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Non-Destructive Fuel Volume Measurements Can Estimate Fine-Scale Biomass across Surface Fuel Types in a Frequently Burned Ecosystem

Quinn A. Hiers [1], E. Louise Loudermilk [2,*], Christie M. Hawley [2], J. Kevin Hiers [1], Scott Pokswinski [1], Chad M. Hoffman [3] and Joseph J. O'Brien [2]

[1] Tall Timbers Research Station, 13093 Henry Beadel Dr., Tallahassee, FL 32312, USA; qhiers.cfds@gmail.com (Q.A.H.); jkhiers@talltimbers.org (J.K.H.); spokswinski@talltimbers.org (S.P.)
[2] Athens Fire Laboratory, Southern Research Station, USDA Forest Service, 320 Green Street, Athens, GA 30602, USA; christie.m.hawley@usda.gov (C.M.H.); joseph.j.obrien@usda.gov (J.J.O.)
[3] Department of Forest and Rangeland Stewardship, Warner College of Natural Resources, Colorado State University, Fort Collins, CO 80538, USA; C.Hoffman@colostate.edu
* Correspondence: eva.l.loudermilk@usda.gov

Abstract: Measuring wildland fuels is at the core of fire science, but many established field methods are not useful for ecosystems characterized by complex surface vegetation. A recently developed sub-meter 3D method applied to southeastern U.S. longleaf pine (*Pinus palustris*) communities captures critical heterogeneity, but similar to any destructive sampling measurement, it relies on separate plots for calculating loading and consumption. In this study, we investigated how bulk density differed by 10-cm height increments among three dominant fuel types, tested predictions of consumption based on fuel type, height, and volume, and compared this with other field measurements. The bulk density changed with height for the herbaceous and woody litter fuels ($p < 0.001$), but live woody litter was consistent across heights ($p > 0.05$). Our models predicted mass well based on volume and height for herbaceous (RSE = 0.00911) and woody litter (RSE = 0.0123), while only volume was used for live woody ($R^2 = 0.44$). These were used to estimate consumption based on our volume-mass predictions, linked pre- and post-fire plots by fuel type, and showed similar results for herbaceous and woody litter when compared to paired plots. This study illustrates an important non-destructive alternative to calculating mass and estimating fuel consumption across vertical volume distributions at fine scales.

Keywords: wildland fuels; 3D fuels bulk density; fuel characterization; fuel consumption; longleaf pine; wiregrass; shrubs; litter; surface fire

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Citation: Hiers, Q.A.; Loudermilk, E.L.; Hawley, C.M.; Hiers, J.K.; Pokswinski, S.; Hoffman, C.M.; O'Brien, J.J. Non-Destructive Fuel Volume Measurements Can Estimate Fine-Scale Biomass across Surface Fuel Types in a Frequently Burned Ecosystem. *Fire* **2021**, *4*, 36. https://doi.org/10.3390/fire4030036

Academic Editors: Alistair M. S. Smith and Wade T. Tinkham

Received: 30 May 2021
Accepted: 9 July 2021
Published: 14 July 2021

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1. Introduction

The pace of discovery in wildland fire science has accelerated in the past two decades with technologically advanced instrumentation for measuring fire behavior [1,2], modeling of fire behavior in conjunction with atmospheric dynamics [3–5], and measuring fine- to coarse-scale attributes of vegetation using various remote sensing technologies [6–10]. Despite these advancements, field vegetation and fuel sampling techniques have been generally stagnant since the 1970s and 1980s [11] and were mainly developed for dry western conifer/mixed-conifer forests where coarse woody fuels are a dominant fuel type [12]. These field sampling and monitoring techniques were adopted nationally [13,14] for wildfires of the western U.S. where coarse-scale estimates of fuels are sufficient for stand-level averages and relationships with wildfire intensity and consumption, as well as inputs for wildfire simulations of tree canopy fires [15,16]. They are less useful for mesic, more productive sites (e.g., southeastern pinelands, midwestern grasslands) where fine fuels in mixed surface fuelbeds (leaf litter, grasses, and shrubs) drive the behavior of frequent, low-intensity fires [17–19]. Because of the prevalence of frequent, low-intensity fires in southeastern U.S. pinelands, which are primarily propagated by fine surface fuels, understanding the spatial distribution of these fuels and their influence on fire behavior is imperative for advancing fire science relevant to prescribed fire management [20].

