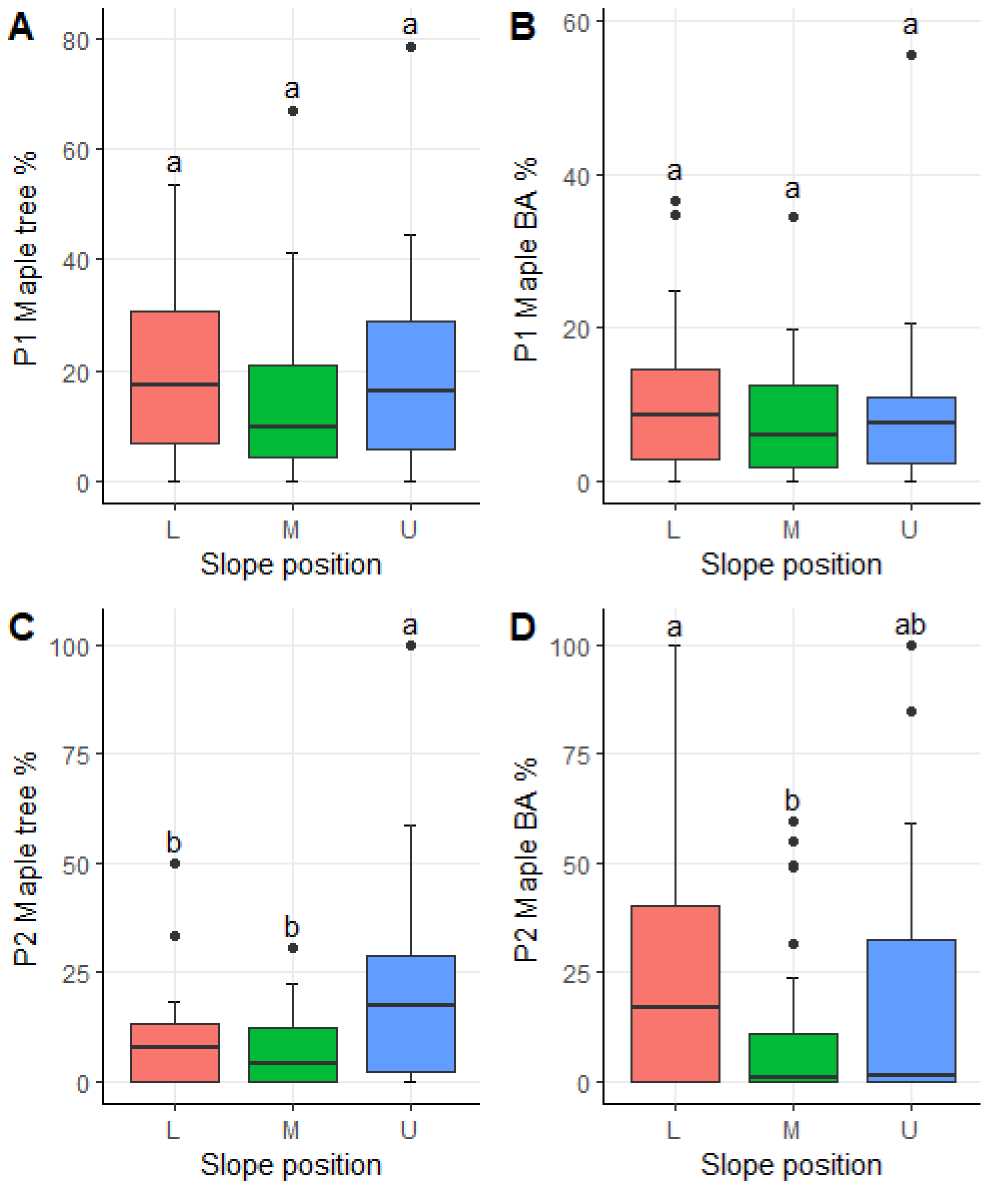

Figure 2.21 The trees/ha and basal area of maple as a percent of the forest composition by slope position for the overstory (graphs A, B) and the understory (graphs C, D).

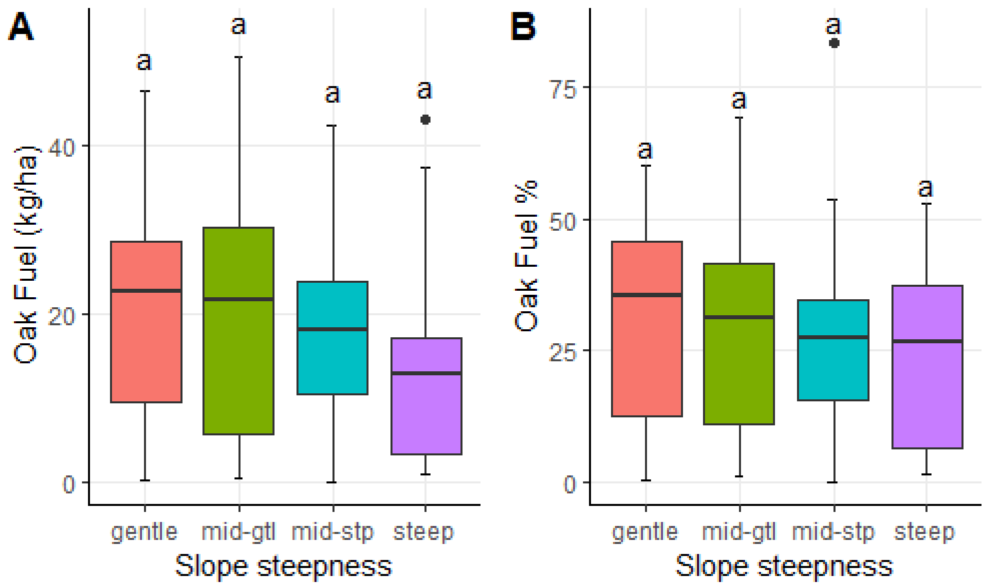

Figure 2.22 Oak fuel load (kg/ha) by slope degree category (A), and oak fuel loading as a percentage of total fuel load by slope steepness (B) (gentle = slope <20°, mid-gentle = 20° < slope <30°, mid-steep = 30° < slope <40°, steep = slope >40°). Boxes with different letters are significantly different ($P < 0.05$) according to the post-hoc Duncan's multiple range test.

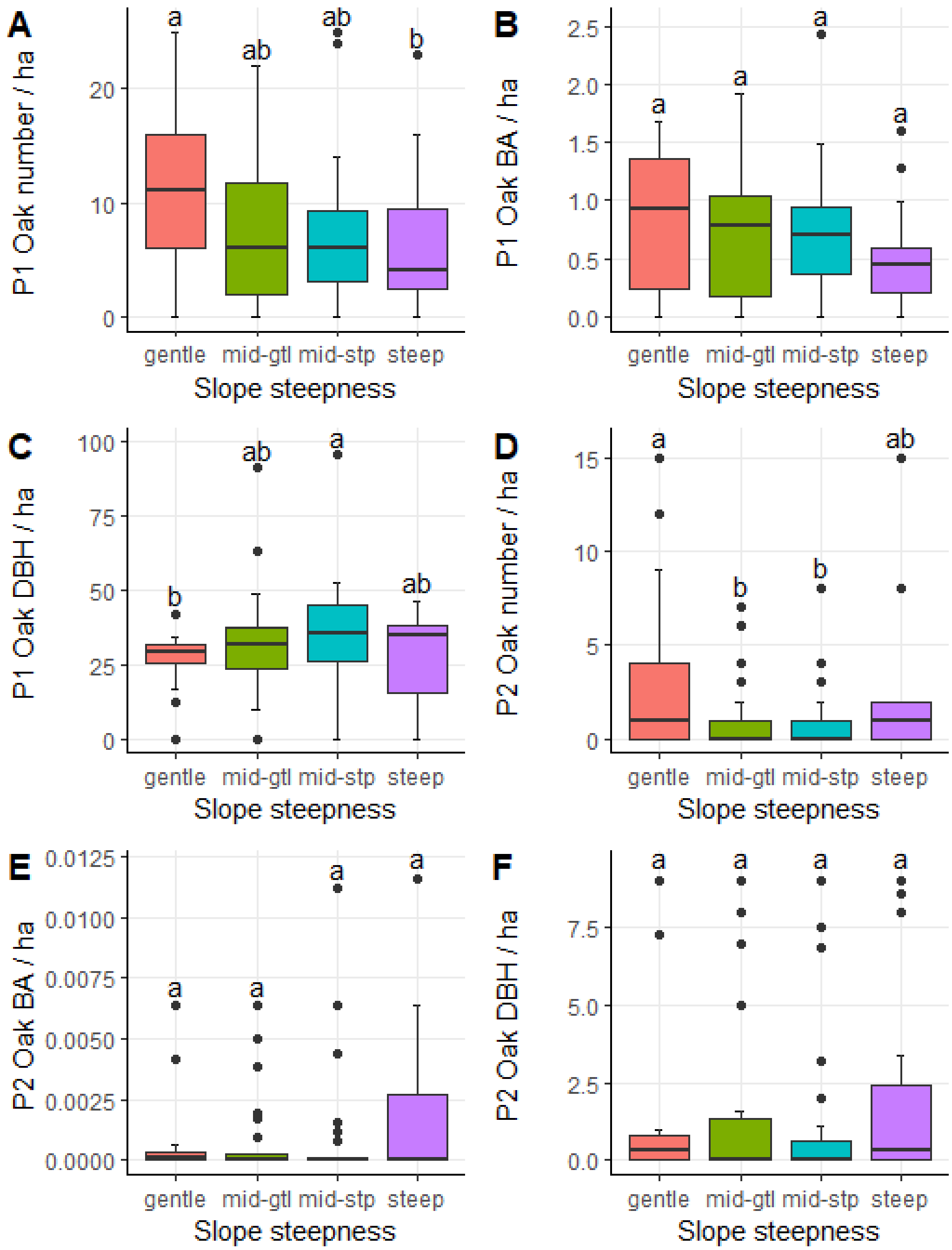

Figure 2.23 The relationship of the attributes of the oak component in the overstory (graphs A – C) and understory (graphs D – F) with slope steepness.

