fire

Article

Effects of Wildland Fuel Composition on Fire Intensity

Ziyu Dong and Roger A. Williams *

School of Environment and Natural Resources, The Ohio State University, Columbus, OH 43210, USA; dong.1006@osu.edu
* Correspondence: williams.1577@osu.edu; Tel.: +1-614-688-4061

Abstract: Assessing the characteristics of fuel flammability during fire is of major significance regarding fire intensity and fire spread control. Under the background of shifting forest composition from heliophytic to mesophytic species in mixed-oak forests, our objective is to determine the impacts of species-driven changes in fuel flammability characteristics and the specific relationships between fuel ignition variations at the species level. Oak and maple fuels were collected from ninety-four plots established in Zaleski State Forest, Ohio. A total of 30 combustion samples were separated (15 oak samples and 15 maple samples), with each combustion sample weighing 20 g to ignite under a laboratory fume hood. Our results determined that oak fuel showed significantly higher flame temperatures than maple fuel, and the fuel consumption and combustion duration time both varied between oak and maple fuel. These findings indicated that the shift from oak forest to mesophytic species could change a fire's behavior. Combined with the cooler, moister, and less-flammable 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.

Keywords: fuel composition; fuel flammability; mixed-oak forest; fire temperature; oak fuel; maple fuel

1. Introduction

Fire management and its related research are often focused on fuel monitoring and manipulation since fuel traits drive a fire's behavior and impact [1]. Evaluating the characteristics of fuel flammability and combustibility during fire is significant, regarding fire intensity and fire spread control [2]. Greater fuel loads and lower fuel moisture increase fire temperatures [3] and can lead to 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 [4].

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 [1]. For example, Curt et al. [5] found that even two areas that have similar weather and fuel types 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. [6], 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 [7]. However, the fire suppression policies during the early 20th century quickly shifted the species composition and structure from heliophytic, fire-adapted species to shade-tolerant, fire-sensitive species [8]. 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

Citation: Dong, Z.; Williams, R.A. Effects of Wildland Fuel Composition on Fire Intensity. *Fire* **2023**, *6*, 312. https://doi.org/10.3390/fire6080312

Academic Editor: Grant Williamson

Received: 15 June 2023
Revised: 1 August 2023
Accepted: 11 August 2023
Published: 13 August 2023

leads to changes in the fuel bed characteristics directly through subsequent litter production [9]. Litter characteristics such as litter dimension and shape, litter chemistry, and litter moisture are different among oak and maple species [10]. Understanding species-level variations in fuel traits associated with a fire's environment is critical to understanding current fire-combustion properties in an eastern oak forest.

McDaniel et al. [11] 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 flammability was negatively correlated with the amount of non-oak fuel load [11]. However, their research did not involve the maple species, which is the rapidly proliferating shade-tolerant species in parts of western Appalachia. Furthermore, microclimates, weather (wind, temperature, and relative humidity), and topography may affect flammability and a fire's behavior. Laboratory data that eliminate external conditions (wind and topography) on fuel flammability are essential to further understanding the variations in fuel traits among species.

In order to better determine the impacts of species-driven changes in fuel flammability characteristics and the specific relationships between fuel ignition variations 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 objectives were to (1) examine how fuel flammability varied between oak and maple, (2) assess how oak and maple fuel influenced fire's behavioral characteristics by measuring flammability metrics (flame 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 hypothesized that (1) the flammability metrics (flame temperature, flame height, flaming duration, and fuel-mass-loss rate) would vary between oak and maple fuel, and (2) the maximum temperature would be strongly correlated to the flame height, fire duration time, and mass-loss percentage.

2. Materials and Methods

2.1. Study Site

Fuels were collected from Zaleski State Forest (82°18′5″ W, 39°21′43″ N) in Vinton County, Ohio. This area lies on the unglaciated Appalachian Plateau, with an altitude between 172.9–354.3 m. The climate of this region is characterized as cool, temperate, and continental, with a mean annual temperature of 11.3 °C and precipitation of 1024 mm [12]. Soils are predominantly Steinsburg and Gilpin series silt loams (Typic Hapludalfs) [13].

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 comprising red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrhart), and black gum (*Nyssa sylvatica* Marsh.).

2.2. Fuel Collection and Preparation

An area of 58 hectares located within Zaleski State Forest, referred to as Morgan Hollow, was selected for this study (Figure 1A). A total of 94 circular 0.04 ha sample plots were established for the purpose of collecting forest attribute data. These 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. Soon after the leaves fell (October 2022), a 30 cm × 30 cm wooden frame was used to collect forest litter fuel, which was randomly established at a distance of 0.5 m from each sample plot's center. All forest litter fuel classified in the 1 h (<0.6 cm diameter) and 10 h (0.7–2.5 cm diameter) fuel classes [14] contained within the 30 cm × 30 cm frame were collected down to the mineral soil. A total of 94 fuel samples were collected from the 94 sample plots established previously.

