fire

Article

Characterization of Wildland Fuels Based on Topography and Forest Attributes in North-Central Appalachia

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Abstract: Forest ecosystem attributes and their spatial variation across the landscape have the potential to subsequently influence variations in fire behavior. Understanding this variation is critical to fire managers in their ability to predict fire behavior and rate of spread. However, a fine-scale description of fuel patterns and their relationship with overstory and understory attributes for north-central Appalachia is lacking due to the complicated quantification of variations in topography, forest attributes, and their interactions. To better understand the fire environment in north-central Appalachia and provide a comprehensive evaluation based on fine-scale topography, ninety-four plots were established across different aspects and slope positions within an oak–hickory forest located in southeast Ohio, USA, which historically fell within fire regime group I with a fire return interval ranging from 7 to 26 years. The data collected from these plots were analyzed by four components of the fire environment, which include the overstory, understory, shrub and herbaceous layers, surface fuels, and fuel conditions. The results reveal that fuel bed composition changed across aspects and slope position, and it is a primary factor that influences the environment where fire occurs. Specifically, the oak fuel load was highest on south-facing slopes and in upper slope positions, while maple fuel loads were similar across all aspects and slope positions. Oak and maple basal areas were the most significant factors in predicting the oak and maple fuel load, respectively. In the shrub and undergrowth layers, woody plant coverage was higher in upper slope positions compared to lower slope positions. Overstory canopy closure displayed a significant negative correlation with understory trees/ha and woody plant variables. The findings in this study can provide a better understanding of fine-scale fuel bed and vegetation characteristics, which can subsequently feed into fire behavior modeling research in north-central Appalachia based on the different characterizations of the fire environment by landscape position.

Keywords: fire environment; fuel composition; vegetation composition; topography

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1. Introduction

The dynamic and complex characteristics of wildland fire make it challenging to predict and model its behavior, as fire can be influenced by factors such as topography, weather, and fuel conditions [1,2]. All these factors and surroundings that can drive or change the ignition, behavior, and extent of fires are recognized as fire environments [3]. On the local and landscape scales, forest attributes are major factors that alter fire environments and related biophysical settings. Specifically, forest structure and composition are direct contributors that affect litter production [4], and subsequently affect fuel bed composition and biomass [5]. Different forest types such as shrublands or more open sites can create a more combustible fire environment with higher air temperatures and lower fuel moisture compared to dense and closed forests [6]. Forests with a lower density after midstory or understory thinning tend to have a greater fire rate of spread due to the high wind speed and turbulence levels that are created by the more open conditions [7,8].

Most studies regarding forest attributes (e.g., stand density, basal area, canopy closure) have focused on examining the specific relationship between forest parameters and fire environments [4,9,10]. For example, Lydersen et al. [11] assessed the specific relationship between overstory structure and fuel loads and built predictive mathematical models. Bahru and Ding [12] investigated the effects of forest attributes including stand density, canopy leaf area, and DBH on species litter production. Some studies used remote sensing or LiDAR-based data to quantify forest attributes, monitor forest inventory, and subsequently simulate fire environment and fire risk based on forest attributes and forest fuel [13,14]. However, less attention has been paid to modeling and linking forest attributes with comprehensive fire environments based on fine-scale field data and explaining forest attributes from a fire environment perspective.

In addition to forest attributes, topography can also modify fire environments and subsequent fire behavior directly or indirectly [15]. Topographic features (aspects, slope percentage, slope position, and elevation) have been identified as the most static environmental drivers of fire, and they can directly change fire environments by altering solar radiation [16]. For example, southern aspects often receive greater solar radiation compared to other aspects in the Northern Hemisphere, resulting in drier conditions and lower fuel moisture [15]. The drier and hotter conditions make south-facing aspects become more combustible compared to other aspects [17]. The indirect influence of topography on fire environments is displayed through the different topographic positions that subsequently support different stand structures, vegetation compositions, and tree densities [18]. For example, two adjacent areas with similar elevation ranges can have different forest types owing to the differing slope and aspects, with shallow south-facing and steep north-facing aspects supporting ponderosa pine forests and mixed-conifer forests, respectively [16]. In southern Ohio, mesophytic species mainly occur on northeastern aspects, and xerophytic species mainly occur on drier and more exposed positions such as south-facing aspects [19]. These different forest compositions create different fuel compositions, and therefore different fire behavior [20]. A better fine-scale understanding of the role of forest attributes, topography, and their interactions with the fire environment is critical for fire behavior estimation, especially in areas that comprise steep slopes.

Oak forests are an important ecosystem in the eastern U.S. due to their economic and habitat values. They are fire-dependent ecosystems that require frequent fire to maintain their presence in the landscape [21]. Due to decades of fire exclusion, however, the fire-dependent ecosystems in the Eastern US have shifted in structure and species composition from more open-canopied upland oak forests to closed-canopy forests occupied by more shade-tolerant or other opportunistic species [22]. 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 is poised to replace oak [23,24]. These non-oak species can lead to a more shady and moist and less flammable fire environment [25–27], and fire may not be able to reach its historical fire intensity [28]. Updated fire environment data with a comprehensive description of fire environments are needed to better understand and predict future fire behavior in an eastern oak forest.

In this study, we comprehensively evaluated a fire environment based on fine-scale topography and forest attribute data. The objective of this study was to (1) determine how forest attribute variables varied across different aspects (N, E, S, W) and slope positions (upper, middle, lower); (2) assess the relationship between forest attributes, including forest overstory (canopy closure, average DBH, forest density, basal area), understory (average DBH, tree density, basal area), undergrowth layer (herb coverage, woody plant coverage, and maximum shrub height), and fuel conditions (fuel load, fuel composition); and (3) determine how topographic factors affect the fuel composition at the single-species level (oak and maple).

2. Materials and Methods

2.1. Field Sampling and Measurement

The study area is located in Zaleski State Forest (82°25′ W, 39°18′ N), in Vinton County, Ohio (Figure 1). This area lies on the unglaciated Appalachian Plateau, which consists of steep hills and valleys and is the most rugged area in the state. An area of 58 hectares located within an oak–hickory forest, referred to as Morgan Hollow, was selected for this study as this forest type dominates this region and accounts for nearly half of the forest cover in the Eastern United States. 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 m 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 forest attributes and fuel characteristics (Figures 1 and 2A–C). The GPS coordinates, aspects (N = 315°–45°, E = 45°–135°, S= 135°–225°, W = 225°–315°), and slope steepness (degrees) were measured and recorded at each plot center (Figure 2A–C). The slope position was recorded by visually dividing the slope into thirds as upper, middle, and lower positions.

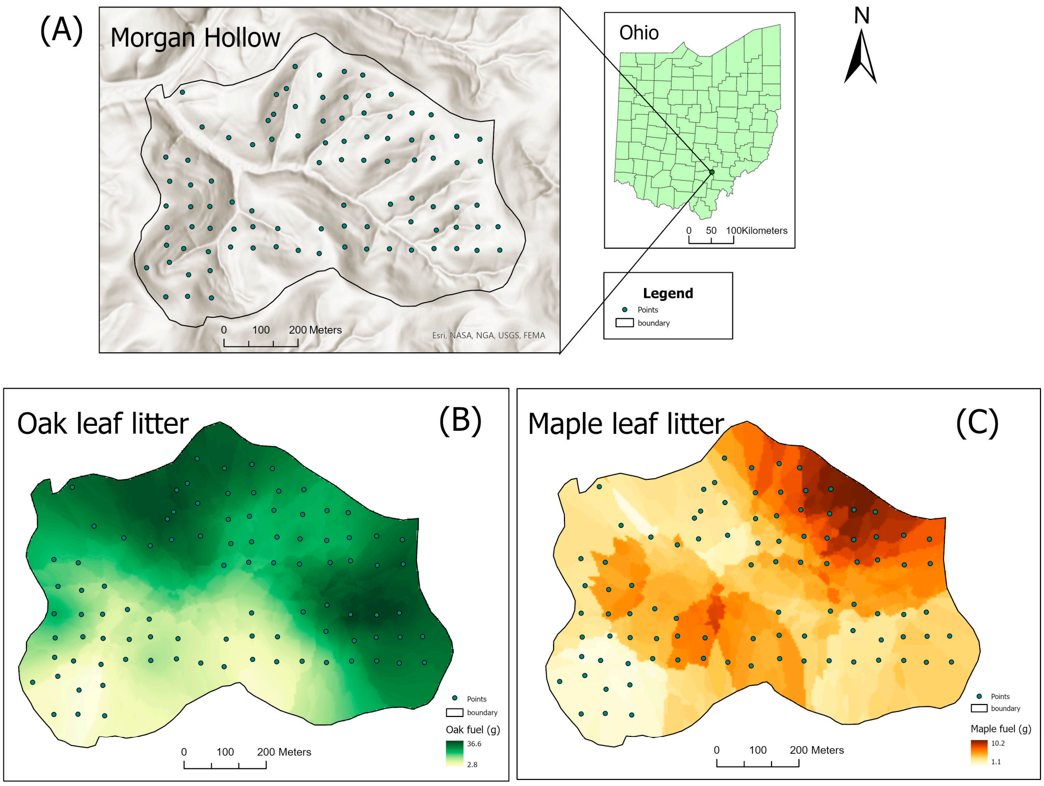

Figure 1. (**A**) Study area (Morgan Hollow) located in Zaleski State Forest, southern Ohio. The black dots indicate the location of 94 sample plots, approximately 60 m apart from each other and distributed evenly in a gridwork across the study site to capture the differences in forest attributes and fuel characteristics; (**B**) oak leaf litter distribution; (**C**) maple leaf litter fuel distribution. Missing points appeared on the northwest and middle south areas of the gridwork due to inaccessible dense vegetation.