Historically, fuels were classified into 'fuel models.' These fuel models have grouped fuels into four categories—grass, brush, timber, and slash [21]. These categories relate to fire behavior differences primarily through coarse relationships with fuel loading and distribution [21]. Since the late 1970s, live and dead woody and herbaceous fuel loading has been calculated through equations that use constant bulk densities over a management unit [22] or estimated using ocular estimates (e.g., [14,23]). They assume a constant fuel bulk density regardless of fuel height, which results in a monotonic increase in fuel load with depth [22,24]. Hence, fuels have historically been viewed through a coarse lens, despite the importance of fine scale fuel variation to fire ecology [17,25,26]. New approaches are needed for better fine-scale estimates of mass, volume, and bulk density of various fuel types found in frequently burned surface fire regimes.

A new 3D fuel method developed by Hawley et al. [27] can quantify the variation in bulk density estimates on a sub-meter scale. Understanding how volume and mass change by fuel type at these finer scales may be an essential parameter in predicting fire behavior [17,19,28] and fire effects on floral diversity patterns [29,30].

Although heterogeneous bulk density can now be captured with the new 3D fuels methodology [27], this technique has the same limitation as many fire effects experiments that aim to measure fuel consumption—namely, it relies on destructive sampling where fuel is removed to measure fuel loading (biomass) and spatially separated paired plots are required to infer fuel consumed by the fire. To capture both pre-fire fuel loading and subsequent consumption by fire, some studies have collected large samples of pre- and post-burn data or attempted to pair the pre- and post-burn plots through their visual similarity and vegetation type [31].

Paired sampling generally works well for examining high intensity/high severity wildland fires where there is complete or near-complete consumption, but less so for frequent low-intensity prescribed fires where consumption is mainly limited to surface fuels. This results in unburned aerial fuels such as shrubs dominating post-burn biomass [31–33]. If mass can be accurately and precisely predicted at fine scales, we can better explore the effects of fuel structure and mass on fire behavior, and vice versa, in this heterogenous vegetation. If a strong relationship can be found between volume, mass, and height in pre-fire plots where destructive sampling occurred, then the mass can be predicted in non-destructive plots pre-fire and provide more accurate and precise measurements of consumption, especially by fuel type.

Southeastern pine ecosystems are a prime example of where the relationship between mass and volume at fine scales are particularly important [18,34]. These ecosystems are characterized by an overstory of pines, a sparse midstory, and an understory of complex surface vegetation consisting of shrubs, grasses, forbs, and leaf litter [25,35]. The structure and composition of this ecosystem is propagated by frequent, low-intensity fires (1–5-year return intervals) producing variable consumption of fine fuels, even within 'complete' (all black) burns [36]. Fire behavior and effects in relation to these surface fuels are difficult to predict because fuel mass, structure, consumption, and bulk density are interwoven at fine scales [19,37]. This creates a challenge to accurately measure or at least estimate them at the landscape level. Given the high spatial complexity of fuel types at the sub-meter scale, these systems require a more detailed perspective to evaluate properly, specifically when evaluating fuel characteristics, such as volume and mass by fuel type.

This study took an empirical approach to examine the relationships of fine-scale fuel attributes at a 1000 cm^3 scale (10 cm × 10 cm × 10 cm) to better characterize bulk density and consumption estimates by fuel type in frequently burned ecosystems where grasses, leaf litter, and small shrubs dominate the fuels. The objectives of this study were to (1) investigate how bulk density varies with height among three dominant fine-scale fuel types, (2) test predictions of biomass based on fuel type, height, and voxelized volume estimations at the 10 cm^3 scale, (3) use these predictions to estimate fuel consumption by linking pre- and post-burn data, and (4) compare consumption estimates with field measurements of consumption.