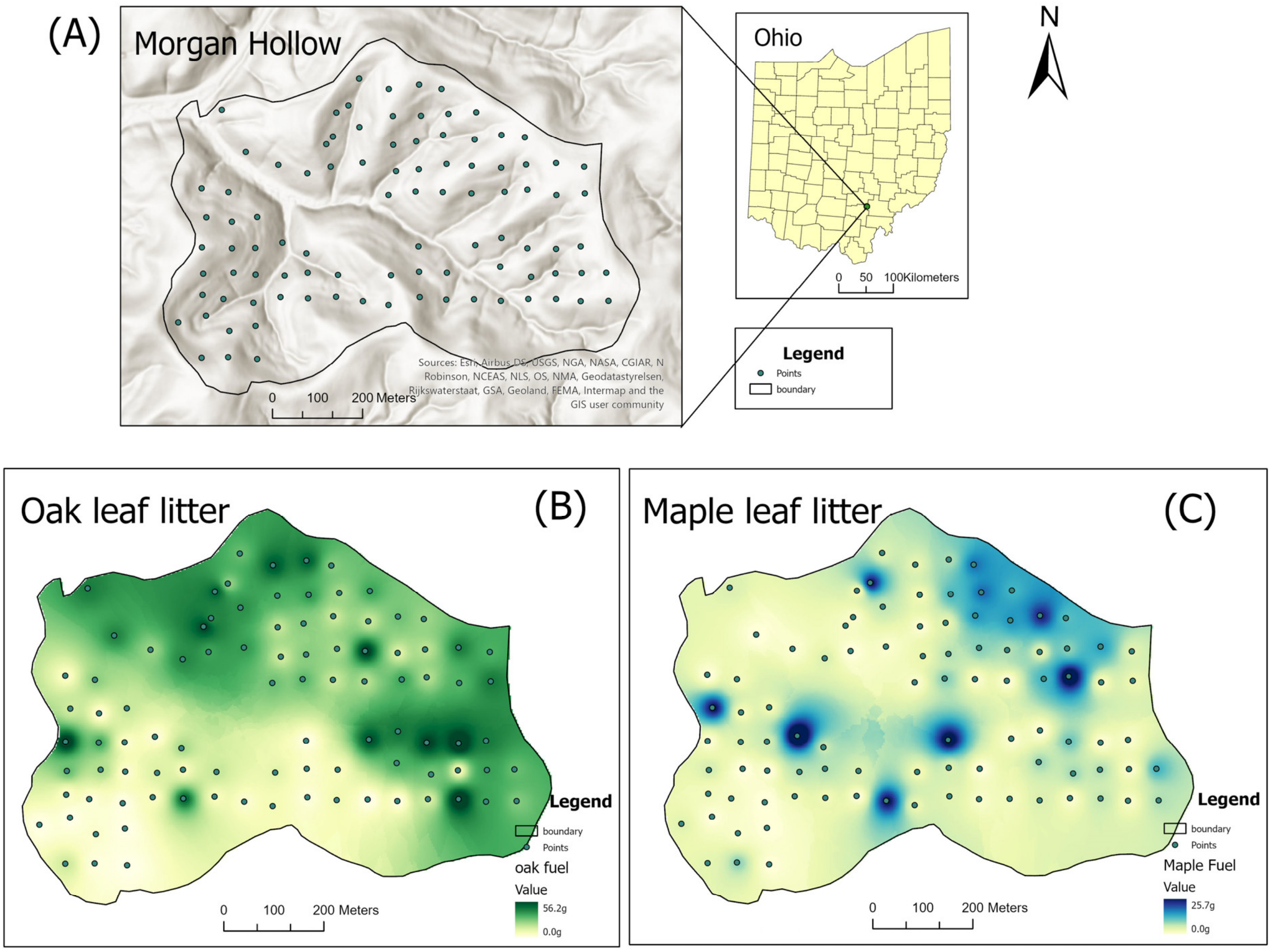

Figure 1. (**A**) Study area (Morgan Hollow) located in Zaleski State Forest, southern Ohio. The black dots indicate the location of the 94 sample plots approximately 60 m apart from each other (depending on the accessibility and forest edge) and distributed evenly in a grid across the study site. (**B**) Oak leaf litter (g) distribution and (**C**) Maple leaf litter (g) distribution over 94 sample plots.

Fuel samples were stored in paper bags and oven-dried at 70 °C for 48 h until they maintained a constant weight. After oven-drying, the samples were stored in paper bags in a dry environment at room temperature to wait for the combustion experiments.

2.3. Combustion Experiments

Combustion experiments were conducted in the lab under a laboratory fume hood. Oak and maple genus species were chosen to determine the different flammability characteristics between species, as oaks were the dominant species in the eastern oak-mixed forests; however, in the absence of fire, red maple and sugar maple have become major competitors and threats to oak. Therefore, to determine how the subsequent changes in litter composition could potentially change fire intensity as measured by temperature, oak and maple leaves were carefully extracted from all oven-dried fuel samples and combusted separately. A total of ~300 g oak and ~300 g maple leaves were separated from fuel samples manually and divided into 30 combustion samples (15 oak samples and 15 maple samples). No distinctions were made among oak species (*Quercus prinus* L., *Quercus. rubra* L., *Quercus coccinea* Muenchh., and *Quercus alba* L.) or maple species (*Acer rubrum* L. and *Acer saccharum* Marsh.) used in this study, as the separation was based on genus. Each combustion sample weighed 20 g and was placed evenly within a 23.5 cm × 34 cm metal tray with the fuel depth of approximately 10 cm. The 10 cm fuel depth in the experiment mimicked the average fuel depth measured in the field, which was 11.5 cm. Two 30.5 cm long thermocouples (K-type) probes connected with HOBO dataloggers were used to collect fire temperatures at different heights, one placed at 0 cm above the fuel surface, and the other one at 10 cm above the fuel surface (Figure 2). The 10 cm 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 [15]. The thermocouple probes extended over the center of the fuel sample. Each sample was ignited to simulate a spot fire with a butane candle lighter at the right corner of each combustion sample. Several flammability metrics were measured during the combustion process, including flame temperature, maximum flame height, combustion duration time, time to reach the highest flame temperature, and the amount of fuel that remained after combustion was completed as 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 s. 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.