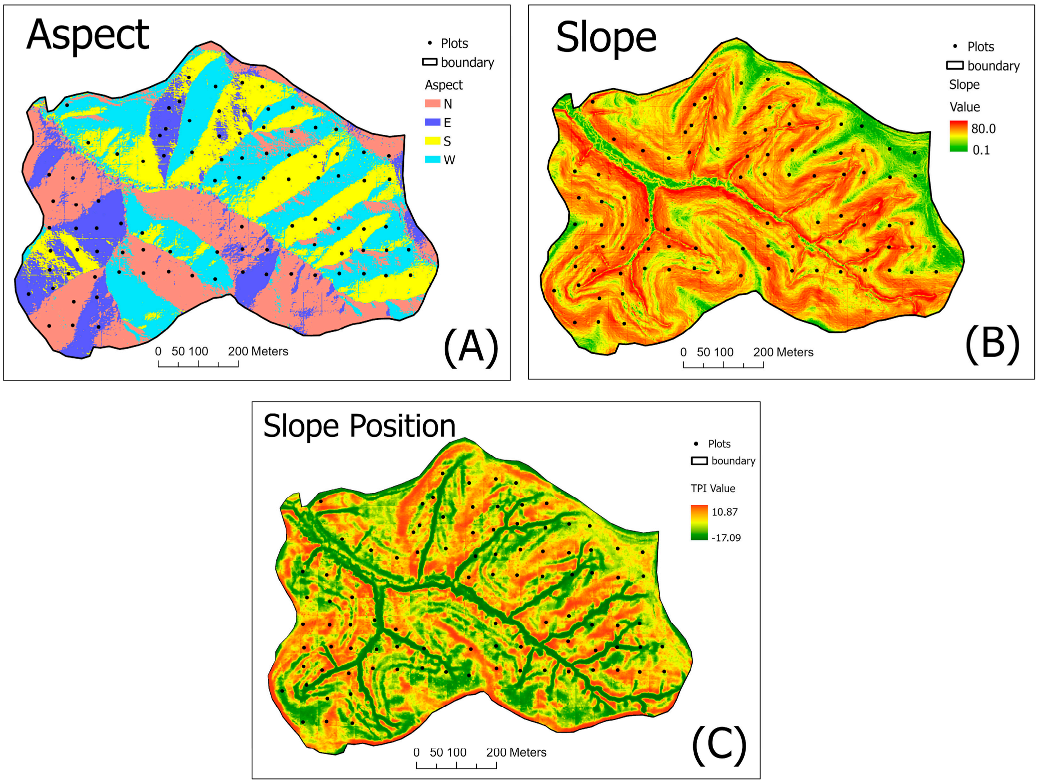

Figure 2. (**A**) Aspects, (**B**) slope degrees, and (**C**) slope position (Topographic Position Index, TPI) of the study site, Morgan Hollow. Total plots, n = 94. Division by aspects, N = 22, E = 22, S = 24, W = 26. Division by slope position, upper = 37, middle = 36, lower = 21.

Forest attribute data from these 94 plots were collected by four components of the fire environment, including (1) overstory (canopy closure, number of trees, DBH, and basal area), (2) understory (tree density, DBH, and basal area), (3) shrub and undergrowth layers (herb coverage, woody plant coverage, and maximum height of shrub), and (4) fuel conditions (1 h and 10 h fuel loads, bulk density, 100 h fuel volume, 1000 h fuel volume).

Within each circular 0.04 ha plot, trees greater than 10 cm DBH were considered a part of the overstory, the DBH of each tree was measured, the numbers of trees and trees species were recorded, and the basal area was calculated. The forest canopy closure (%) was measured with a GRS Densitometer.

A smaller circular, 0.01 ha plot that was circumscribed at the same plot center to measure the understory, recorded trees >1.4 m in height and <10 cm in DBH. The DBH, species, basal area, and number of trees were collected and calculated in each 0.01 ha sample plot. The percentage of herb and woody plant coverage was visually estimated and recorded, and the height of the tallest shrub was measured.

The volume of 100 h and 1000 h fuels was determined using a modified method used by Tao and Williams [29]. Two transects of 30 m in length each were established through the plot center at 90 degrees to each other, in a north–south, east–west direction. For each log that intersected the transect, the diameter of each log that fell within the 100 h (2.5–7.6 cm diameter) and 1000 h (7.7–20.3 cm diameter) time lag fuel size class [30] was measured with calipers at the midpoint of the log and recorded. The volume of logs recorded in each time lag fuel class was determined by the following:

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

where d1, d2, and dn are the mid-diameters (cm) of each of the n pieces intersecting the transect, and L is the total length of both transects (total 60 m).

Litter samples, which include 1 h (0–0.6 cm diameter) and 10 h (0.6–2.5 cm diameter) fuels [30], were collected after leaf fall from 30 October to 5 November 2022, and during the period of the opening of the prescribed burn window. One 30 cm × 30 cm subplot was randomly established at 0.5 m from each plot center. The depth of forest litter in the mineral soil was measured within this plot to calculate fuel bulk density, and all forest litter contained within this subplot was collected down to the mineral soil, including all forest fuel classified in the 1 h and 10 h fuel class, consisting of leaf litter, grasses, twigs, dead wood debris, bark debris, and single stems. Fuel samples were bagged and labeled for further analysis in the laboratory.

2.2. Laboratory Method

Litter fuel samples were stored in paper bags and oven-dried at 70 °C for 48 h until they maintained a constant weight. Oven-dried samples were weighed to the nearest 0.1 g to determine the combined 1 h and 10 h fuel load. The fuel bulk density of each plot was calculated by dividing the total fuel load of 1 h and 10 h fuel by the volume the litter fuel occupied (litter depth multiplied by plot area 30 cm × 30 cm) [27]. The litter fuel samples were subsequently separated into species groupings of oak (*Quercus* spp.), maple (*Acer* spp.), and other species and weighed to determine the proportional biomass by species composition. Oak and maple species groups were chosen as oak, a fire-dependent species, is the dominant forest species and the species of regeneration focus, and maple is the main competitor to oak.

2.3. Statistical Analysis

All statistical analyses were performed in R, version 4.2.2 (R Core Team, 2022). Forest attribute variables were compared among aspects (N, E, S, W) and slope positions (upper, middle, lower) using two-way ANOVA followed by a standard Bonferroni correction and a post hoc Tukey–Kramer test (significance level $\propto = 0.05$). Principal component analysis (PCA) was performed to reduce the dimensionality of the data set, clustering oak and maple forest attributes. Correlation analysis and a standard Bonferroni correction were conducted to determine the relationship between forest attribute variables. The data set was log-transformed to reduce the effect of outliers in the data when performing correction analyses. Simple linear regression analyses were performed to determine the relationship between fuel load and basal area of oak and maple species.

3. Results

Fire environment and forest attribute data were analyzed by different strata including overstory, understory, shrub and undergrowth layers, and fuel conditions. For all strata, forest attributes varied between plots, especially in the understory and undergrowth layers. The greatest variability was observed in the number of trees and basal area per hectare of the understory with Coefficients of Variation (CVs%) of 91.74% and 92.99%, respectively (Table 1).

Table 1. Summary statistics for observed 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

Table 1. *Cont.*

Forest Variable	Min	Max	Average	SD	CV%
Shrub and undergrowth					
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
Fuel					
100 h fuel m^3/ha	0.31	11.14	4.85	2.37	48.85
1000 h fuel m^3/ha	0.00	48.34	15.96	10.80	67.70
Bulk density (kg/m^3)	1.88	19.36	7.30	2.82	38.61
1 and 10 h Fuel (kg/ha)	379.72	2683.67	821.39	358.49	43.64

Dividing the forest attributes into oak and maple species, our results 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 (Table 2). The contribution of maple to the total number of trees was 17.3%, and that 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 that of maple fuel was 6.2%.