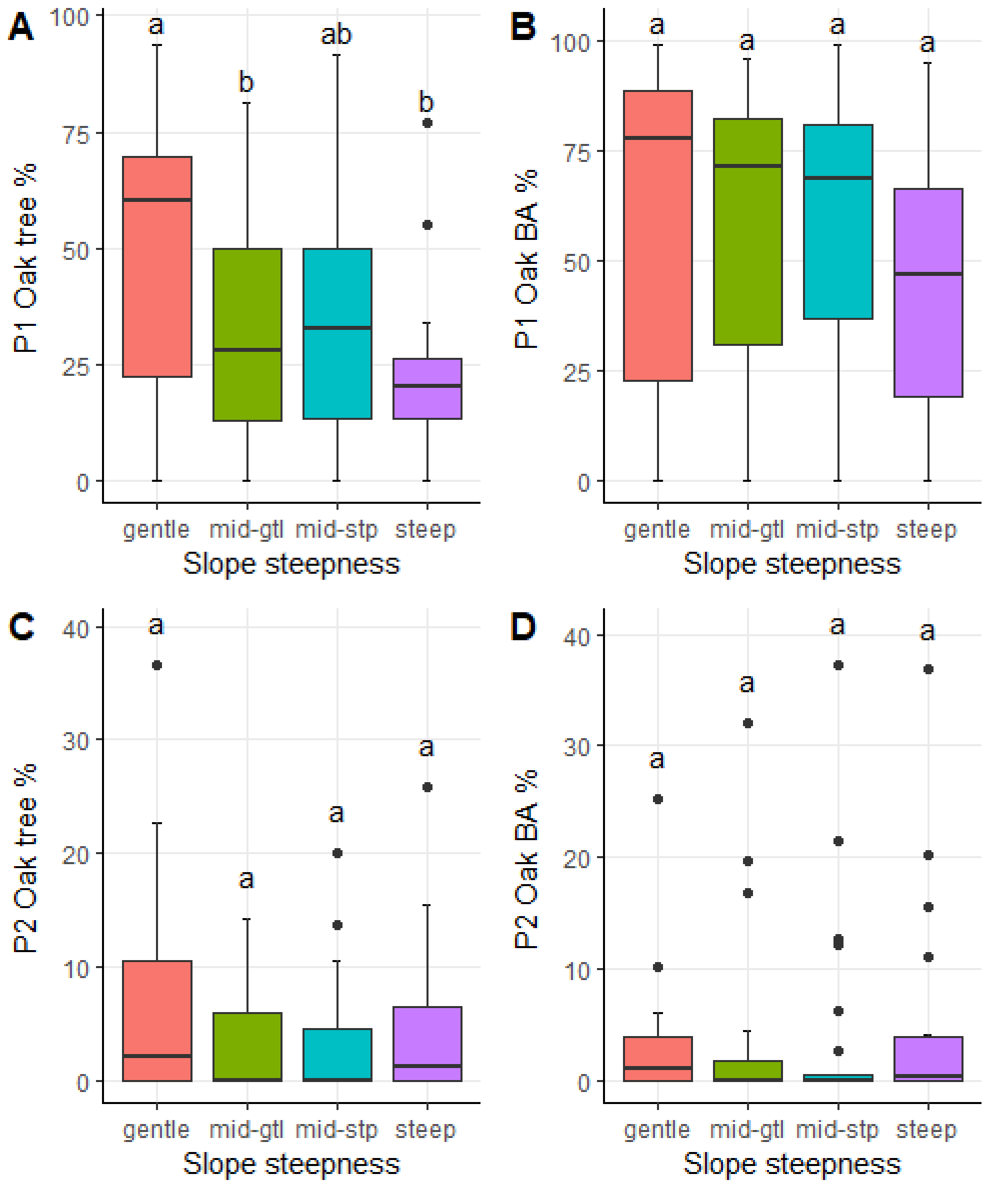

Figure 2.24 The trees/ha and basal area of oak as a percent of the forest composition by slope steepness for the overstory (graphs A, B) and the understory (graphs C, D).

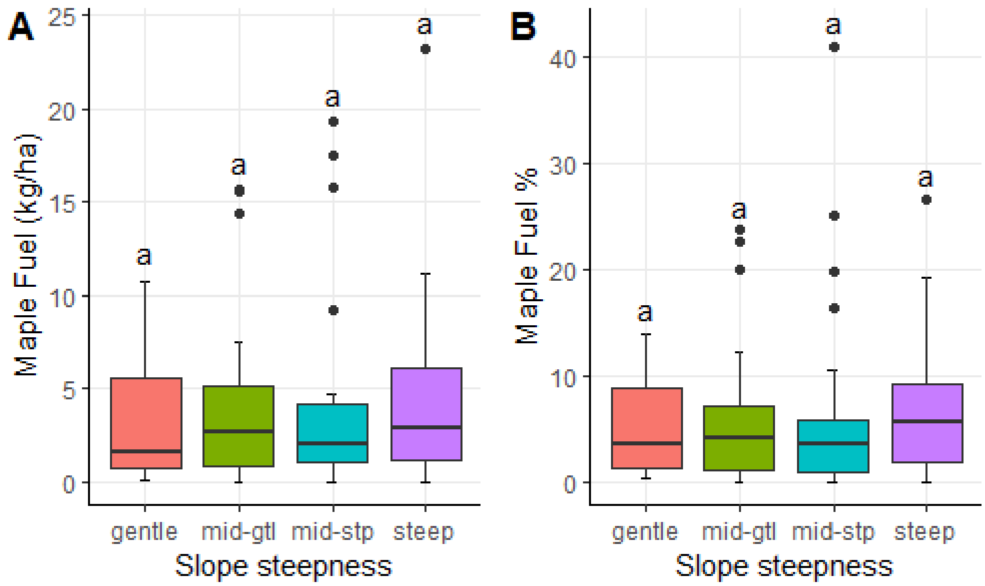

Figure 2.25 Maple fuel load (kg/ha) by slope degree category (A), and maple fuel loading as a percentage of total fuel load by slope steepness (B)