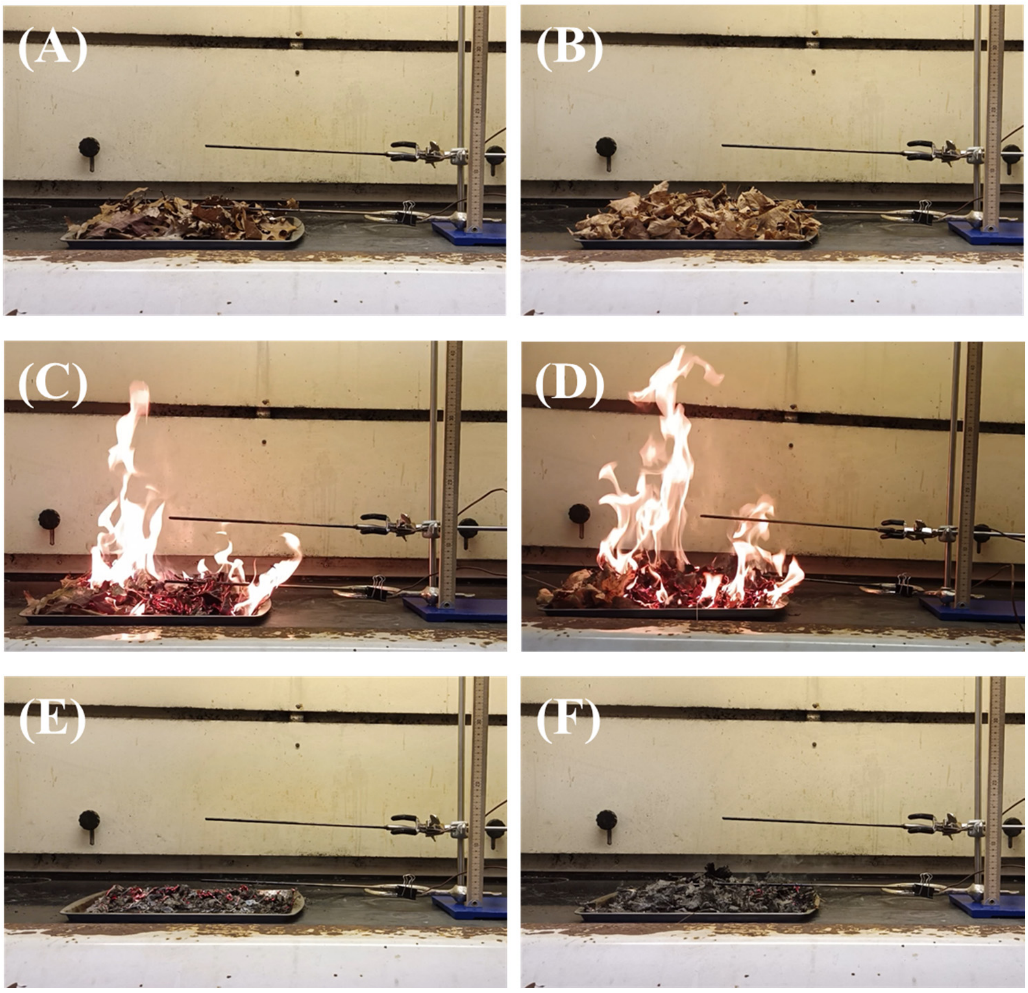

Figure 2. Fuel sample combustion experiment. (**A**) Prior to burning of the oak sample, (**B**) prior to burning of the maple sample, (**C**) during the burning of the oak sample, (**D**) during the burning of the maple sample, (**E**) post-burn of the oak sample, and (**F**) post-burn of the maple sample.

2.4. Flammability Components and Metrics

Three flammability components (combustibility, comsumability, and sustainability) and five flammable metrics were measured and calculated to compare the differences between oak and maple fuel [16–20]. (1) Combustibility, defined as the rapidity of the combustion after ignition, including the metrics of flame height (cm) and rate of temperature increase (ΔT/sec). (2) Consumability refers to the quantity of mass consumed by combustion and can be measured by the metrics of mass loss percentage (%). (3) Sustainability refers to the ability of the fuel to sustain combustion, including the metrics of combustion duration time (s) and flame temperature (°C) [16–20].

2.5. 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 ∝ = 0.05) to compare the means of the two species groups. The relationships between flammability metrics were analyzed using regression and Pearson's correlation coefficient. A significant correlation was assumed when $r > 0.30$ and $p \leq 0.05$. All statistical analyses were performed in R, version 4.2.2 (R Core Team, 2022).

3. Results

3.1. Oak and Maple Flammability Metrics

The flammability metrics varied between oak and maple fuel are displayed in Table 1.