Table 2. Summary statistics for oak and maple attributes at the Morgan Hollow study site (n = 94).

Forest Variable	Min	Max	Average	SD	CV%
Total					
Trees/ha	6.00	68.00	25.13	13.07	52.03
Basal area (m^2/ha)	0.07	2.44	1.19	0.45	37.95
Fuel load (kg/ha)	379.72	2683.67	821.39	358.49	43.64
Oak					
Trees/ha	0.00	25.00	7.89	6.45	81.75
Tree % in total	0.00	93.75	34.31	26.14	76.17
Basal area (m^2/ha)	0.00	2.43	0.69	0.52	75.69
Basal area % in total	0.00	99.38	53.97	32.94	61.03
Fuel load (kg/ha)	0.00	618.53	225.31	163.35	72.50
Fuel load % in total	0.00	83.59	27.60	18.24	66.09
Maple					
Trees/ha	0.00	18.00	4.15	4.10	98.84
Tree % in total	0.00	78.26	17.31	16.03	92.60
Basal area (m^2/ha)	0.00	0.47	0.10	0.10	99.22
Basal area % in total	0.00	55.65	8.77	9.20	104.85
Fuel load (kg/ha)	0.00	282.81	48.31	57.23	118.46
Fuel load % in total	0.00	40.98	6.21	7.27	116.94

3.1. Fuel and Regrowth Layer

Surface fuels were analyzed by aspect as they are the fuels that directly carry fires in the Eastern U.S. The 1 h and 10 h fuel load (kg/ha), bulk density (kg/m^3), and 100 h fuel volume (m^3/ha) did not show differences across aspects (p = 0.448, 0.463, 0.685, respectively; Figure 3A–C), but the 1000 h fuel volume (m^3/ha) displayed a higher value on the west-facing aspect compared to south-facing aspects (p = 0.03, Figure 3D).

The slope position was divided into three categories of upper, middle, and lower slope position. Surface fuels were analyzed by slope positions with all aspects grouped. The surface fuels did not have differences across different slope positions, with each slope position exhibiting similar surface fuel conditions (1 h and 10 h fuel load, p = 0.716; 100 h fuel volume, p = 0.312; 1000 h fuel volume, p = 0.774; and bulk density, p = 0.884; Figure 3). The surface fuel variables did not show differences between slope positions by aspect ($p > 0.05$).

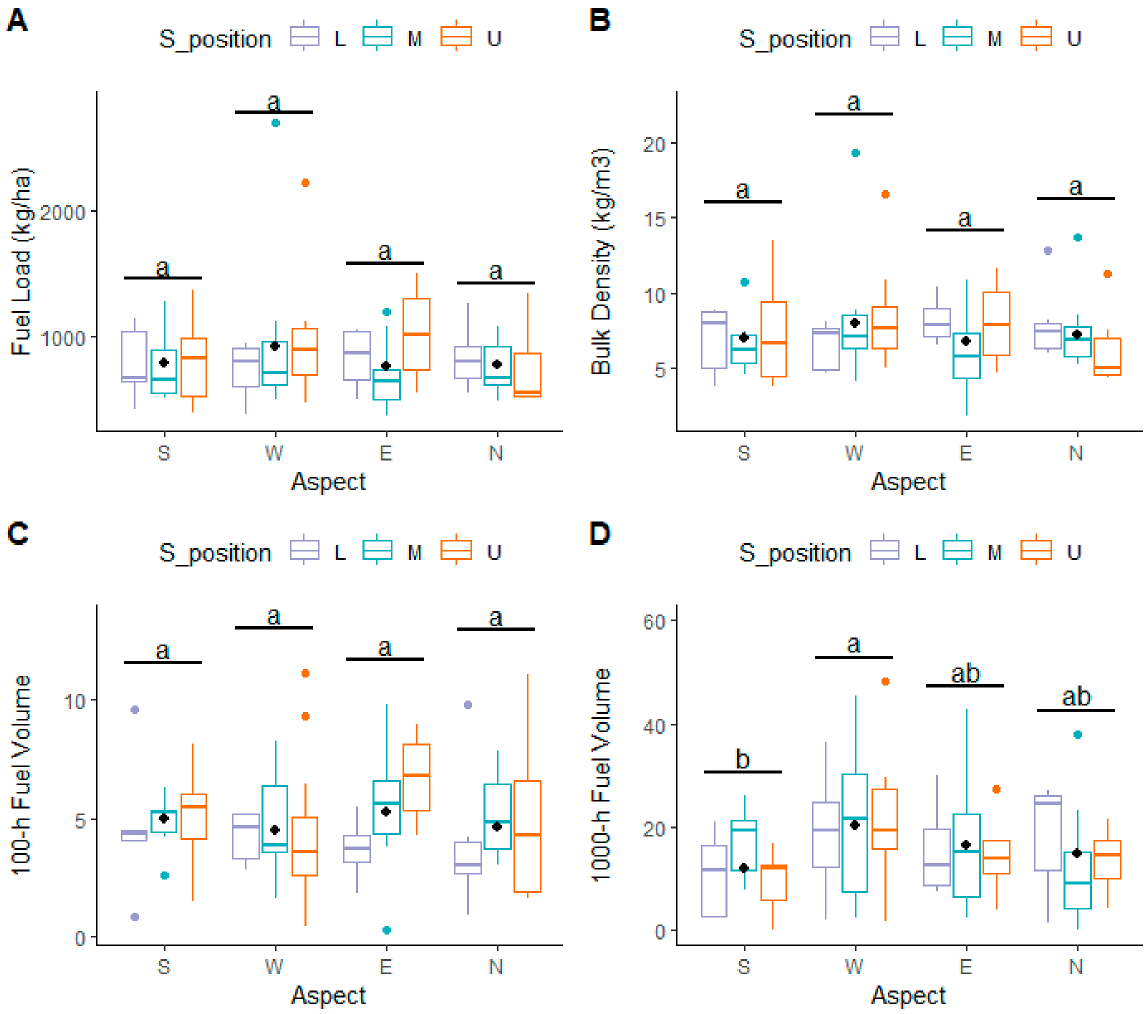

Figure 3. Surface fuel conditions at different aspects in three slope positions (L—lower, M—middle, U—upper). Specifically, (**A**) 1 h and 10 h fuel load (kg/ha), (**B**) 1 h and 10 h fuel bulk density (kg/m^3), (**C**) 100 h fuel volume (m^3/ha), and (**D**) 1000 h fuel volume (m^3/ha) over aspects in three slope positions. Figures with the same lower-case letters are not different between aspects within each graph (post hoc Tukey–Kramer test, $p = 0.05$). Black diamonds represent group means for each aspect. S_position means slope positions.

When separating 1 h and 10 h fuels by the oak and maple genus (*Quercus* spp. and *Acer* spp.), hereafter referred to as oak and maple litter fuels, the oak litter fuel load (kg/ha) and oak litter fuel as a percentage of total 1 h and 10 h fuel load were higher on south-facing aspects compared to east-facing aspects ($p = 0.03$), and those on west-facing aspects were higher than those on east- and north-facing aspects ($p = 0.0075$, 0.041; Figure 4A). The oak litter fuel percentage on south- and west-facing aspects is higher than those on east-facing ($p < 0.001$, $p = 0.002$) and north-facing aspects ($p = 0.016$, 0.038; Figure 4B). The maple litter fuel load and maple litter fuel percentage did not show differences among all aspects ($p = 0.083$, 0.054; Figure 4C,D).

Oak litter fuel load (kg/ha) and oak litter fuel as a percentage of total 1 h and 10 h fuel load were higher in the upper slope position compared to the lower ($p = 0.001$, 0.002) and middle slope positions ($p = 0.005$, 0.008; Figure 4A,B). The maple litter fuel load and maple litter fuel as a percentage of total 1 h and 10 h fuel load did not show differences among slope positions ($p = 0.055$, 0.174; Figure 4C,D). Both oak and maple litter fuel load and litter fuel as a percentage of total 1 h and 10 h fuel load did not show differences between slope positions by aspect.