2. Materials and Methods

2.1. Site Description

Fuel measurements were collected from Pebble Hill Plantation (PHP), located in the Red Hills region of southern Georgia, USA (30°35′ N, 84°20′ W). The Red Hills is a temperate sub-tropical region experiencing annual mean precipitation of 1359 mm (recorded 21 km to the south at Tall Timbers Research Station, averaged between 1878–2010) and mean monthly temperatures ranging from 26.8 °C in July to 10.4 °C in January ([38], averaged between 1981–2010).

PHP is a 1222-ha plantation that has a history of timber and patch agriculture dating to the mid-1800s and is currently managed for hunting of northern bobwhite quail (*Colinus virginianus* L.). This management scheme allowed the succession of old agricultural fields to old-field pine-grasslands while maintaining frequent fire return intervals on portions of native groundcover [39]. In these pine-grassland communities, the overstory is dominated by longleaf pine (*Pinus palustris* Mill.) and a few shortleaf pine (*Pinus echinata* Mill.), averaging a stand density of 9.6 ± 6.3 m^2/ha and basal area of 10.9 ± 6.3 m^2/ha (Robertson and Ostertag, 2007). Meanwhile, the understory is a continuous matrix of grasses, forbs, and shrub hardwoods [39]. Understory species consist of wiregrass (*Aristida stricta* Michx.), bluestem (*Andropogon* spp.), *Vaccinium* spp., American beautyberry (*Callicarpa americana* L.), oaks (*Quercus* spp.), and hickory (*Carya* spp.).

Our clip plots were distributed amongst three 0.20-ha burn units at PHP. These burn units historically have been hand-burned every two years and were currently in a two-year rough. Collectively, 14 clip plots were non-randomly selected for pre-fire destructive sampling to best represent the fuel types in each burn unit: shrub, herbaceous, or surface fuels. This resulted in a stratified inventory of five shrub, five herbaceous, and four surface clip plots, all of which were centered on either a focal shrub, a wiregrass individual, or an open patch in the shrub-grass matrix lacking dominant shrub or grass clumps, respectively. Due to time constraints, there were only four clip plots selected for post-fire sampling—three shrub plots and one open patch plot. However, each of these was chosen as a paired plot to a pre-fire clip plot where they were selected based on how similar they were to a pre-fire plot regarding dominant fuel type and visual estimations of load and fuel distribution.

2.2. Sampling

To characterize three-dimensional, fine-scale variation in the clip plots, the voxel sampling approach found in Hawley et al., 2018 was used, which we briefly describe here. A rectangular, adjustable 3D sampling frame was used to collect fuel data up to 1 m in height at three different scales: entire clip plot (0.25 m^3), single stratum (every 10 cm; 0.025 m^3), and individual voxels (0.001 m^3). Sampling was limited to below 1 m because shrubs and herbaceous material rarely grow above a meter in these frequently burned systems. The frame itself was 0.5 m × 0.5 m × 1 m and subdivided into ten 10 cm vertical intervals/strata. Each stratum contained twenty-five 1000 cm^3 cells/voxels, totaling 250 voxels for the entire frame's volume (Figure A1).

Using a top-down approach, sampling began at 100 cm, and the sliding square frame was lowered 10 cm at a time. Within each stratum and voxel, presence/absence was recorded for each fuel type. The biomass was then destructively harvested by clipping and bagging the material. After each stratum was clipped, the frame was lowered another 10 cm to the next height stratum, and the volume and biomass were collected again until the last stratum (0–10 cm) was reached. All biomass was collected in June of 2019.

The samples were sorted into the various fuel type categories indicated by the voxel data. Fuel types were then combined or eliminated into three fuel categories. The biomass samples were dried at 70 °C for 48 h, consistent with many protocols [28,31].

For the pre-fire clip plots, both the voxelized volume and biomass data were collected. However, only the volume data were collected pre-fire for post-fire clip plots, and then both residual volume and biomass were collected post-fire (Table A1).