Table 1. Combustion statistics for oak and maple (n = 15 for each species) foliage in the combustion 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 (°C) [1]	167.10	134.66	214.33	25.85	15.47
Max temperature, 10 cm (°C) [2]	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
Rate of temperature increase	3.27	2.16	5.12	0.93	28.37
	--------------------------- Maple ---------------------------				
Percent fuel mass loss	87.11	77.95	91.00	3.20	3.67
Max surface temperature (°C) [1]	142.39	116.73	162.64	13.34	9.37
Max temperature, 10 cm (°C) [2]	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
Rate of temperature increase	2.70	1.80	3.72	0.57	21.26

[1] Maximum flame temperature at fuel surface. [2] Maximum flame temperature at 10 cm above fuel surface.

3.1.1. Combustibility

The combustibility of oak and maple fuel were examined by measuring the maximum flame height, maximum flame temperature, time, and calculating the rate of temperature increase. In our study, oak fuel temperatures were significantly higher than maple at the fuel's surface (0 cm, $p = 0.0027$, Figure 3A), with the average temperatures of oak and maple fuel samples of 167.10 °C and 142.39 °C, respectively. The maximum temperatures at 10 cm above the fuels' surfaces displayed high variation, with oak fuel temperatures slightly higher than maple fuel (Figure 3B), where the averag fuel temperature was 79.48 °C and 75.03 °C for oak and maple, respectively. The rate of temperature increase (ΔT/sec) was calculated by using the maximum flame temperature divided by the time to reach that temperature. At the fuel's surface (0 cm), oak displayed a slightly higher rate of temperature increase values than maple (Figure 4A). However, maple fuel showed a slightly higher flame height than oak fuel (Figure 4B).

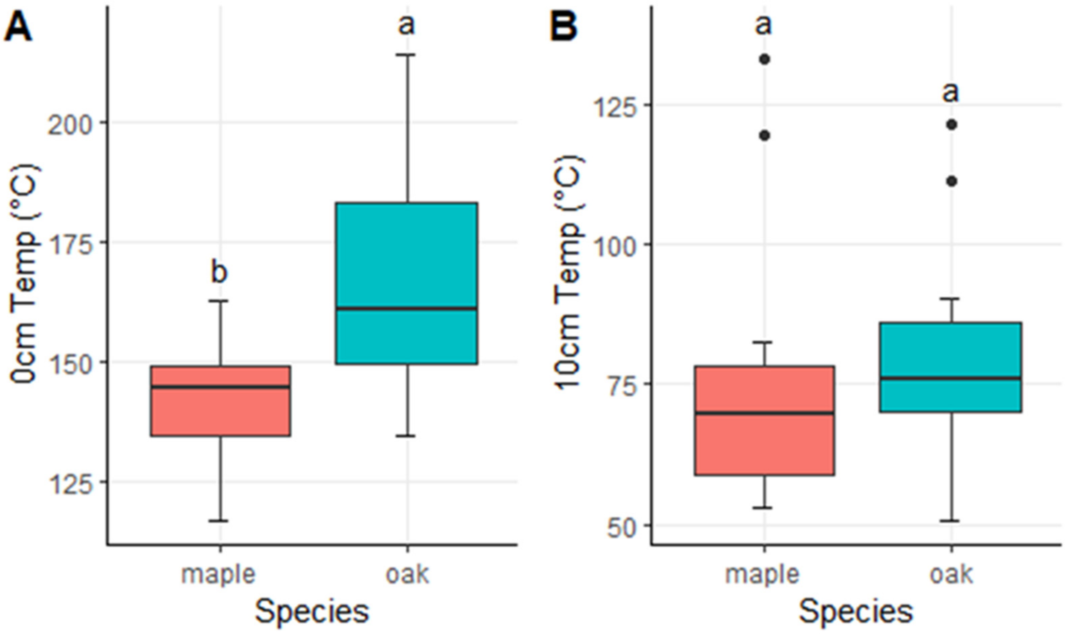

Figure 3. (**A**) The maximum temperature at the fuel surface (0 cm) and (**B**) the maximum temperature at 10 cm above the fuel surface for maple and oak. Figures with the same lower case letters are not significantly different between species within each graph (Duncan's MRT, $p = 0.05$).