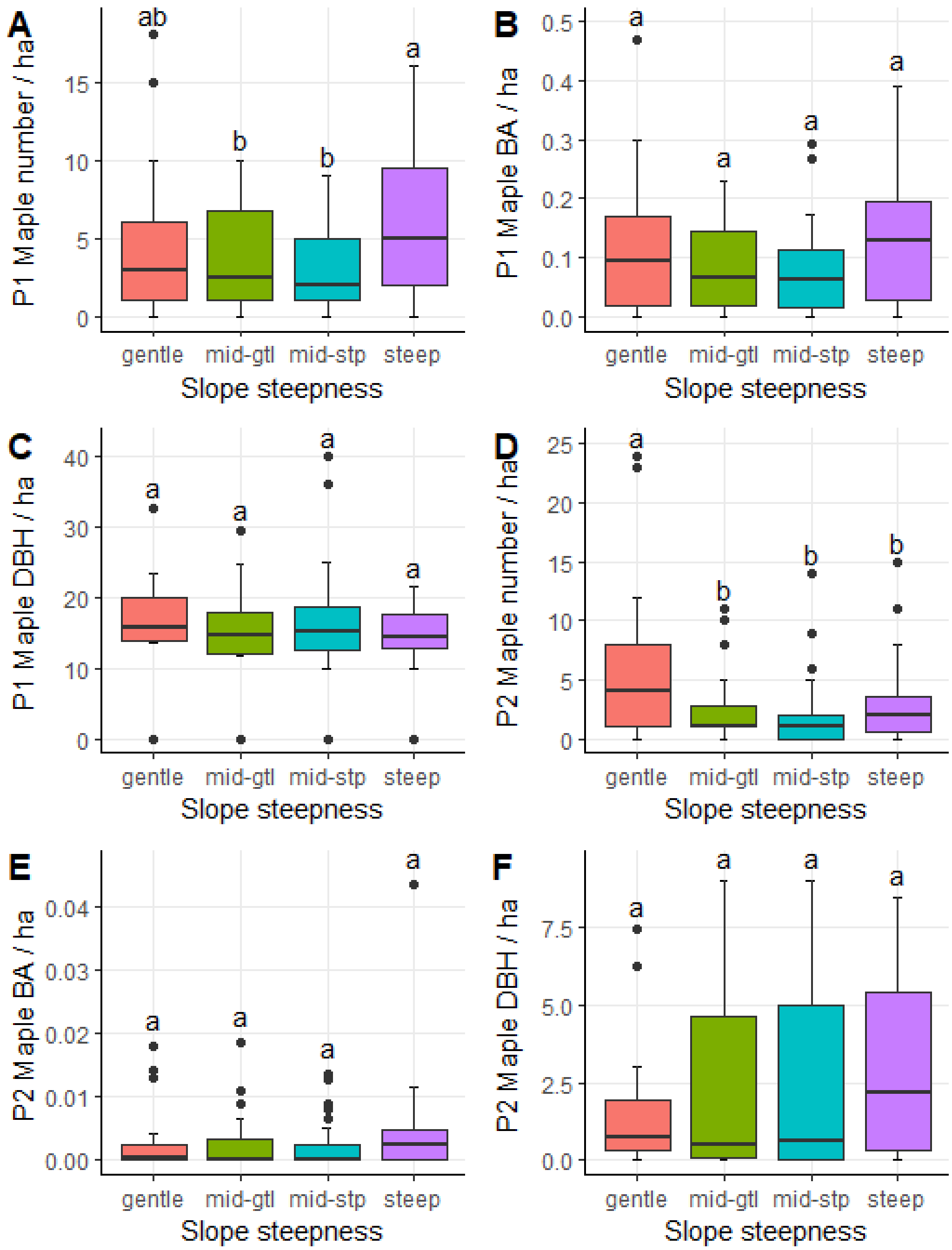

Figure 2.26 The relationship of the attributes of the maple component in the overstory (graphs A – C) and understory (graphs D – F) with slope steepness.

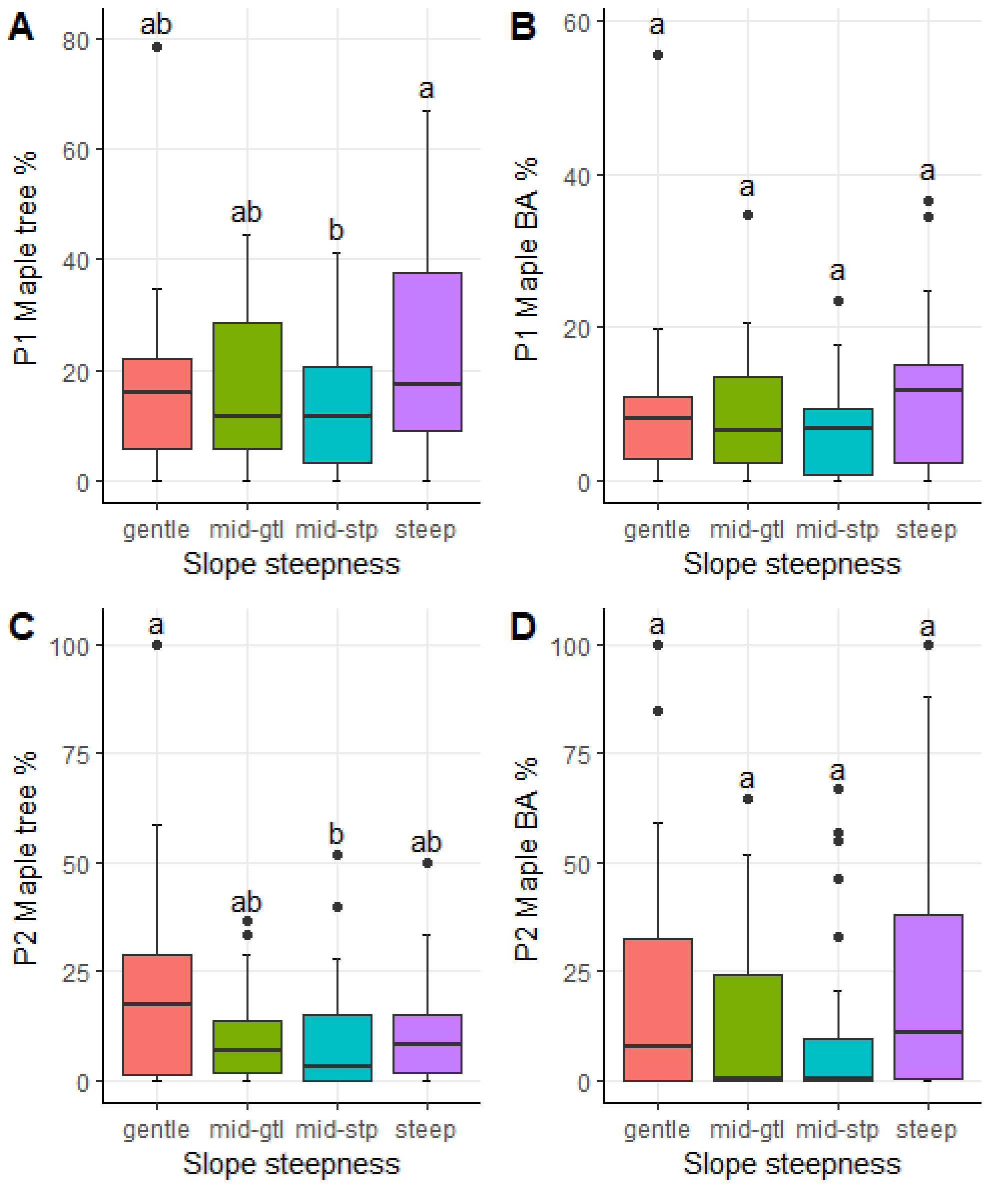

Figure 2.27 The trees/ha and basal area of maple as a percent of the forest composition by slope steepness for the overstory (graphs A, B) and the understory (graphs C, D).

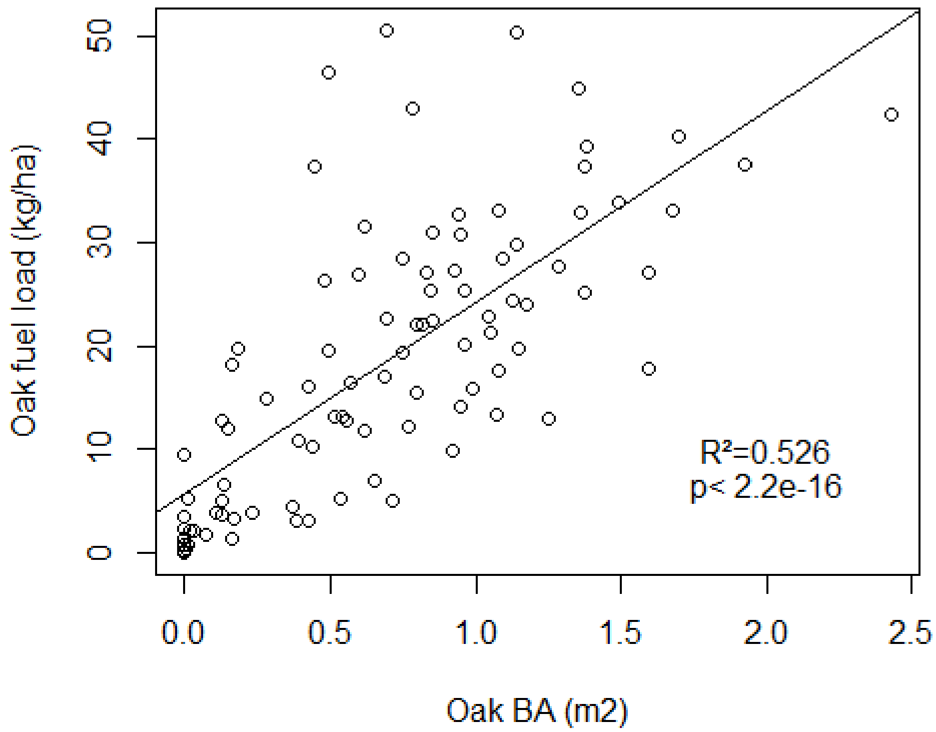

Figure 2.28 The linear regression between oak basal area (tree>10cm DBH) and oak fuel load (kg/ha).