2.3. Statistical Analyses

For the analyses, vegetation was consolidated into three primary fuel categories: herbaceous, woody litter, and live woody material. The herbaceous category included bunchgrass, wiregrass, forbs, and vines. Woody litter and live woody material primarily represented shrubs, although some overstory trees contributed to the litter category. Woody litter included non-oak and oak litter and leaves along with dead standing material. Woody live encompassed both non-oak and oak live material (living stems, twigs, and foliage).

To estimate total volume for each stratum's fuel categories, the voxel presence/absence data were used. If the fuel category was present in a voxel, then that fuel category had a volume of 1000 cm^3, or 0.001 m^3. All 250 voxels in each clip plot were subjected to this volume calculation, and total volumes were estimated for each 10 cm height stratum. However, only strata that had both volume and biomass recorded were used in the analysis. As such, the smallest volume used was 1000 cm^3 and the smallest biomass used was 0.01 g per stratum.

To determine if bulk density changes with height, a Kruskal–Wallis and pairwise Wilcoxon test was used for both the woody live and herbaceous fuel categories between four height increments (0–10, 10–20, 20–30, and 30–40 cm). A Mann–Whitney U test was conducted to examine if woody litter bulk density changes with height between two height increments (0–10 cm and 10–20 cm).

To investigate the relationship between volume and mass, a linear regression for the woody live fuel category was performed using the lm() function in the R stats package. Normality of the residuals was assessed using the Shapiro–Wilk test ($p < 0.001$) and transformed mass using the square root function to obtain normality (Shapiro–Wilk: $p = 0.73$). Following this transformation, a linear regression was calculated to predict mass based on voxelized volume alone. In this regression, height increments between 10–70 cm were used for the live woody fuel type to minimize residual error.

Despite a log transformation, assumptions of a linear regression could not be met for the herbaceous and woody litter categories. As such, exponential, nonlinear regressions were performed with height and volume as predictors of mass. The nls() function in the R stats package was used to fit the nonlinear models. Given that the majority (>95%) of herbaceous material occurred in height increments between 0–40 cm, only the data associated with these height increments were used in the regression, and heights between 0–20 cm were used for the woody litter fuel type. Prediction vs. actual plots were created using our regressions equations and linear regressions run to compare the predicted to the observed data. For all tests, significance was set at $p < 0.05$. For reference, we considered plot-level regressions for volume and mass, but found that the relationships were not significant, possibly due to the small sample size.

The linear and nonlinear regressions for each fuel type were used to calculate fuel loading in the post-fire plots using the voxelized volume data taken before the burns. Fuel consumption was calculated as the biomass collected following the fire subtracted from the fuel loading calculated pre-fire. To compare this method of calculating fuel loading and consumption to using paired plots, the biomass collected post-fire was subtracted from the biomass collected pre-fire to obtain fuel consumption.

3. Results

3.1. Live Woody

There were no significant differences in bulk density (H = 13.29, df = 9, p = 0.15; Table 1, Figure 1) between height increments. Therefore, the layer height was not used as a predictor in the linear regression.

Table 1. Bulk density medians and interquartile ranges for the three fuel categories (live woody, herbaceous, and woody litter material) at each stratum (0–100 cm) with sample sizes in parentheses. "NA" indicates strata that either had no observations or a single observation where an average could not be calculated. All numbers represent the average bulk density at that stratum given in kg/m^3. Medians within fuel categories are similar if followed by a common letter ($p > 0.05$). Medians not followed by a letter had less than five observations and were not included in the analyses.

	Bulk Density of Fuel Categories (kg/m^3)		
Strata (cm)	**Live Woody**	**Herbaceous**	**Woody Litter**
0–10	1.05 ± 3.23 a (11)	1.56 ± 1.33 a (12)	1.35 ± 1.18 a (12)
10–20	0.97 ± 0.74 a (12)	0.41 ± 0.32 b (12)	0.38 ± 0.24 b (8)
20–30	0.84 ± 0.37 a (11)	0.14 ± 0.17 c (12)	NA
30–40	0.87 ± 0.42 a (10)	0.09 ± 0.04 d (12)	NA
40–50	0.79 ± 0.37 a (8)	0.06 ± 0.05 d (11)	NA
50–60	0.60 ± 0.20 a (7)	0.05 ± 0.01 d (8)	NA
60–70	0.62 ± 0.20 a (7)	0.04 ± 0.01 d (6)	NA
70–80	0.48 ± 0.49 (4)	0.13 ± 0.06 (2)	NA
80–90	0.54 ± 0.23 (3)	NA	NA
90–100	0.54 ± 0.47 (3)	NA	NA