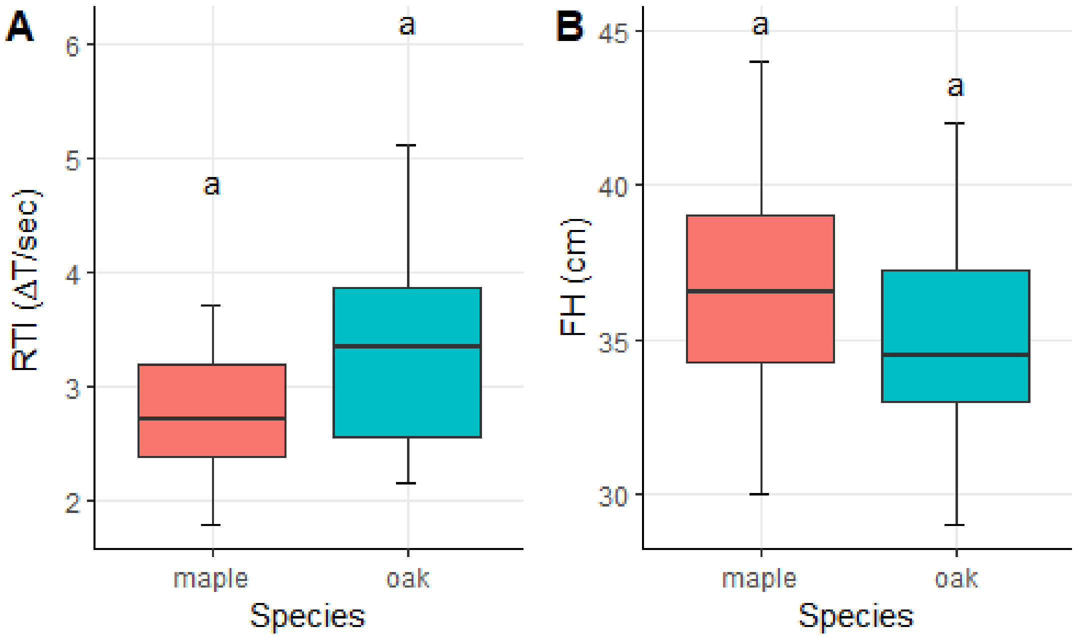

Figure 4. (**A**) The rate of temperature increases at the fuel surface and (**B**) the maximum flame height during combustion for oak and maple. Figures with the same lower case letters are not significantly different between species within each graph (Duncan's MRT, $p = 0.05$).

3.1.2. Consumability

The fuel consumption, as well as fuel mass loss percentage, had significant differences between oak and maple fuel ($p < 0.001$, Figure 5A). Oak had a higher fuel consumption compared to maple, with a range from 90.20% to 93.55% for oak and a range from 77.95% to 91.00% for maple.

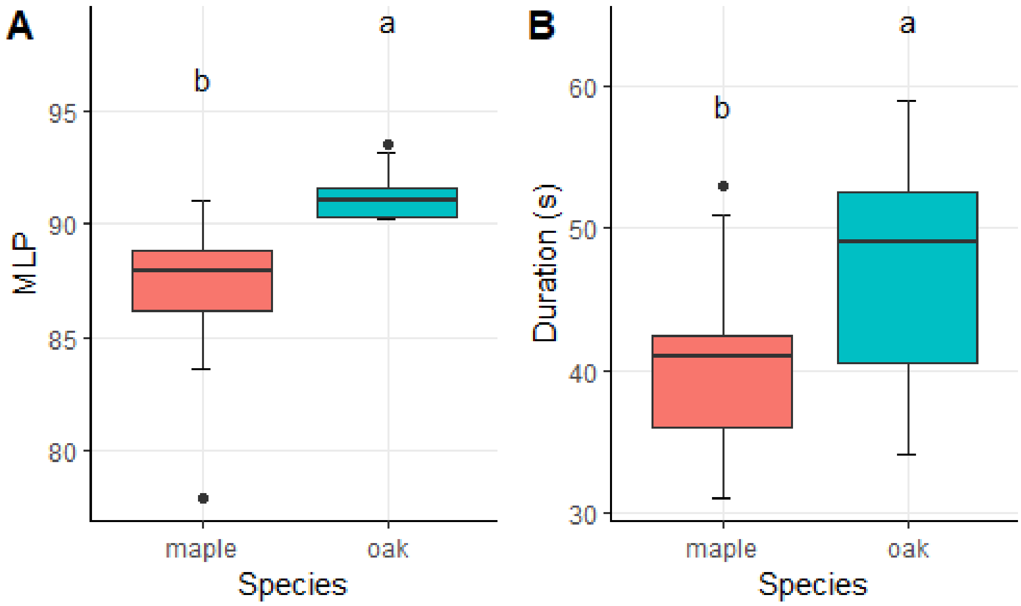

Figure 5. (**A**) Oak and maple fuel mass loss percentage and (**B**) the duration time of combustion. Figures with the same lower case letters are not significantly different between species within each graph (Duncan's MRT, $p = 0.05$).

3.1.3. Sustainability

The combustion duration time of oak was significantly longer than maple ($p = 0.0152$, Figure 5B), with an average of 46.67 s for oak compared to 40.13 s for maple.

3.2. Relationship between Flammability Metrics

Linking flammability metrics together can be used as a way to predict fire risk when only a limited number of metrics can be measured. For example, the maximum flame temperature can be a potential indicator to estimate the fire duration time. In this study, for all combustion samples combined, relating maximum temperature at 0 cm to flammability metrics revealed a positive correlation with fire duration time (r = 0.52, Table 2) and the mass loss (r = 0.40), whereas the mass loss was also significantly and positively correlated to the fire duration time (r = 0.45). However, we did not find significant correlations when analyzing the maple and oak data separately, possibly due to the limited number of samples.

Table 2. Pearson's correlation coefficient between ignition variables for the combined data of oak and maple.

	MLP [3]	MaxT0 [1]	MaxT10 [2]	Duration (s)
maxT0 [1]	0.40 *			
maxT10 [2]	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. [1] maxT0 = max surface temperature (°C). [2] maxT10 = Max temperature at 10 cm (°C). [3] MLP = fuel mass loss percentage.