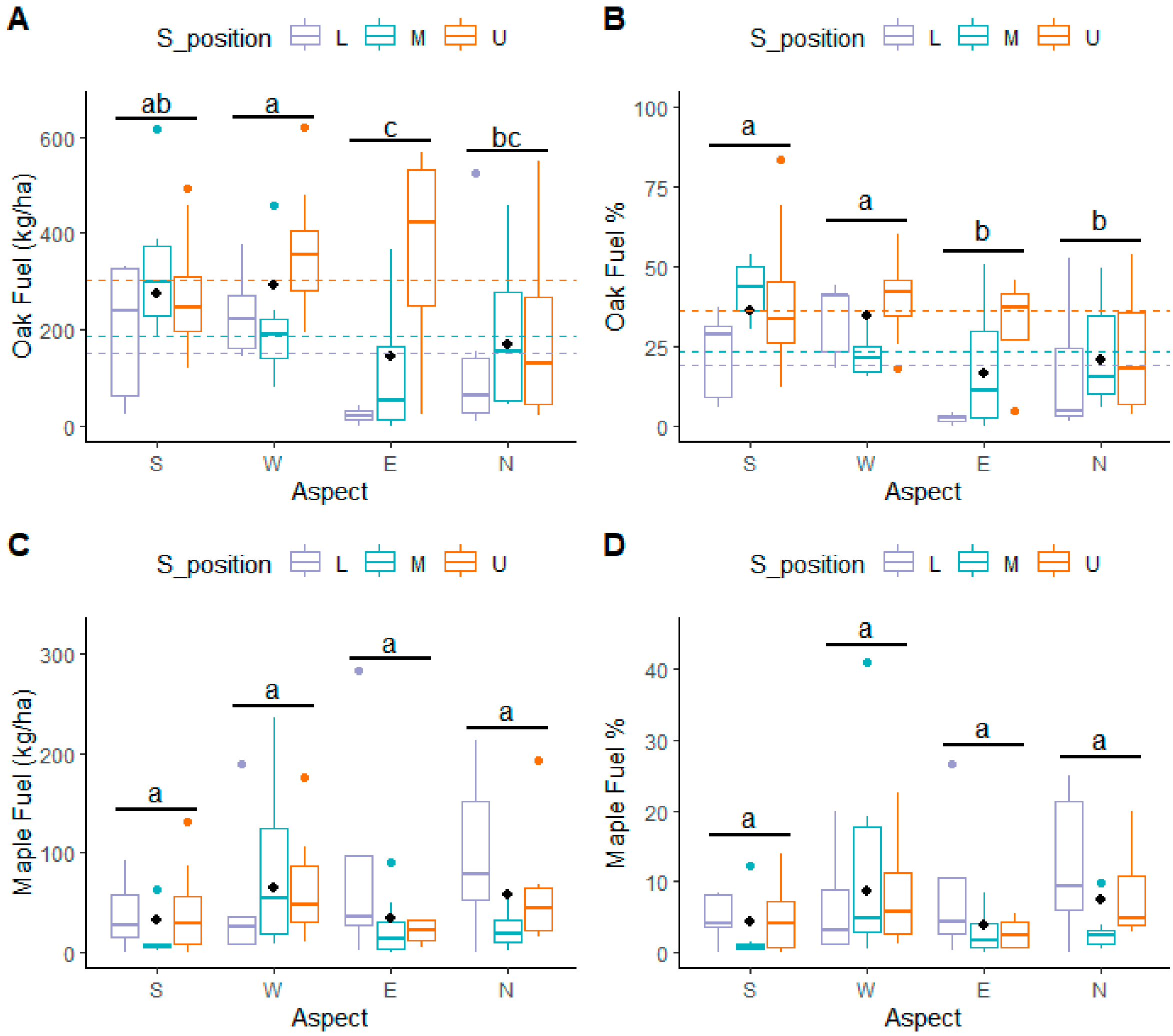

Figure 4. Oak and maple fuel at different aspects in three slope positions (L—lower, M—middle, U—upper). Specifically, (**A**) oak fuel load (kg/ha), (**B**) oak litter fuel as a percentage of total 1 h and 10 h fuel load (%), (**C**) maple fuel load (kg/ha), and (**D**) maple litter fuel as a percentage of total 1 h and 10 h fuel load (%) over aspects in three slope positions. Figures with the same lower-case letters are not different between aspects within each graph (post hoc Tukey–Kramer test, $p = 0.05$). Black diamonds represent group means for each aspect. Dashed lines represent group means for each slope position. S_position in the legend means slope positions.

When examining the shrub and regrowth layer, which includes herbaceous coverage, woody plant coverage, and maximum shrub height, the maximum shrub height (m) was higher on west-facing aspects compared to north-facing aspects ($p = 0.05$, Figure 5C). The herb coverage and woody plant coverage did not show differences among all aspects ($p = 0.061, 0.051$; Figure 5A,B).

In the shrub and regrowth layer, woody plant coverage was higher in upper slope positions compared to lower slope positions ($p < 0.001$, Figure 5B). The herb coverage and maximum shrub height did not show differences among slope positions ($p = 0.131, 0.092$; Figure 5A,C). The variables did not show differences between slope positions by aspect.

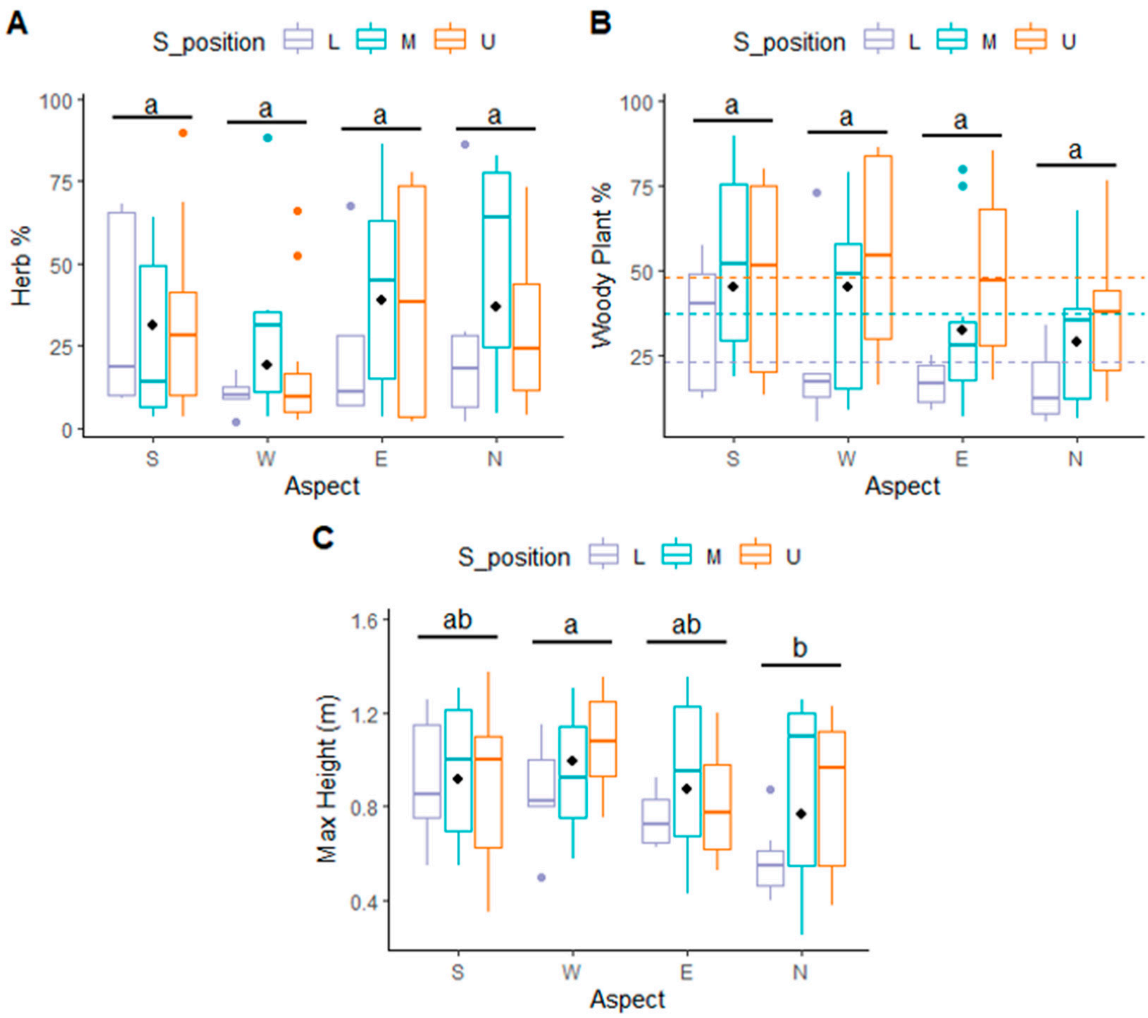

Figure 5. Shrub and regrowth layer attributes at different aspects in three slope positions (L—lower, M—middle, U—upper). Specifically, (**A**) herb coverage (%), (**B**) woody plant coverage (%), and (**C**) maximum shrub height (m) over aspects in three slope positions. Figures with the same lower-case letters are not different between aspects within each graph (post hoc Tukey–Kramer test, $p = 0.05$). Black diamonds represent group means for each aspect. Dashed lines represent group means for each slope position. S_position means slope positions.