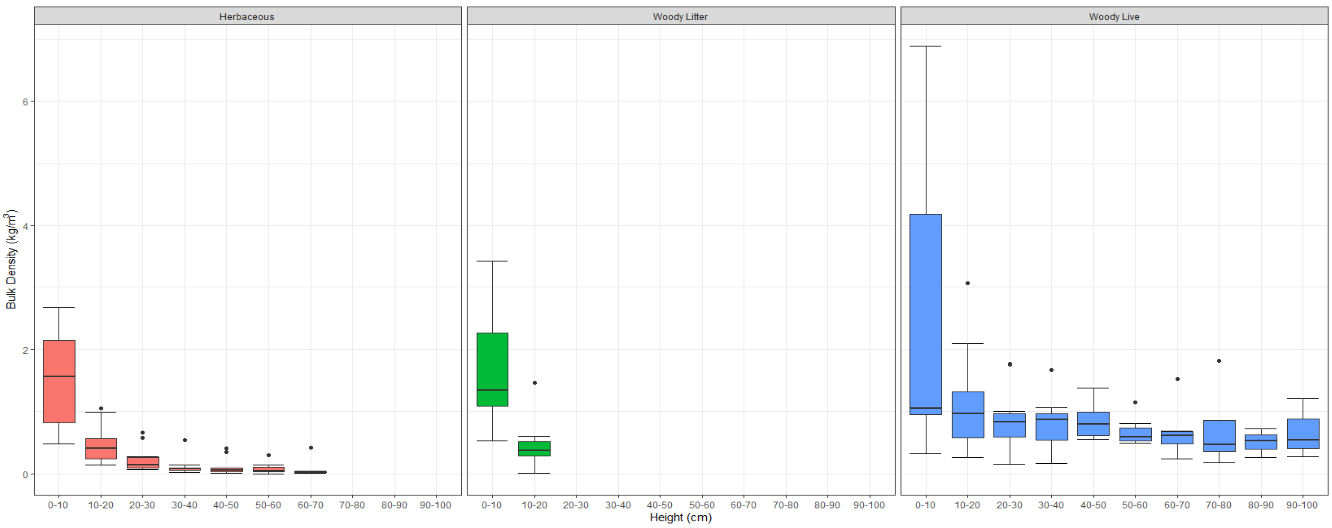

Figure 1. Bulk density values for all fuel types from stratum 0 to 100 cm, in 10 cm increments.

A significant regression equation was found ($F(1,53) = 42.911$, $p < 0.001$), with an R^2 of 0.44 (Figure 2). The estimates for the linear regression coefficients can be found in Table 2. The prediction vs. the actual plot showed a positive correlation between the predicted and observed data ($F(1,63) = 39.27$, $p < 0.001$, $R^2 = 0.37$; Figure 3).