4. Discussion

Flame temperature is used as one of the major components in the assessment of fuel flammability [21]. Our study demonstrated that oak and maple fuel differed in their flame temperatures, as measured in degrees Celsius, and oak had a significantly higher flame temperature than maple fuel at the fuel's surface. These results were consistent with other studies where oak exhibited higher flammability and flame temperature than non-oak species [11]. The lower flammability species were characterized by a shorter flame duration time and little fuel consumption [21], which were consistent with our results that maple displayed a significantly shorter combustion duration time and lower fuel mass loss when comparing oak with maple. The correlation between fuel mass loss, fuel temperature, and combustion duration time indicated that higher fire temperatures could lead to greater fuel mass loss and a longer combustion duration time.

According to Dickinson et al. [10], the hypothesis is fire intensity tends to be lower in eastern U.S. forests due to the shifted forest composition from oaks to mesophytic species (e.g., maple) in deciduous oak forests. Some researchers suggest that non-oak fuel can decrease ignition probability and dampen litter flammability from the fuel moisture perspective [11] or by analyzing flammability metrics instead of real fire temperature [22]. Our findings supported this hypothesis by using real fuel combustion temperature data acquired from K-type thermocouples and by 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 [10]. The flammability 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) [8]. The content of lignin can mitigate the litter decomposition rate, with high lignin litter decomposing slower [23]. The percentage of lignin was typically higher in chestnut oak, scarlet oak, and white oak than in mesophytic species [8,24]. Some research found that high lignin in decomposed litter could strongly determine flammability and lead to more char formation [25]. For these reasons, oak's resistance to decay and flammability are higher than mesophytic species such as maple.

Thermocouples at the fuel's surface recorded significantly higher temperatures for the oak fuel than for the maple fuel. Surface fuel temperatures displayed a positive correlation with flammability metrics of flaming duration time ($r = 0.45$) and fuel mass loss ($r = 0.40$); however, correlations were weakened when measuring flame temperature at 10 cm. Therefore, the recorded temperature at the fuel's surface was a better predictor of flaming duration time and fuel consumption, suggesting that the temperature captured by the surface thermocouple better reflected combustion conditions within the fuel bed, whereas the temperatures recorded by the elevated location were more responsive to flame characteristics [4], such as flame intensity and fireline intensity. Furthermore, the temperature recorded at 10 cm represented greater heat radiation that could be received by the unburnt fuel [26], meaning that the fuel could have a greater ability to pre-heat the unburnt fuel, thereby potentially creating a higher fire rate of spread if they had a higher flame temperature at lifted height. However, in this experiment, the flame temperature at 10 cm was not found to be significantly different between oak and maple.

Our average flame height data of oak (34.87 cm) was within the range recorded by Kane et al. [27], which was from 33.6 cm to 81.4 cm for eight 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. [28], where the average maximum temperature for deciduous leaves was 61.6 °C. The reason might be the different fuel sample loads (15 g in their study vs. 20 g in our study), and a higher fuel load can result in higher fire temperatures due to higher energy generated by more fuel. The other reason might be the fuel composition, which they used mixed litter samples, whereas we used single-genus litter samples.

Regarding flame height, our results showed that there were no significant differences between oak and maple and no strong correlation between flame height and other flammability metrics (flame temperature, combustion duration time, rate of temperature increase, and fuel-mass-loss percentage). However, McDaniel et al. [11] found that flame height significantly differed between oak and non-oak species, and a strong correlation was found between flame height and flame temperature. Part of the inconsistency may have been due to the leaf curling. In the field, mesophyte-dominant litterbeds tend to be shallower.

In our experiments, oak litter tended to be flatter than maple litter (Figure 2A,B), and flat leaves created less-aerated fuel beds with diminutive flame heights [21]. Therefore, more "fluffy" maple fuel in our experiment produced a subtle higher flame; plus, the flame became 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, whereas fuel temperatures were 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 was consistent with Dudaite et al. [29]. Higher temperatures affected litter ash nutrient composition and could change the ash's pH due to the solubility elements in ash [4,30]. At higher temperatures, the C/N ratio will increase and result in lower rates of N mineralization in the soil [31], 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 [30]. The nutrient-poor conditions created by higher fire intensity can limit tree growth and restore endangered ecosystems [4,30]. 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 [32]. Compared with other species, red oak was best grown in nutrient-poor and dry conditions [33]. 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 [12].

McDaniel et al. [11] 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 beds. The mesophyte-dominant litterbeds gained more moisture at saturation moisture contents compared to oak-dormient litterbeds and subsequently create a wetter fuelbeds [34]. The lower fire temperature created by maple fuels combined with the cooler, moister, and less flammable 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 [8,35]. With the continued increase in the abundance of maple, prescribed fire may become less effective at maintaining oak dominance [36].

5. Conclusions

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 flammability, 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 could 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 have been due to the leaf curling. The unpaired flame height and fuel temperature between oak and maple suggested that flame heights were mainly explained by the physical properties of leaves, whereas fuel temperatures were mostly explained by leaf chemistry. Overall, these findings indicated that the shift from oak forest to mesophytic species alone could potentially change fire behavior. Combined with the cooler, moister, and less flammable 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.

Author Contributions: Conceptualization, Z.D. and R.A.W.; methodology, Z.D. and R.A.W.; investigation, Z.D. and R.A.W.; data curation, Z.D.; writing—original draft preparation, Z.D.; writing—review and editing, R.A.W.; visualization, Z.D.; supervision, R.A.W.; project administration, R.A.W.; funding acquisition, R.A.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Foundation, award number 2132798, and by the McIntire–Stennis Act of 1962 (P.L. 87-788), project number OHO00053-MS.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon reasonable request to the corresponding author. The data are not publicly available due to ongoing research efforts.