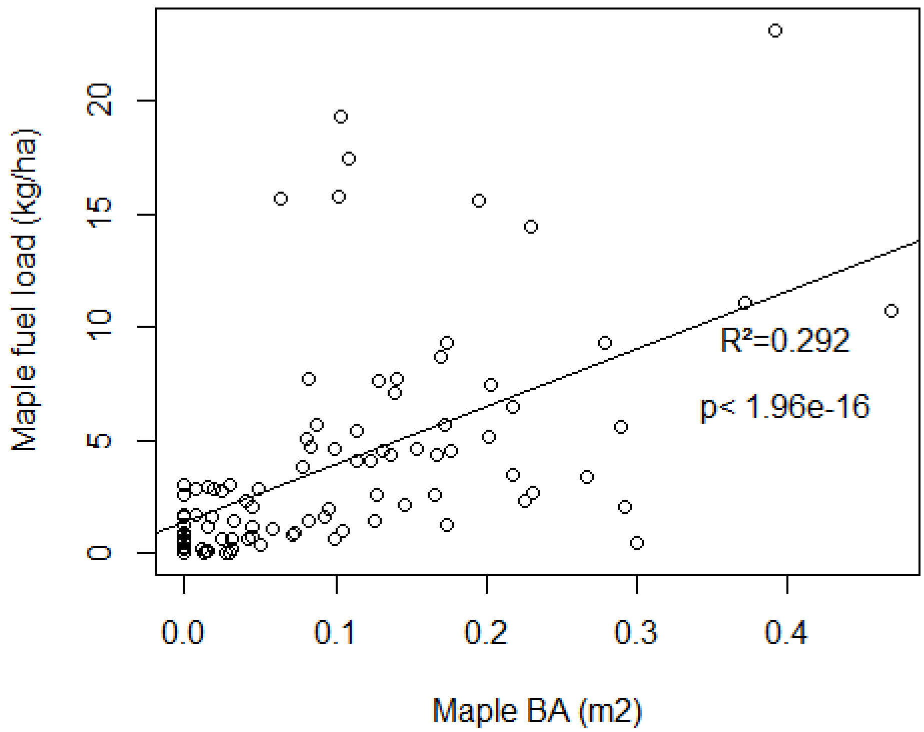

Figure 2.29 The linear regression between maple basal area (tree>10cm DBH) and maple fuel load (kg/ha).

Chapter 3 Effects of Fuel Composition on Fire Intensity

Introduction

Fire management and related research are often focused on fuel monitoring and manipulation since its traits drive fire behavior and impacts (Lydersen et al., 2015). Assessing the characteristics of fuel flammability and heat released during the fire is of major significance regarding fire intensity and fire spread control (Curt et al., 2011). Greater fuel loads and lower fuel moisture increase fire temperatures (Graham & McCarthy, 2006) and can lead to the larger burned areas and higher ignition hazards. In addition, fuel treatments can influence the effects of fire on species composition and ash production, which can harm endangered ecosystems and soil (Quigley et al., 2019).

Accurate knowledge of fuel is critical for evaluating potential fire behavior; however, due to their intrinsic variability, it is challenging to quantify or describe fuel conditions (Lydersen et al., 2015). For example, Curt et al., (2013) found that even two areas that have similar weather and fuel type can generate contrasting patterns of fire recurrence because fuel size, shape, and connectivity can play a major role in the fire interval. According to Zhao et al., (2016), litter particle size is key to explaining species variation in fuel bed ignitability, and the potential of some species to affect fire is disproportionate to their abundance. Some fuel characteristics, such as surface-to-volume ratio, fuel species composition, fuel distribution, etc., remain to be further investigated.

Oak forests are a major component of the Eastern Deciduous Forest, and their existence needs frequent fire as a key disturbance to maintain oak dominance (Bataineh et al., 2022). However, the fire suppression policy during the 20th century quickly shifted the species composition and structure from heliophytic, fire-adapted species to shade-tolerant, fire-sensitive species (Nowacki & Abrams, 2008). Red maple (*Acer rubrum L.*), sugar maple (*Acer saccharum Marsh*.), and other mesophytic species are increasingly replacing oaks (*Quercus spp.*) and creating a shadier, cooler, and moister fire environment. In addition, this change in vegetation leads to changes in the fuel bed characteristics directly through the subsequent litter production (Capellesso et al., 2016). Litter characteristics such as litter dimension and shape, litter chemistry, and litter moisture are different among oak and maple species (Dickinson et al., 2016). Understanding species-level variation in fuel traits associated with the fire environment is critical to understanding the current fire combustion properties in the eastern oak forest.

McDaniel et al. (2021) examined the impacts of species-driven changes in upland oak forests on litter flammability. They found that leaf litter traits and moisture dynamics varied between oak and non-oak species; specifically, the flammability of oak fuel was higher than non-oak fuel and that flammability was negatively correlated with the amount of non-oak fuel load (McDaniel et al., 2021). However, their research did not involve maple species, which is the rapidly proliferating shade-tolerant species in south Ohio. Furthermore, microclimate, weather (wind, temperature, relative humidity), and topography may affect the flammability and fire behavior. Laboratory data that eliminate external conditions (wind and topography) on fuel flammability is essential to further understanding the variation of fuel traits among species.

In order to better determine the impacts of species-driven changes in fuel flammability characteristics and the specific relationship between fuel ignition variation at the species level, an analysis of fuel composition and fire behavior should be conducted under controlled laboratory conditions. In this study, we compared the flammability of oak and maple fuel by measuring the maximum flame temperature, flame height, combustion duration time, and fuel mass loss percentage. Our objective was to (1) examine how fuel flammability varies between oak and maple, (2) assess how oak and maple fuel influence fire behavior characteristics by measuring flammability metrics (fuel temperature, flame height, flame duration time, and fuel mass loss rate), and (3) evaluate the correlation between flammability metrics and how the correlations varied between oak and maple. We hypothesize that 1) maple will have less fuel flammability than oak due to the differences in the chemical and physical properties of litter, 2)the flammability metrics (flame temperature, flame height, flaming duration, fuel mass loss rate) will vary between oak and maple fuel, and 3)the maximum temperature will be strongly correlated to the flame height, fire duration time, and mass loss percentage.

Methods

<u>Fuel collection and preparation</u>

Fuels were collected from Zaleski State Forest (82°25'W, 39°18'N), in Vinton County, Ohio. Soon after leaf fall (October 2022), a 30cm x 30cm wooden frame was used to collect forest fuel (Fig 3.1), in which all forest fuel classified in the 1-hour (< 0.6 cm diameter) and 10-hour (0.7 – 2.5 cm diameter) fuel class (leaf litter, grasses, twigs, and woody vegetation) contained within the 30cm x 30cm frame were collected down to the mineral soil. A total of 94 fuel samples were collected from 94 plots established previously. Fuel samples were stored in paper bags and oven-dried at 70℃ for 48 hours until they maintain a constant weight to reduce the disturbance of fuel moisture in ignition experiments. Samples were stored in paper bags after oven-dried in a dry environment at room temperature to wait for the combust.

Ignition experiments

Ignition experiments were conducted in the lab under a laboratory fume hood. To determine the different flammability characteristics between species, oak and maple leaves were carefully extracted from all fuel samples and were combusted separately. A total of 30 combustion samples were separated (15 oak sample and 15 maple samples) and no distinctions were made among oak species (*Quercus prinus* L., *Quercus. rubra* L., *Quercus coccinea* Muenchh., *Quercus alba* L.) or maple species (*Acer rubrum* L.*, Acer saccharum* Marsh.), as the separation was based on genus. Each combustion sample weighed 20g and placed evenly within a 26cm x 33cm metal tray, the fuel structure simulates the structure in the field without artificial compaction. Two 30.5cm long thermocouples (K-type) probes connected with HOBO dataloggers were used to collect fire temperatures at different heights, one placed at 0cm above the fuel surface, and the other one at 10cm above the fuel surface (Fig. 3.2). The 10cm elevated location was expected to capture the radiative intensity of the fire, which can represent the heat radiation received by unburnt fuels and may also vary between oak and maple fuel (Yip et al., 2021). The thermocouple probes were centered over each fuel sample such that the probes extended over the center of the fuel sample. Each sample was ignited following a pattern of spot fire with a butane candle lighter at the right corner of each combustion sample, and several flammability metrics were measured during the combustion process, including maximum flame height, combustion duration time, and fuel mass loss percentage. To measure the flame height, a centimeter-scale ruler was placed vertically near the thermocouple holder. Video equipment was used to capture the entire combustion process, which was placed horizontally about half a meter away from the ignition sample. After combustion, the maximum flame height was measured by reviewing the recorded video every 1/30 second. Ignition duration time was measured from the initial ignition time to extinction of a visible flame through the video. Following combustion, the residual ash that remained was weighed after cooling to calculate the fuel mass loss percentage.