3.2. Overstory and Understory Layer

Overstory and understory attributes were analyzed as they can change fire environments by influencing solar radiation, wind speed, and fuel composition. Principal component analysis (PCA) was used as a method to reduce the dimensionality of the overstory and understory attribute data set. The three principal components explained a cumulative variance of 79.95%, with eigenvectors shown in Table 3. No distinction or grouping was observed for the overstory and understory attributes in different aspects (Figure 6) or slope positions (Figure 7), considering the results obtained, which indicates that the overstory and understory forest attributes are similar among aspects and slope positions.

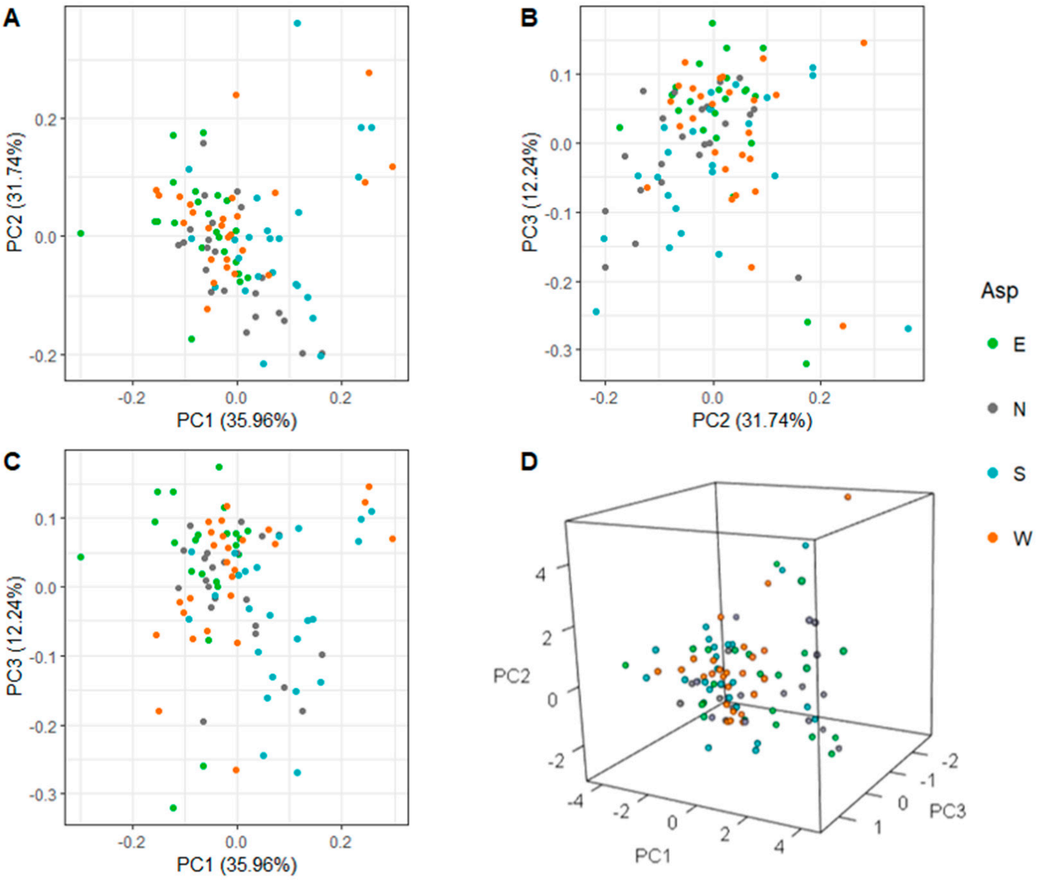

Figure 6. Principal component analysis (PCA) for overstory and understory attributes by aspects. (**A**) PC1 vs. PC2, (**B**) PC2 vs. PC3, (**C**) PC2 vs. PC3; (**D**) three-dimensional layout of the principal components indicate that no distinction or grouping was observed over different aspects.

Table 3. Eigenvectors from principal component analysis (PCA) of overstory and understory forest attributes measured at Morgan Hollow.

Variable	PC1	PC2	PC3
Canopy closure %	−0.18	0.36	−0.78
DBH	0.54	−0.12	−0.22
Trees/ha	−0.19	0.50	0.53
U-DBH [1]	−0.29	0.46	0.002
U-trees/ha [1]	−0.28	−0.52	0.15
Basal area	0.43	0.34	0.15
U-basal area [1]	−0.54	−0.11	−0.10
Proportion of Variance %	35.96	67.70	79.95

[1] U—understory variables.

Performing PCA by genus groups of oak (*Quercus*) and maple (*Acer*) resulted in two principal components. Principal Component 1 and Principal Component 2 of the PCA explained 35.57% and 28.1% of the variation in the data set, respectively (Table 4, Figure 8). PC 1 represents a combination of overstory and understory attributes where positive values of overstory DBH (0.51), trees/ha (0.38), and basal area (0.61) are associated with negative values of understory DBH (−0.31), trees/ha (−0.16), and basal area (−0.33, Table 3). PC 2 represents the combination where both overstory and understory attributes have negative loadings, suggesting a negative relationship between them.

Table 4. Eigenvectors from principal component analysis (PCA) of overstory and understory oak and maple attributes measured at Morgan Hollow.

Variable	PC1	PC2
DBH	0.51	−0.10
Trees/ha	0.38	−0.48
Basal area	0.61	−0.27
U-DBH [1]	−0.31	−0.56
U-trees/ha [1]	−0.16	−0.21
U-basal area [1]	−0.33	−0.58
Proportion of Variance %	35.57	28.10

[1] U—means understory variables.

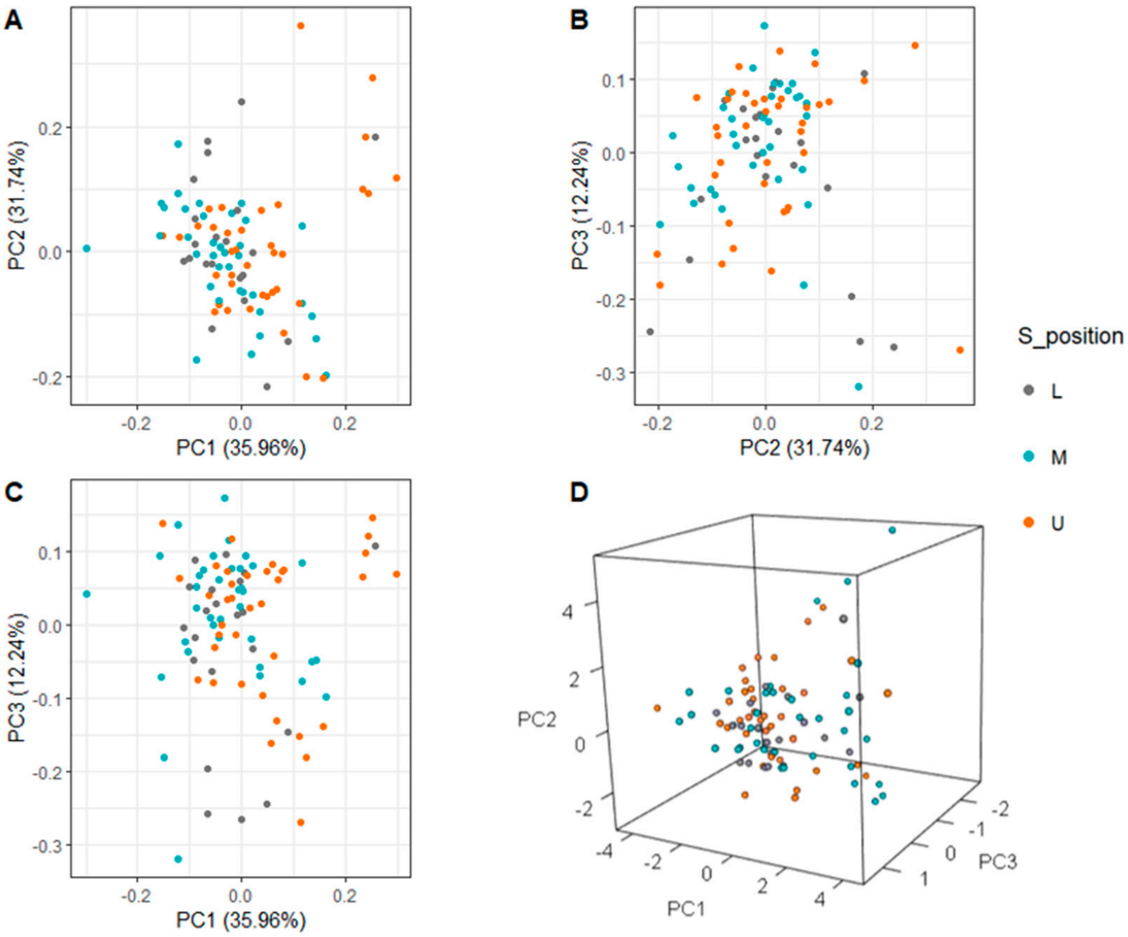

Figure 7. Principal component analysis (PCA) for overstory and understory attributes by slope positions (L—lower, M—middle, U—upper). (**A**) PC1 vs. PC2, (**B**) PC2 vs. PC3, (**C**) PC2 vs. PC3; (**D**) three-dimensional layout of the principal components indicates that no distinction or grouping was observed over three slope positions. S_position means slope positions.