Acknowledgments: We thank Fitia Rajaonarivelo for her help in the field data collection and sampling.

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

References

1. Lydersen, J.M.; Collins, B.M.; Knapp, E.E.; Roller, G.B.; Stephens, S. Relating Fuel Loads to Overstorey Structure and Composition in a Fire-Excluded Sierra Nevada Mixed Conifer Forest. *Int. J. Wildland Fire* **2015**, *24*, 484. [CrossRef]
2. Curt, T.; Schaffhauser, A.; Borgniet, L.; Dumas, C.; Estève, R.; Ganteaume, A.; Jappiot, M.; Martin, W.; N'Diaye, A.; Poilvet, B. Litter Flammability in Oak Woodlands and Shrublands of Southeastern France. *For. Ecol. Manag.* **2011**, *261*, 2214–2222. [CrossRef]
3. Graham, J.B.; McCarthy, B.C. Effects of Fine Fuel Moisture and Loading on Small Scale Fire Behavior in Mixed-Oak Forests of Southeastern Ohio. *Fire Ecol.* **2006**, *2*, 100–114. [CrossRef]
4. Quigley, K.M.; Wildt, R.E.; Sturtevant, B.R.; Kolka, R.K.; Dickinson, M.B.; Kern, C.C.; Donner, D.M.; Miesel, J.R. Fuels, Vegetation, and Prescribed Fire Dynamics Influence Ash Production and Characteristics in a Diverse Landscape under Active Pine Barrens Restoration. *Fire Ecol.* **2019**, *15*, 5. [CrossRef]
5. Curt, T.; Borgniet, L.; Bouillon, C. Wildfire Frequency Varies with the Size and Shape of Fuel Types in Southeastern France: Implications for Environmental Management. *J. Environ. Manag.* **2013**, *117*, 150–161. [CrossRef] [PubMed]
6. Zhao, W.; Cornwell, W.K.; van Pomeren, M.; van Logtestijn, R.S.P.; Cornelissen, J.H.C. Species Mixture Effects on Flammability across Plant Phylogeny: The Importance of Litter Particle Size and the Special Role for Non-*Pinus* Pinaceae. *Ecol. Evol.* **2016**, *6*, 8223–8234. [CrossRef]
7. Bataineh, M.; Portner, B.; Pelkki, M.; Ficklin, R. Prescribed Fire First-Order Effects on Oak and Maple Reproduction in Frequently Burned Upland Oak–Hickory Forests of the Arkansas Ozarks. *Forests* **2022**, *13*, 1865. [CrossRef]
8. Nowacki, G.J.; Abrams, M.D. The Demise of Fire and "Mesophication" of Forests in the Eastern United States. *BioScience* **2008**, *58*, 123–138. [CrossRef]
9. Capellesso, E.S.; Scrovonski, K.L.; Zanin, E.M.; Hepp, L.U.; Bayer, C.; Sausen, T.L. Effects of Forest Structure on Litter Production, Soil Chemical Composition and Litter-Soil Interactions. *Acta Bot. Bras.* **2016**, *30*, 329–335. [CrossRef]
10. Dickinson, M.B.; Hutchinson, T.F.; Dietenberger, M.; Matt, F.; Peters, M.P. Litter Species Composition and Topographic Effects on Fuels and Modeled Fire Behavior in an Oak-Hickory Forest in the Eastern USA. *PLoS ONE* **2016**, *11*, e0159997. [CrossRef]
11. McDaniel, J.K.; Alexander, H.D.; Siegert, C.M.; Lashley, M.A. Shifting Tree Species Composition of Upland Oak Forests Alters Leaf Litter Structure, Moisture, and Flammability. *For. Ecol. Manag.* **2021**, *482*, 118860. [CrossRef]
12. Boerner, R.E.J.; Brinkman, J.A. Fire Frequency and Soil Enzyme Activity in Southern Ohio Oak–Hickory Forests. *Appl. Soil Ecol.* **2003**, *23*, 137–146. [CrossRef]
13. Hutchinson, T.F.; Long, R.P.; Ford, R.D.; Sutherland, E.K. Fire History and the Establishment of Oaks and Maples in Second-Growth Forests. *Can. J. For. Res.* **2008**, *38*, 1184–1198. [CrossRef]
14. National Wildfire Coordinating Group. 2023. NWCG Glossary of Wildland Fire, PMS 205.
15. Yip, A.; Haelssig, J.B.; Pegg, M.J. Multicomponent Pool Fires: Trends in Burning Rate, Flame Height, and Flame Temperature. *Fuel* **2021**, *284*, 118913. [CrossRef]
16. Anderson, H.E. Forest Fuel Ignitibility. *Fire Technol.* **1970**, *6*, 312–319. [CrossRef]
17. Schroeder, R.A.; Sapsis, D.B.; Stephens, S.L.; Chambers, M. Assessing the Flammability of Domestic and Wildland Vegetation. *J. Environ. Manag.* **1994**, *12*, 130–137. [CrossRef]
18. White, R.H.; Zipperer, W.C. Testing and Classification of Individual Plants for Fire Behaviour: Plant Selection for the Wildland -Urban Interface. *Int. J. Wildland Fire* **2010**, *19*, 213. [CrossRef]
19. Ganteaume, A.; Marielle, J.; Corinne, L.-M.; Thomas, C.; Laurent, B. Effects of Vegetation Type and Fire Regime on Flammability of Undisturbed Litter in Southeastern France. *For. Ecol. Manag.* **2011**, *261*, 2223–2231. [CrossRef]