Statistical analysis

Oak and maple fuel flammability was analyzed via one-way analysis of variance (ANOVA) followed by a Duncan's multiple range test (significance level $\propto = 0.05$) to compare the means of the two species groups. The relationship between flammability metrics were analyzed using regression and Pearson’s correlation coefficient. Significant correlation was assumed when $r > 0.30$ and $p \leqslant 0.05$. All statistical analyses were performed in R, version 4.2.2 (R Core Team, 2022).

Results

<u>Oak and maple flammability</u>

The flammability metrics varied between oak and maple fuel (Table 3.1). Oak fuel temperatures were significantly higher than maple at the fuel surface (0cm, Fig. 3.5A) with the average temperature of oak and maple fuel samples 167.10 °C and 142.39 °C respectively. The maximum temperature at 10cm above fuel surface had high variation, with oak fuel temperatures were slightly higher than maple fuel (Fig. 3.5B), where the average oak fuel temperature of 79.48°C, and the average maple fuel temperature of 75.03°C.

The fuel consumption, as well as fuel mass loss percentage, had significant differences between oak and maple fuel (Fig. 3.3, Fig.3.6A). Oak had a higher fuel consumption compared to maple with a range from 90.20% to 93.55% for oak and range from 77.95% to 91.00% for maple.

The combustion duration time of oak was significantly longer than maple (Fig.3.6B) with an average of 46.67secs and 40.13secs respectively. However, maple fuel showed a slightly higher flame height than oak fuel (Fig.3.4, Fig.3.6C).

<u>Relationship between flammability metrics</u>

For the overall combustion samples, relating maximum temperature (0cm) to flammability metrics revealed a positive correlation with fire duration time (r=0.52, Table 3.2), and the mass loss (r=0.40), while the mass loss was also significantly and positively correlated to the fire duration time (r=0.45).

Discussion

Our study demonstrated that oak and maple fuel differed in their heat of combustion (HOC) as measured in degrees Celsius, and oak had significantly higher flame temperatures than maple fuel. These results were consistent with other studies that oak exhibited higher HOC than non-oak species (McDaniel et al., 2021). The lower HOC species were characterized by a shorter flame duration time and little fuel consumption (Engber & Varner, 2012), which are consistent with our results that when compared oak with maple, maple showed a significantly shorter combustion duration time and lower fuel mass loss. The correlation between fuel mass loss, fuel temperature, and combustion duration time indicates that higher fire temperatures can lead to a greater fuel mass loss and a longer combustion duration time. However, we did not find significant correlations when analyzing the maple and oak data separately, possibly due to the limited number of samples.

According to Dickinson et al. (2016), the hypothesis is fire intensity tends to be lower due to the shifted forest composition from oaks to mesophytic species (e.g., maple) in deciduous oak forests in the eastern US. Some researchers suggest that non-oak fuel can decrease ignition probability and dampen litter flammability from the fuel moisture perspective (McDaniel et al., 2021), or by analyzing flammability metrics instead of real fire temperature (J. M. Kane et al., 2021). Our findings supported this hypothesis using real fuel combustion temperature data acquired from K-type thermocouples and demonstrating the significantly lower fire temperatures of maple fuel compared with oak. Differences between oak and maple in leaf shape and dimensions combined with differences in litter chemistry, litter drying, and rate of litter decomposition can determine fuel bed characteristics and combustion (Dickinson et al., 2016). The heat content of litter is a function of many factors, such as the amount of litter, carbon content (e.g., cellulose and lignin), and leaf chemistry (volatiles) (Nowacki & Abrams, 2008). The content of lignin can mitigate litter decomposition rate, with high lignin litter decomposing slower (Chakravarty et al., 2020). In our experiment, oak species were mainly consistent of white oak (*Quercus alba* L.), chestnut oak (*Quercus prinus* L.), red oak (*Quercus alba* L.), and scarlet oak (*Quercus coccinea* Muenchh.). The percentage of lignin was typically higher in chestnut oak, scarlet oak, and white oak than in mesophytic species (Blair et al., 1990; Nowacki & Abrams, 2008). Some research found that the high lignin in the decomposed litter can strongly determine heat release and lead to more char formation (Fushimi et al., 2003). For these reasons, oak's resistance to decay and flammability are higher than mesophytic species such as maple.

Thermocouples at the fuel surface and 10cm above the fuel surface both recorded higher temperatures for the oak fuel than for the maple fuel. Surface fuel temperatures displayed a strong correlation with flammability metrics of flaming duration time (r=0.45) and fuel mass loss (r=0.40); however, correlations were weakened when measuring HOC at 10cm. Therefore, the recorded temperature at the fuel surface was a better predictor of flaming duration time and fuel consumption, suggesting that the temperature captured by the surface thermocouple better reflects combustion conditions within the fuel bed, whereas the temperatures recorded by the elevated location were more responsive to flame characteristics (Quigley et al., 2019), such as flame intensity and fireline intensity. Furthermore, the temperature recorded at 10cm represents greater heat radiation that can be received by the unburnt fuel (Yuan et al., 2020), meaning that oak fuel has a greater ability to pre-heat the unburnt fuel and thereby creating a higher fire rate of spread compared to maple litter.

Our average flame height data of oak (34.87cm) was within the range recorded by Kane et al. (2008), which was from 33.6cm to 81.4cm for 8 oak species. Our average maximum temperature data of oak and maple (79.5 °C and 75.0 °C, respectively) was higher than the data acquired by Ganteaume et al. (2014), where the average maximum temperature for deciduous leaves was 61.6°C. The reason might be the different fuel sample loads (15g in their study vs. 20g in our study), and a higher fuel load can result in higher fire temperatures due to higher heats of combustion generated by more fuel. The other reason might be the fuel composition, which they used mixed litter samples, while we used single-genus litter samples.

Regarding flame height, our results showed that maple produced a slightly higher flame than oak, which may be due to the leaf curling. In the field, mesophyte-dominant litterbeds tend to be shallower. However, in our experiments, oak litter tended to be flatter than maple litter (Fig.3.7), and flat leaves create less aerated fuel beds, with diminutive flame height (Engber & Varner, 2012). Therefore, more “fluffy” maple fuel in our experiment produced a subtle higher flame; plus, the flame becomes slightly elevated due to slightly elevated fuel. The inconsistent leaf curling of oak and maple in the laboratory and field combined with the unpaired flame height and fuel temperature between oak and maple revealed that flame heights were mainly explained by the physical properties of leaves, specifically, aeration of the fuel bed, while fuel temperatures are mostly explained by leaf chemistry.

The maximum fuel temperatures in our study displayed a positive correlation with the fuel mass loss, meaning that higher fire temperatures produced less residual ash and greater fuel consumption in the combustion process, which is consistent with Dudaite et al., 2013. Higher temperatures affected litter ash nutrient composition and can change the ash's pH due to the solubility elements in ash (Quigley et al., 2019; Úbeda et al., 2009). At higher temperatures, the C/N ratio will increase and result in lower rates of N mineralization in the soil (Boerner et al., 2000), and the water-soluble elements (Ca^{2+}, Mg^{2+}) will be released by the ash and cause higher desegregation of soil mineral particles, thus leaving them more vulnerable to erosion transport (Úbeda et al., 2009). The nutrient-poor conditions created by higher fire intensity can limit tree growth and restore endangered ecosystems (Quigley et al., 2019; Úbeda et al., 2009). However, if the creation of nutrient-poor conditions can be caused by higher fire intensity, fire temperatures that are insufficient to volatilize mineral nutrients can result in an immediate increase in nutrient availability (Gray & Dighton, 2006). Compared with other species, red oak was best grown in nutrient-poor and dry conditions (Abrams, 1992). Therefore, frequent and high-intensity fires can contribute to the dominance of oak species by generating nutrient-limited conditions and constraining the growth of maple and other mesophytic species (Boerner & Brinkman, 2003).

McDaniel et al., (2021) found that oak species gained less moisture initially than non-oaks (winged elm and hickory) and lost moisture more quickly by comparing single-species fuel bed. The mesophyte-dominant litterbeds gained more moisture at saturation moisture contents compared to oak-dormient litterbeds and subsequently create a wetter fuelbeds (Kreye et al., 2018). The lower fire temperature created by maple fuels combined with the cooler, moister, and less flammability forest condition generated by these mesophytic species, allowing these mesophytes to self-perpetuate may indicate that fire intensities may not be able to reach their historical fire intensities (Alexander et al., 2021; Nowacki & Abrams, 2008). With the continued increase in the abundance of maple, prescribed fire may become less effective at maintaining oak dominance (Arthur et al., 2015).

Conclusion

This study determined the impacts of species-driven changes in fuel flammability characteristics and the specific relationship between fuel ignition variation at the species level. We compared the flammability of oak and maple fuel by measuring the maximum flame temperature, flame height, combustion duration time, and fuel mass loss percentage.