The grouping of oak and maple in Figure 8 indicates that oak species have a higher overstory DBH, number of trees, and basal area compared to maple species, while in the understory layer, maple tends to have a higher understory DBH, number of trees, and basal area compared to oak. In other words, maple species are shorter and occupy more understory with more understory trees, higher understory DBH, and basal area compared to oak; oaks are taller and occupy more overstory with higher overstory trees, overstory basal area, and DBH compared to maple.

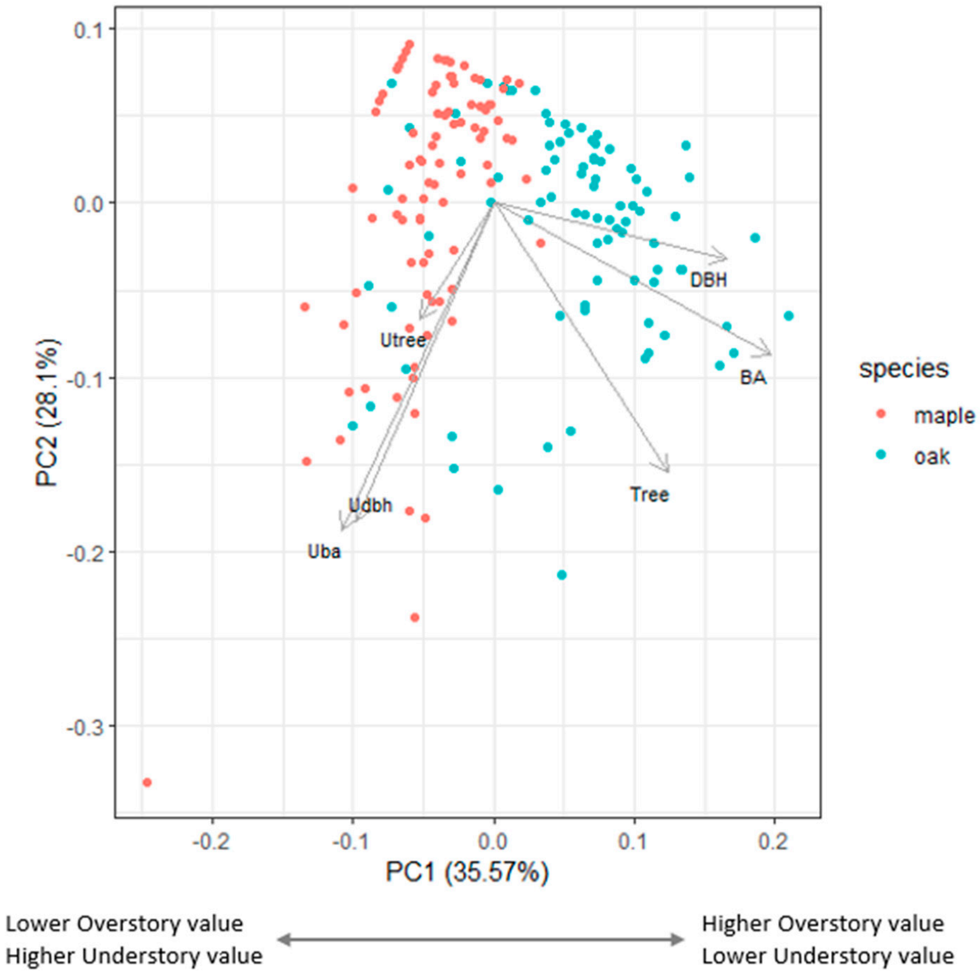

Figure 8. Biplot of principal component analysis (PCA) for overstory and understory oak and maple attributes. U—understory variables. Overstory values include DBH, trees/ha, and basal area. Understory values include U-DBH, U-trees/ha, and U-basal area.

The ANOVA followed by post hoc Tukey–Kramer test indicated that overstory oak tree/ha shows a higher value on south-facing aspects compared to east-facing aspects ($p = 0.035$, Figure 9A). Oak basal area is higher on south- and west-facing aspects than north- ($p = 0.005$, 0.006) and east-facing aspects ($p = 0.012$, 0.016; Figure 9B). When considering slope position, overstory oak tree/ha and basal areas are higher in upper slope positions compared to lower slope positions ($p < 0.001$, Figure 9A,B) and middle slope positions ($p < 0.001$, $p = 0.006$). Overstory maple trees/ha and basal area did not show differences among aspects and slope positions (Figure 9C,D). The variables did not show differences between slope positions by aspect.

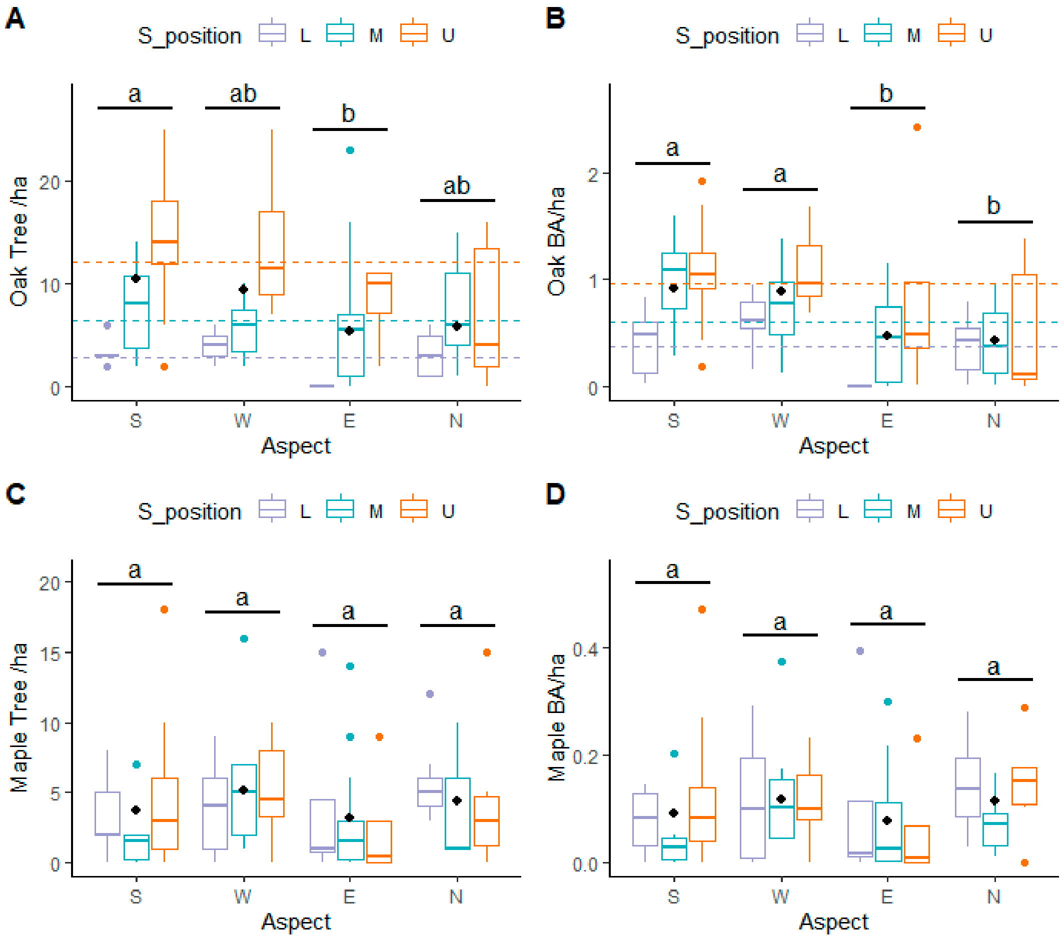

Figure 9. Oak and maple tree numbers per hectare and basal area of overstory at different aspects in three slope positions (L—lower, M—middle, U—upper). Specifically, (**A**) oak tree numbers/ha, (**B**) oak basal area (m^2/ha), (**C**) maple tree numbers/ha, and (**D**) maple basal area over aspects in three slope positions. Figures with the same lower-case letters are not different between aspects within each graph (post hoc Tukey–Kramer test, $p = 0.05$). Black diamonds represent group means for each aspect. Dashed lines represent group means for each slope position. S_position in legend means slope positions.