20. Rivera, J.D.D.; Davies, G.M.; Jahn, W. Flammability and the Heat of Combustion of Natural Fuels: A Review. *Combust. Sci. Technol.* **2012**, *184*, 224–242. [CrossRef]
21. Engber, E.A.; Varner, J.M. Patterns of Flammability of the California Oaks: The Role of Leaf Traits. *Can. J. For. Res.* **2012**, *42*, 1965–1975. [CrossRef]
22. Kane, J.M.; Kreye, J.K.; Barajas-Ramirez, R.; Varner, J.M. Litter Trait Driven Dampening of Flammability Following Deciduous Forest Community Shifts in Eastern North America. *For. Ecol. Manag.* **2021**, *489*, 119100. [CrossRef]
23. Chakravarty, S.; Rai, P.; Vineeta; Pala, N.A.; Shukla, G. Litter Production and Decomposition in Tropical Forest. In *Practice, Progress, and Proficiency in Sustainability*; Bhadouria, R., Tripathi, S., Srivastava, P., Singh, P., Eds.; IGI Global: Hershey, PA, USA, 2020; pp. 193–212. [CrossRef]
24. Blair, J.M.; Parmelee, R.W.; Beare, M.H. Decay Rates, Nitrogen Fluxes, and Decomposer Communiies of Single-and Mixed-Species Foliar Litter. *Ecology* **1990**, *71*, 1976–1985. [CrossRef]
25. Fushimi, C.; Araki, K.; Yamaguchi, Y.; Tsutsumi, A. Effect of Heating Rate on Steam Gasification of Biomass. 2. Thermogravimetric-Mass Spectrometric (TG-MS) Analysis of Gas Evolution. *Ind. Eng. Chem. Res.* **2003**, *42*, 3929–3936. [CrossRef]
26. Yuan, X.; Liu, N.; Xie, X.; Viegas, D.X. Physical Model of Wildland Fire Spread: Parametric Uncertainty Analysis. *Combust. Flame* **2020**, *217*, 285–293. [CrossRef]
27. Kane, J.M.; Varner, J.M.; Hiers, J.K. The Burning Characteristics of Southeastern Oaks: Discriminating Fire Facilitators from Fire Impeders. *For. Ecol. Manag.* **2008**, *256*, 2039–2045. [CrossRef]
28. Ganteaume, A.; Jappiot, M.; Curt, T.; Lampin, C.; Borgniet, L. Flammability of Litter Sampled According to Two Different Methods: Comparison of Results in Laboratory Experiments. *Int. J. Wildland Fire* **2014**, *23*, 1061. [CrossRef]
29. Dudaite, J.; Baltrenaite, E.; Ubeda, X.; Tamkeviciute, M. Effects of temperature on the properties of pine and maple leaf litter ash. a laboratory study. *Environ. Eng. Manag. J.* **2013**, *12*, 2107–2116. [CrossRef]
30. Úbeda, X.; Pereira, P.; Outeiro, L.; Martin, D.A. Effects of Fire Temperature on the Physical and Chemical Characteristics of the Ash from Two Plots of Cork Oak (*Quercus Suber*): Effects of fire temperature on ash from cork oak. *Land Degrad. Dev.* **2009**, *20*, 589–608. [CrossRef]
31. Boerner, R.E.J.; Morris, S.J.; Sutherland, E.K.; Hutchinson, T.F. Spatial Variability in Soil Nitrogen Dynamics after Prescribed Burning in Ohio Mixed-Oak Forests. *Landsc. Ecol.* **2000**, *15*, 425–439. [CrossRef]
32. Gray, D.M.; Dighton, J. Mineralization of Forest Litter Nutrients by Heat and Combustion. *Soil Biol. Biochem.* **2006**, *38*, 1469–1477. [CrossRef]
33. Abrams, M.D. Fire and the Development of Oak Forests. *BioScience* **1992**, *42*, 346–353. [CrossRef]
34. Kreye, J.K.; Varner, J.M.; Hamby, G.W.; Kane, J.M. Mesophytic Litter Dampens Flammability in Fire-excluded Pyrophytic Oak–Hickory Woodlands. *Ecosphere* **2018**, *9*, e02078. [CrossRef]
35. Alexander, H.D.; Siegert, C.; Brewer, J.S.; Kreye, J.; Lashley, M.A.; McDaniel, J.K.; Paulson, A.K.; Renninger, H.J.; Varner, J.M. Mesophication of Oak Landscapes: Evidence, Knowledge Gaps, and Future Research. *BioScience* **2021**, *71*, 531–542. [CrossRef]
36. Arthur, M.A.; Blankenship, B.A.; Schörgendorfer, A.; Loftis, D.L.; Alexander, H.D. Changes in Stand Structure and Tree Vigor with Repeated Prescribed Fire in an Appalachian Hardwood Forest. *For. Ecol. Manag.* **2015**, *340*, 46–61. [CrossRef]