Our results demonstrated that oak and maple fuel differed in their heat of combustion (HOC) as measured in degrees Celsius, and oak had significantly higher flame temperatures than maple fuel. When comparing the combustion duration time and fuel mass loss of oak and maple, maple showed a significantly shorter combustion duration time and lower fuel mass loss. The correlation between fuel mass loss, fuel temperature, and combustion duration time indicated that higher fire temperatures can lead to greater fuel mass loss and a longer combustion duration time. Regarding flame height, our results showed that maple produced a slightly higher flame than oak, which may be due to the leaf curling. The unpaired flame height and fuel temperature between oak and maple revealed that flame heights were mainly explained by the physical properties of leaves, while fuel temperatures are mostly explained by leaf chemistry. Overall, these findings indicate that the shift from oak forest to mesophytic species can change fire behavior. Combined with the cooler, moister, and less flammability forest conditions generated by these mesophytic species, fires may not be able to reach their historical fire intensities, suggesting that updated data and new insights are needed for fire management.

Table 3.1 Combustion statistics for oak and maple (n=15 for each species) foliage in the ignition experiment.

Variable	Average	Min	Max	SD	CV%
			Oak		
Percent fuel mass loss	91.30	90.20	93.55	1.07	1.18
Max surface temperature (^oC)	167.10	134.66	214.33	25.85	15.47
Max temperature, 10cm (^oC)	79.48	50.67	121.18	18.18	22.87
Combustion duration (secs)	46.67	34.00	59.00	7.62	16.33
Flame height (cm)	34.87	29.00	42.00	3.55	10.19
			Maple		
Percent fuel mass loss	87.11	77.95	91.00	3.20	3.67
Max surface temperature (^oC)	142.39	116.73	162.64	13.34	9.37
Max temperature, 10cm (^oC)	75.03	53.04	133.01	22.92	30.55
Combustion duration (secs)	40.13	31.00	53.00	6.13	15.27
Flame height (cm)	36.57	30.00	44.00	3.84	10.49

Table 3.2 Pearson's correlation coefficient between ignition variables for the combined data of oak and maple.

	MLP	maxT0	maxT10	Duration (s)
maxT0	0.40*			
maxT10	0.11	0.40*		
Duration (s)	0.45*	0.52**	0.21	
Flame height (cm)	0.10	-0.11	0.04	-0.36

** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level
maxT0 = max surface temperature (^oC), maxT10 = Max temperature at 10cm (^oC)
MLP = fuel mass loss percentage

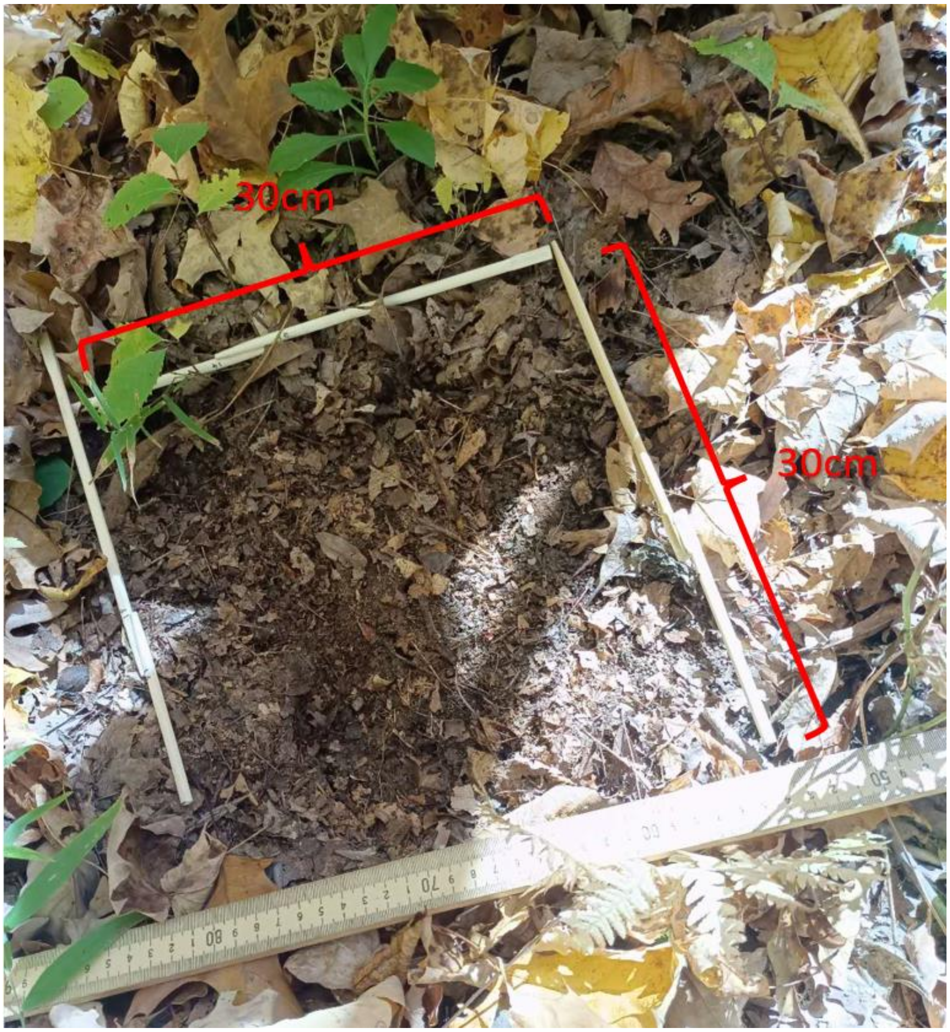

Figure 3.1 The 30cm x 30cm woody frame used to collect 1-hour (< 0.6 cm diameter) and 10-hour (0.7 – 2.5 cm diameter) fuel (leaf litter, grasses, twigs, and woody vegetation) down to the mineral soil.

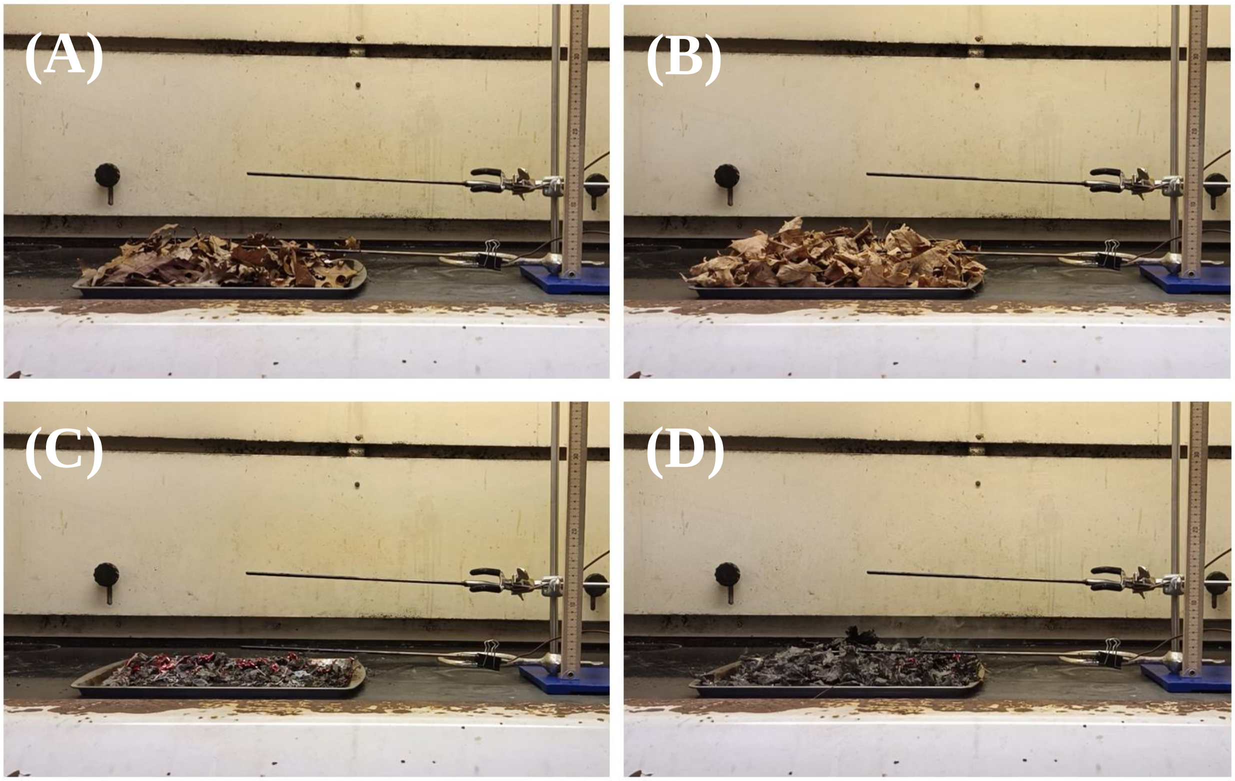

Figure 3.2 Fuel sample ignition experiment. (A) prior to burning with oak sample, (B) prior to burning with maple sample, (C) post-burn with oak sample, (D) post-burn with maple sample.