3.3. Correlation

Pearson's correlation coefficient was calculated between the various parameters of overstory, understory, and regrowth layer attributes (Figure 10).

Pearson's correlation coefficient was found to be significant for most of the variables (significance level is shown in Figure 10). Overstory canopy closure (CC) showed a significant negative correlation with understory trees/ha and the regrowth variables of woody plant coverage and maximum shrub height (correlation coefficient shown in Figure 10). Both overstory and understory DBH showed a significant negative correlation with their trees/ha, indicating that larger-diameter trees are associated with fewer trees, while both overstory and understory basal area showed significant positive correlations with their DBH and trees/ha. Overstory DBH, trees/ha, and basal area showed a significant negative correlation with understory DBH, understory trees/ha, and basal area, respectively. When considering shrub and regrowth layers, woody plant coverage and max height are significantly positively correlated with overstory DBH and negatively correlated with overstory trees/ha. Considering the correlation between shrub layer and understory, the woody plant coverage and max height are negatively correlated with understory DBH and positively correlated with understory trees/ha.

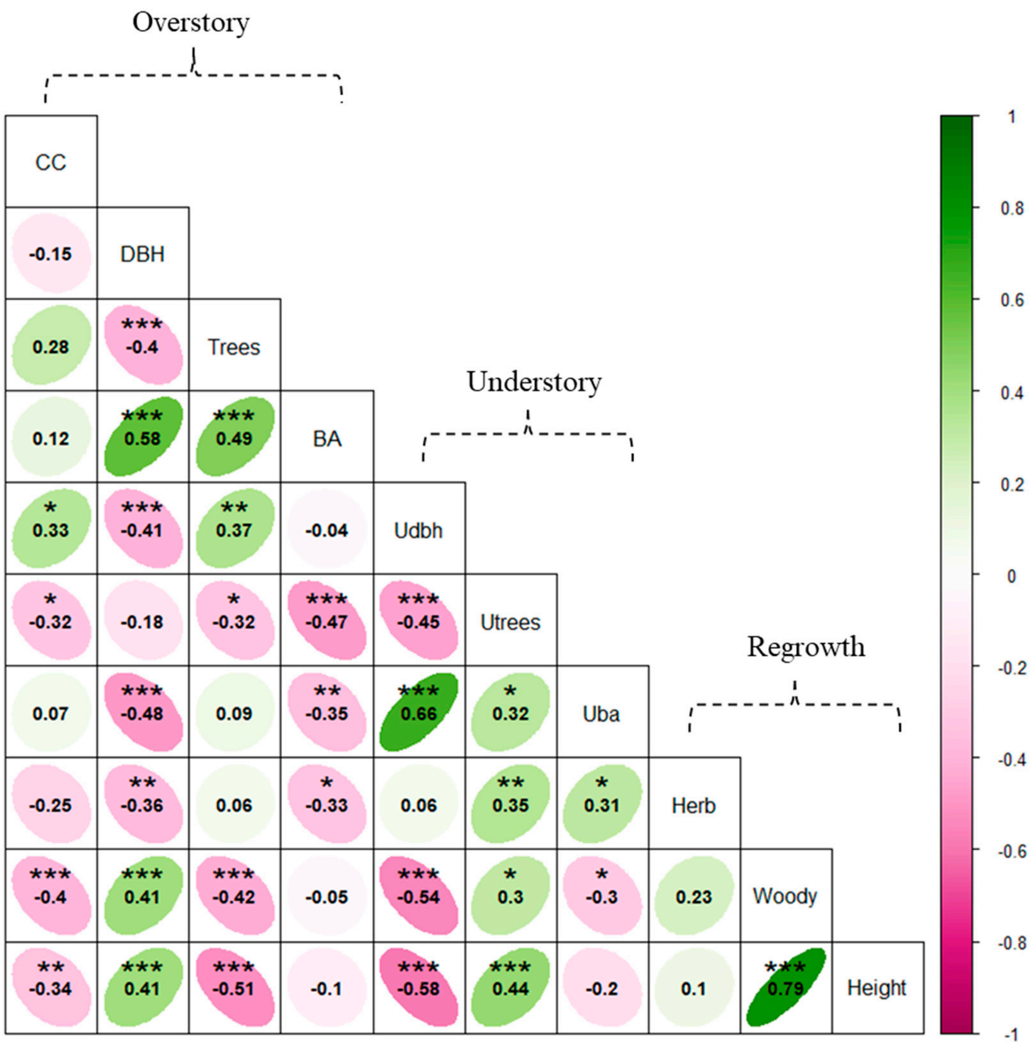

Figure 10. Plots of the relationship between forest attributes pairs. U—understory variables. Overstory variables include DBH, trees/ha, and basal area. Understory variables include U-DBH, U-trees/ha, and U-basal area. Shrub and regrowth layer variables include herb coverage (%), woody plant coverage (%), and maximum shrub height (m). * Significant at the 0.05 level, ** significant at the 0.01 level, *** significant at the 0.001 level.

Dividing the data set into oak and maple genus, all overstory variables (trees/ha, basal area, mean DBH) were strongly correlated with the fuel loading for both oak and maple (Tables 5 and 6). No significant correlations were found between the oak fuel load and percent with the understory variables (Table 5). However, the maple fuel load and the maple fuel percent were significantly correlated with the basal area and mean DBH of the understory (Table 6).

Across all overstory variables for both oak and maple species, basal area was the most significant factor in predicting the fuel load with a correlation coefficient of 0.725 and 0.540, respectively. A simple linear regression between basal area and fuel load was created and produced an R^2 of 0.526 and 0.292 for oak and maple, which means the overstory oak basal area can solely explain 52.6% of the variance in the oak fuel load, and the overstory maple basal area can solely explain 29.2% of the variance in maple fuel load (Figures 11 and 12).

Table 5. Pearson's correlation coefficient between oak litter fuel load (kg/ha), oak litter fuel as a percentage of total 1 h and 10 h fuel load (%), and oak attributes at the Morgan Hollow study site.

r	Overstory Oak			Understory Oak		
	Tree Number/ha	Basal Area (m^2/ha)	DBH (cm)	Tree Number/ha	Basal Area (m^2/ha)	DBH (cm)
Litter 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.

Table 6. Pearson's correlation coefficient between maple litter fuel load (kg/ha), maple litter fuel as a percentage of total 1 h and 10 h fuel load (%), and maple attributes at the Morgan Hollow study site.

R	Overstory Maple			Understory Maple		
	Tree Number/ha	Basal Area (m^2/ha)	DBH (cm)	Tree Number/ha	Basal Area (m^2/ha)	DBH (cm)
Litter 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.

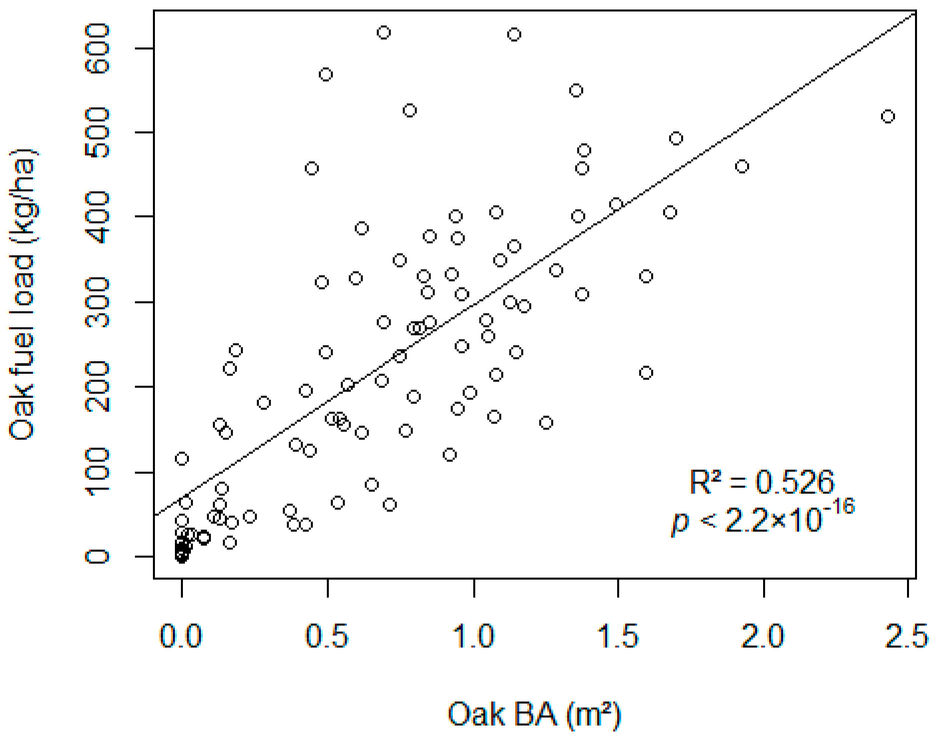

Figure 11. The linear regression between oak basal area (tree > 10 cm DBH) and oak litter fuel load (kg/ha).