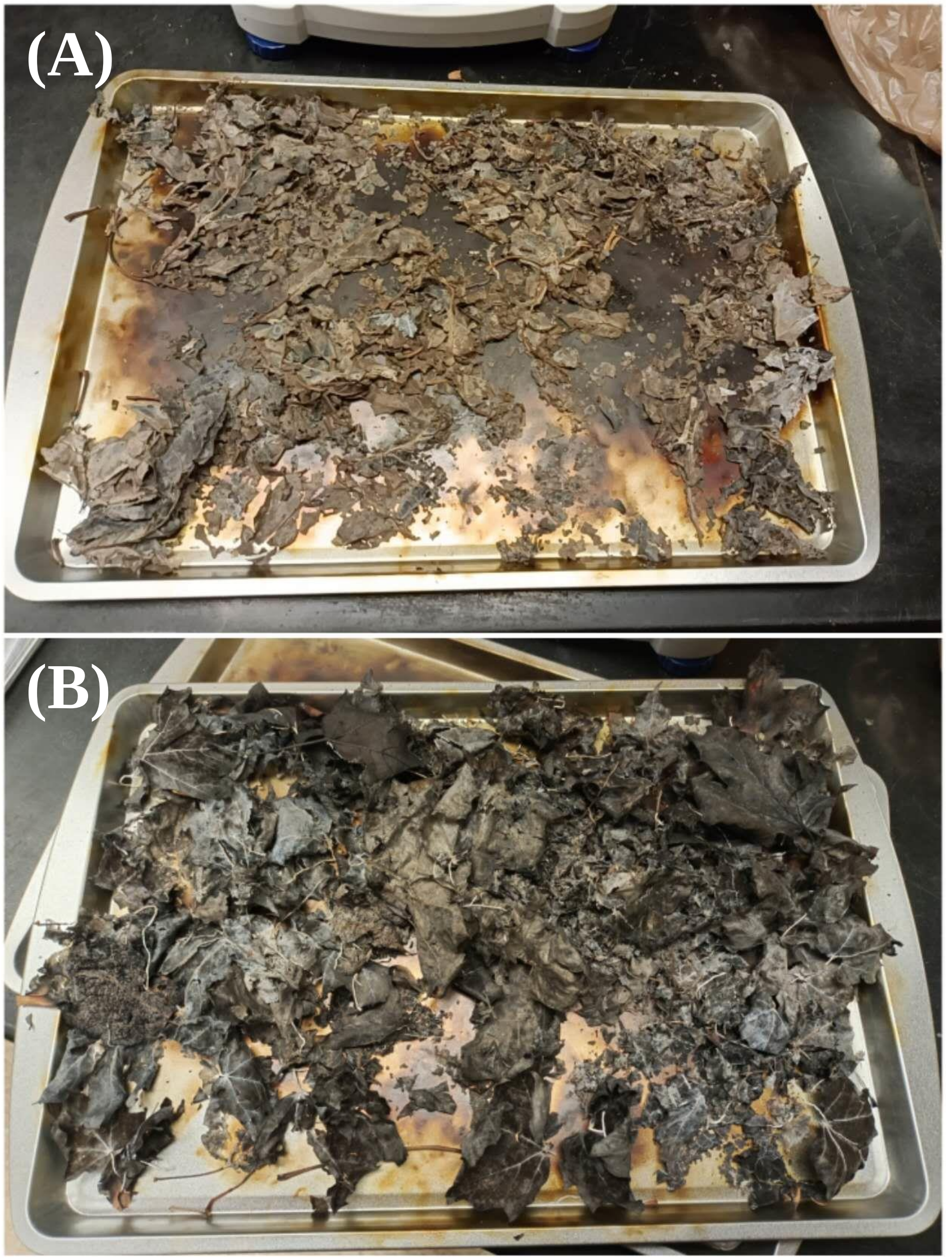

Figure 3.3 The differences in oak residual ash (A) and maple residual ash (B) showed that oak had a higher fuel consumption compared to maple.

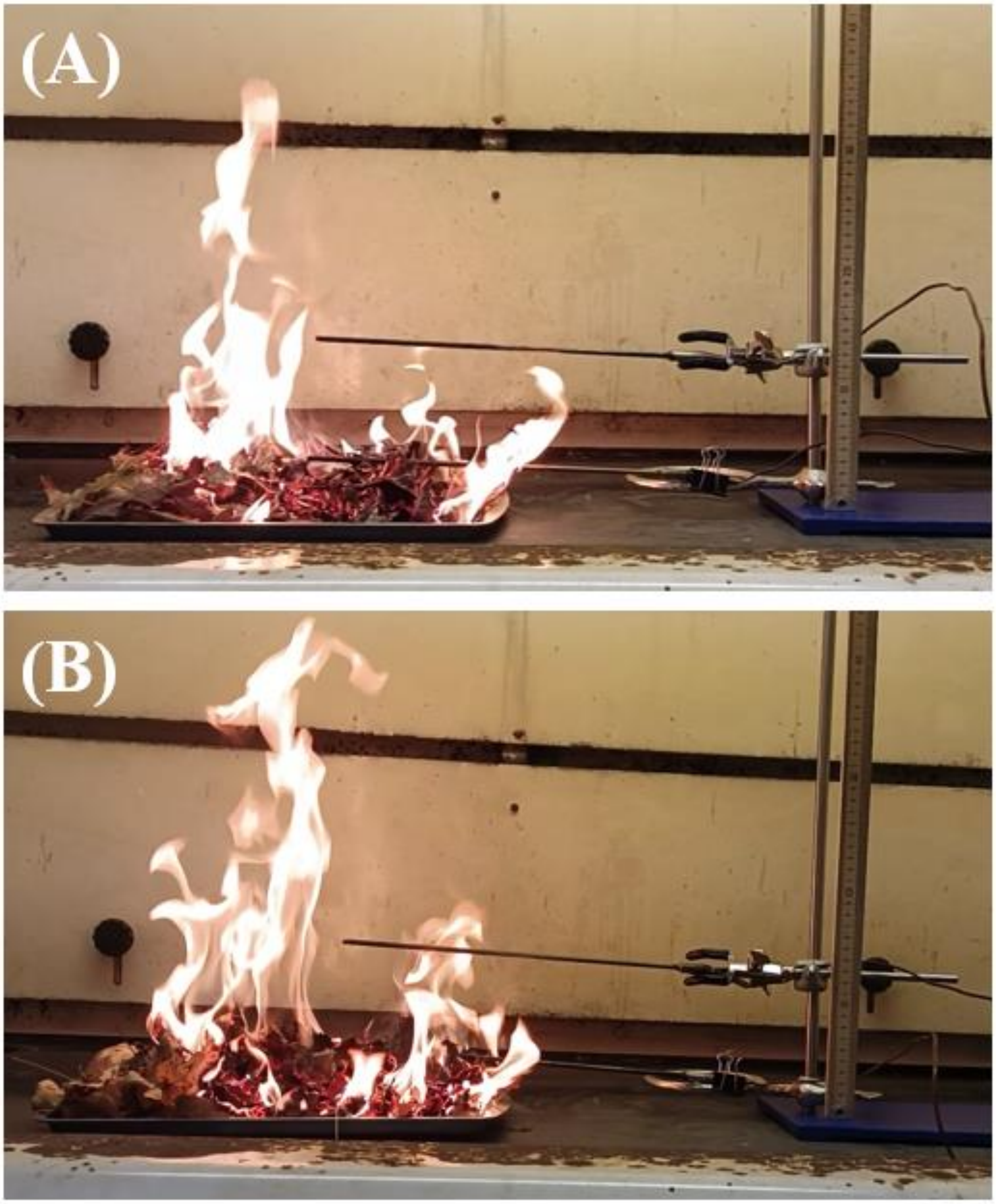

Figure 3.4 (A) oak maximum flame height, (B) maple maximum flame height from selected samples during the ignition experiment. Maple fuel showed a slightly higher flame height than oak fuel.