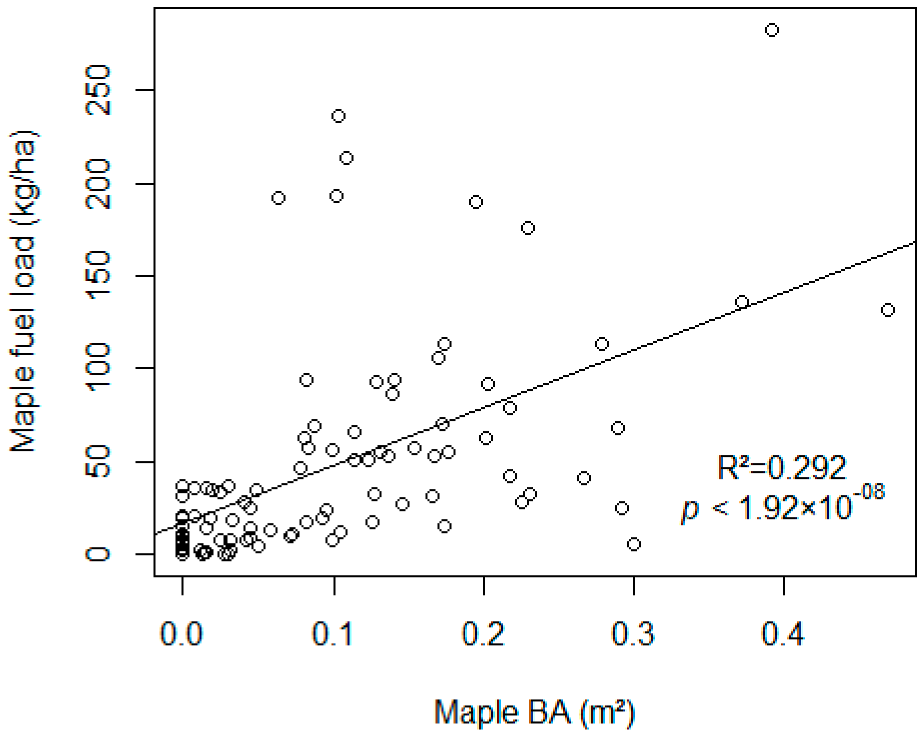

Figure 12. The linear regression between maple basal area (tree > 10 cm DBH) and maple litter fuel load (kg/ha).

4. Discussion

The findings of this study demonstrate that topographic variables exert considerable influences on species distributions and the environment in which litter beds develop and fires occur [31,32]. Iverson et al. [33] 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 in 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 a high distribution variability and tended to be more general in their site selection. Species abundance and composition, in turn, can influence fuel bed composition, causing different fire intensities [34].

Our results reveal that fuel bed composition changed across aspects and slope position, and it is a primary factor that influences the environment where fire occurs [26]. Our analysis shows that there is no distinct difference in overstory and understory attributes among aspects and slope positions; however, the major differences are found in the litter fuel compositions, in which the south-facing and west-facing aspects have a higher oak litter fuel than other aspects. Previous studies have demonstrated that oak tends to burn at higher temperatures than maple fuel and therefore cause higher fire intensities [26,27]. Combined with studies that determined south-facing and west-facing aspects as exhibiting higher fire temperatures than other aspects for both fall and spring burns [17], we can conclude that fuel bed composition and vegetation composition are some of the most significant factors that can change fire environments, creating different fire intensities over topographic positions.

Pearson's correlation coefficient was found to be significant for most of the forest attribute variables. The results showed that overstory, understory, shrub, and surface woody plants are strongly correlated to each other, suggesting that the covariance and interaction between forest attributes need to be taken into consideration when using these variables to create models.

4.1. Aspect

A previous study found that the fine-scale variation in microclimate arising from topographic positions in mountainous landscapes can change the influence of fire interval and subsequent tree establishment [35]. Linking microclimate created by forest structure with fuel bed generated by species composition revealed the potential differences in fire probability among topographic positions, with south-facing aspects containing a greater proportion of oak leaves, thus leading to a higher fire intensity than aspects containing non-oak species [26,27,34]. Schwemlain and Williams [17] found that south- and west-facing slopes produced the hottest fires compared to other aspects, both in spring and fall. All those factors combined displayed the greater potential of fire and a higher level of fire damage on south-facing aspects [15], especially in the upper slope position. Overall, even though there were no differences in the total 1 h and 10 h fuel load among all aspects, southern aspects had the highest oak component in the fuel loading. This suggests that under normal conditions, we should expect the most intense fires on the south-facing slopes. In addition, the south-facing slopes had the lowest volume of 1000 h 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 [36].

Contrasted with south-facing aspects, the north-facing aspect is expected to have the lowest fire risks. The lower proportion of oak fuel can reduce the litter bed flammability by increasing fuel moisture since non-oak fuel exhibits greater moisture gain and a slower drying rate, which can extend its influence into the mixed litter beds [37]. The woody plants and shrubs can serve as ladder fuels during the fire, which increases the probability of crown fire under extreme weather [38], while the low woody plant coverage and shrub height on the northern aspects suggested that there was less chance of producing crown fire on the north-facing aspects.

Eastern and western aspects were considered to have intermediate intensity and risks 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 forest attributes, the percentage of oak fuel is significantly higher on west slopes compared to east slopes, suggesting that west slopes could have a greater potential for higher rates of spread as a result of a higher fire intensity and pre-heating of fuels due to the higher flammability of oak fuel compared to other species [26,37].

4.2. Slope Position

Our results suggest that the upper slope positions have the potential to produce the higher level of fire intensity owing to the high level of oak fuel load and woody plant coverage. This agrees with a study by Schwemlain and Williams [17] which found the hottest fire temperatures in upper slope positions in oak forests, regardless of the time of year. The high coverage of wood vegetation enhances the continuity of fuel and facilitates an increment in the fire spread velocity [39]. In addition, the high percentage of oak fuels made the upper position more flammable than other positions [27]. Contrary to the upper position, the lower positions were considered the lowest level of fire intensity, with less oak fuel proportions and less woody plant coverage. The fire potential in the middle slope position might be more dependent on aspects. Thus, from the perspective of fuel composition, a higher fire intensity should be expected in the upper slope positions among all aspects, especially the south-facing aspects; in contrast, the lowest fire intensity would likely occur on the lower position, especially on the north-facing aspects. This would be exacerbated with drier fuel conditions on upper slopes compared to lower slope positions [17].

4.3. Oak and Maple

Oak forests are an important ecosystem in the Eastern U.S. 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 [40]. 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 prescribed fires or wildfires pass through these systems. Our results 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 [40]. Over the 94 sample plots, the contribution of maple to the total number of trees was 17.3%, and that to the basal area was 8.8% in the overstory. According to the PCA, however, maple species tend to occupy understory with more understory trees and higher understory DBH and basal area compared to oak, suggesting that maple has the potential to overtake oak species. Combined with the results that oak species have a lower number of trees and basal area on east- and north-facing aspects, the process of shifting from oak to mesophytic species tends to occur on east- and north-facing aspects first.

5. Conclusions

This study demonstrated that topographic variables play an important role in species-level fuel bed composition and variation. The different fuel composition is a primary factor that influences the environment where fire occurs, explaining the differences in fire intensities among landscape positions from a fire environment perspective. Among different landscape locations, the south-and west-facing aspects tend to have a higher proportion of oak litter fuels, especially in upper slope positions, and warmer air temperatures, lower relative humidity, and drier fuels. In contrast, the north- and east-facing aspects are expected to have a lower proportion of oak litter fuels. Our results indicate that fuel bed composition is a potential factor that influences the fire environment and subsequent fire intensity. Our data show that there is no distinction between the overstory and understory attributes among aspects and slope positions when not dividing species; however, when divided by oak and maple species, major differences are found in oak species attributes and corresponding fuel compositions. These findings can provide fire managers with a better prediction of fire behavior based on the different characterization of the fire environment by landscape position.

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