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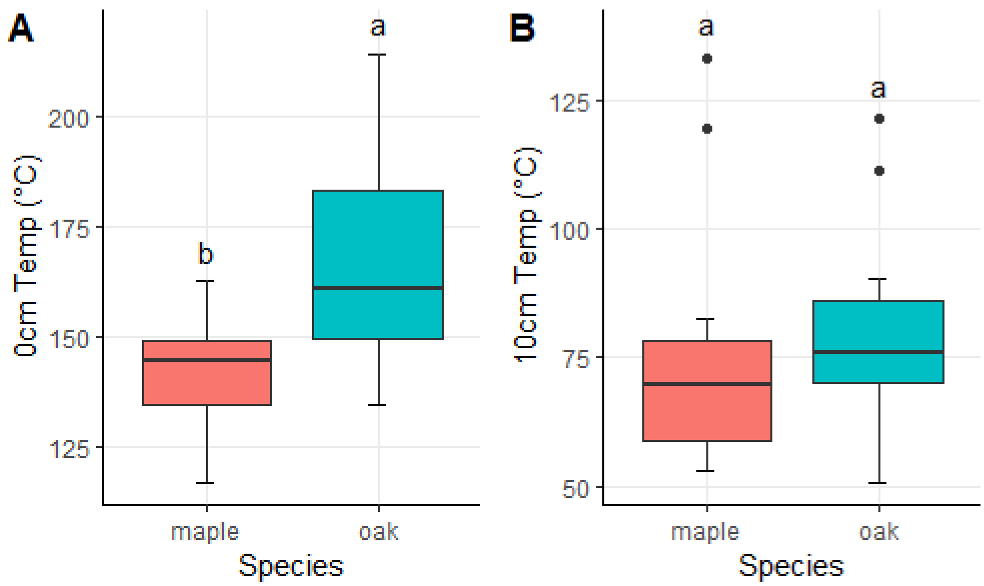

Figure 3.5 The maximum temperature at the fuel surface (0cm, chart A) and at 10 cm above the fuel surface (chart B) for maple and oak.

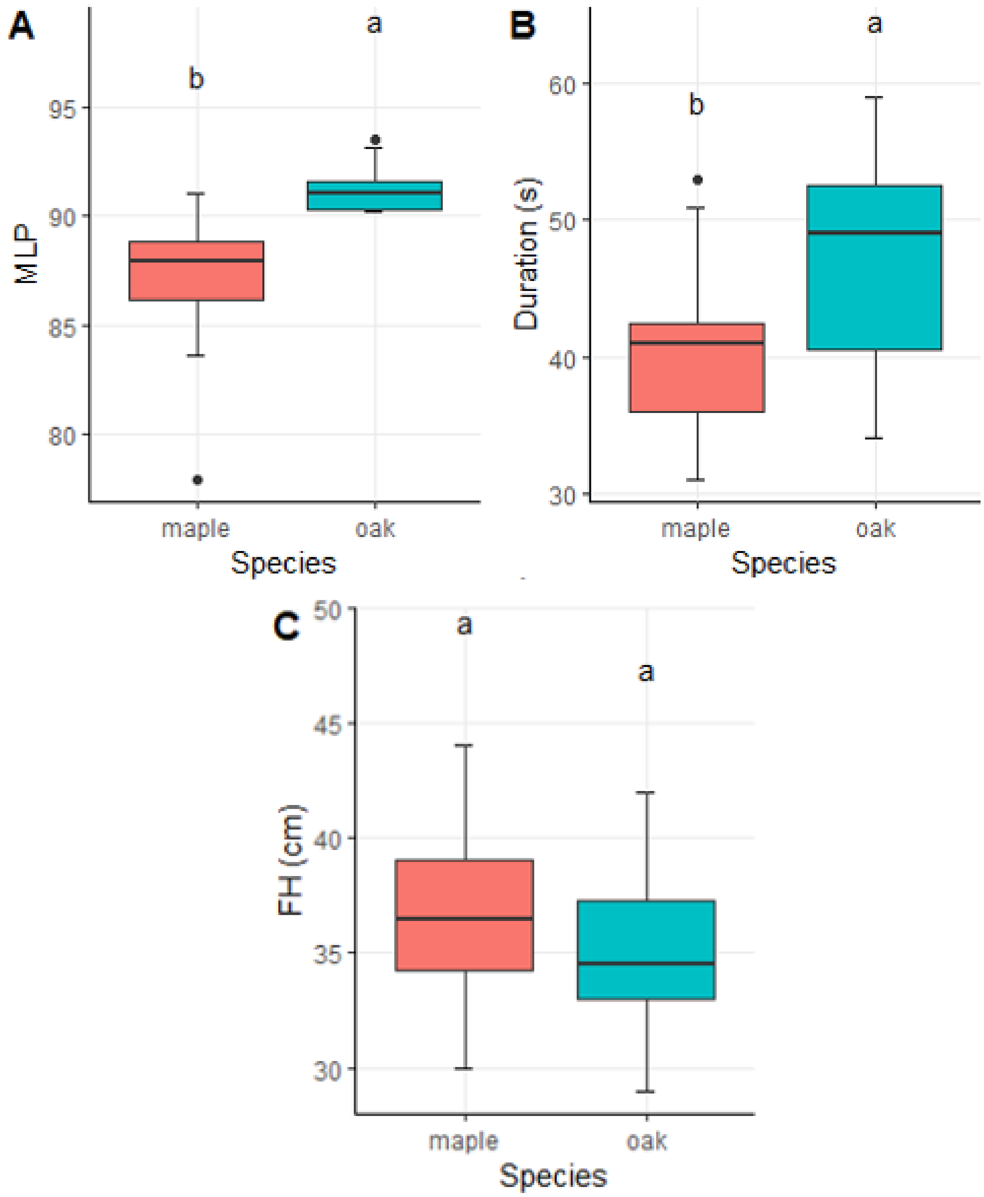

Figure 3.6 Oak and maple fuel mass loss percentage (Chart A), the duration time of combustion (Chart B), and the maximum flame height during combustion for oak and maple (Chart C).

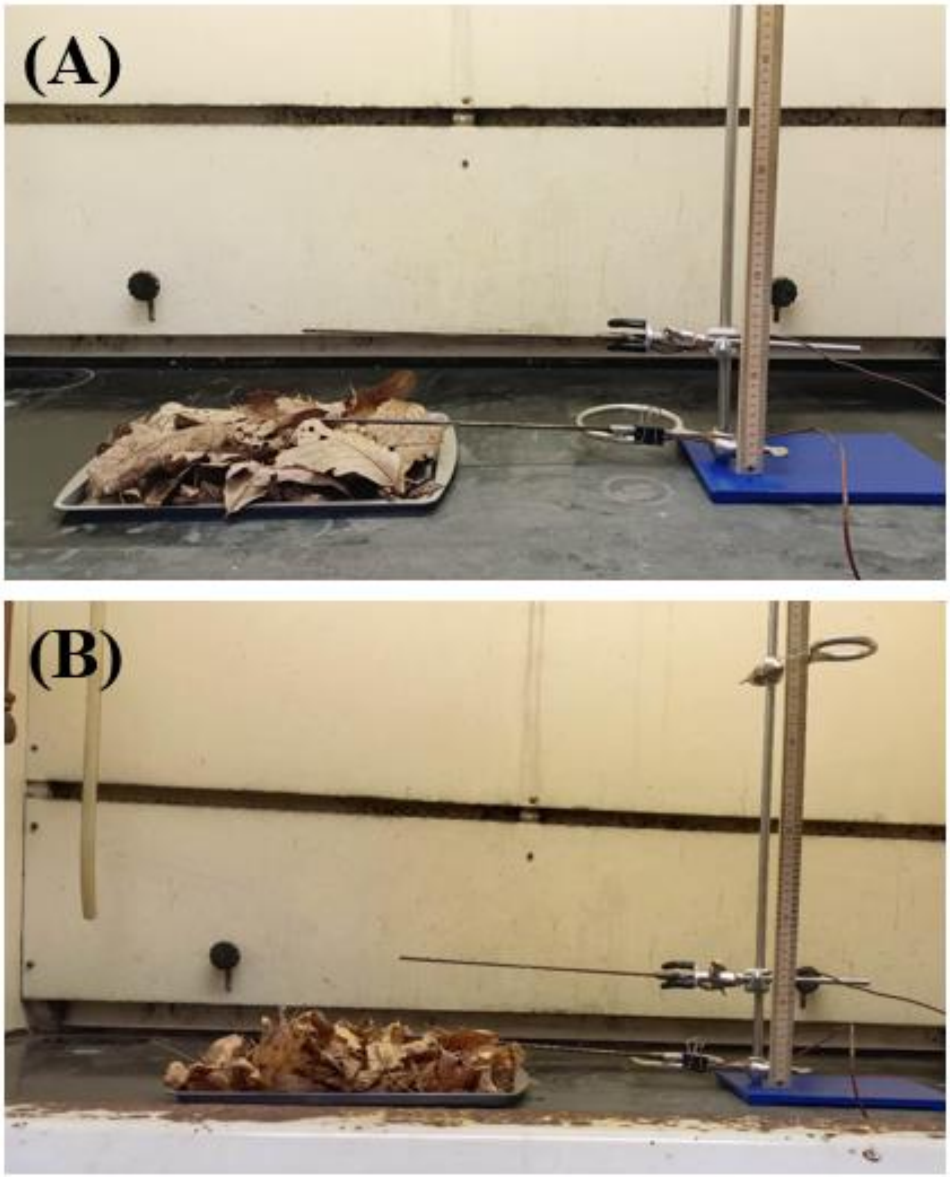

Figure 3.7 The differences in leaf curling for oak (A) and maple (B) in our experiments, where oak lays flatter as compared to maple. This condition was inconsistent with field, where maple tends to be flatter than oak.

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