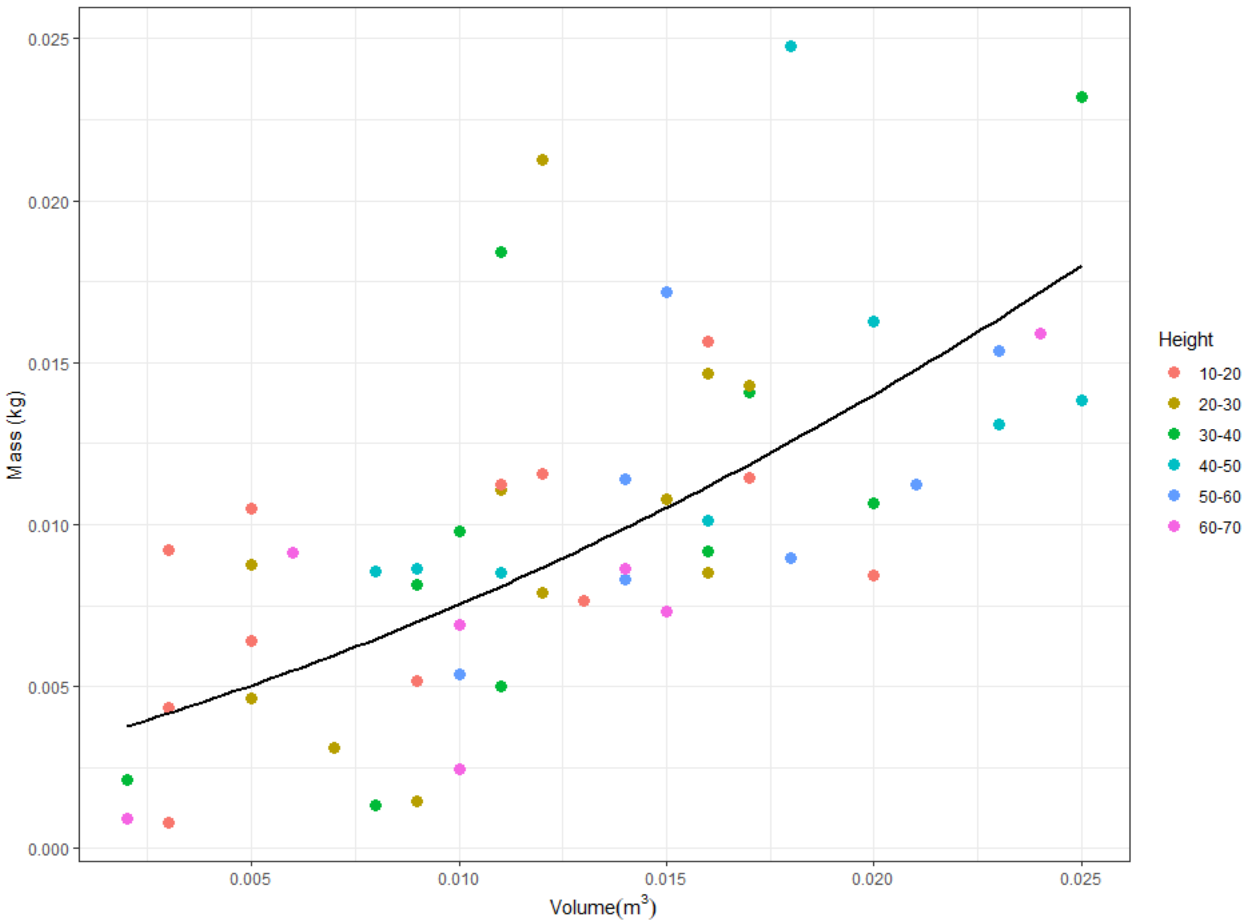

Figure 2. Regression for live woody fuel material with volume as a predictor of mass (mass has been backtransformed from square root). The equation was significant ($p < 0.001$), with an R^2 of 0.44. Only mass and volume observations associated with the strata between 10 and 70 cm were included.

Table 2. Estimates, R^2, and residual standard errors for linear and nonlinear regression equations for the three fuel types predicting mass (kg) based on volume and height. For live woody, only volume was used as a predictor. Standard deviation of estimates in parentheses.

	Estimate Live Woody	**Estimate Herbaceous**	**Estimate Woody Litter**
Intercept	0.0552 (0.00678)	6.96×10^{-8} (2.93×10^{-7})	0.00155 (0.00171)
Volume	3.16 (0.482)	535 (169)	143 (45.4)
Height 10–20 cm	NA	−1.11 (0.228)	−0.624 (1.56)
Height 20–30 cm	NA	−1.40 (0.429)	NA
Height 30–40 cm	NA	−1.43 (0.734)	NA
R^2	0.44	NA	NA
Residual Standard Error	0.0217	0.00911	0.0123

Using this equation, the loading was calculated for each plot, pre-fire, using only the voxelized volume (Figure 3). The median and interquartile range (IQR) fuel consumption was 7.95 ± 20.42 g (Table 3). For the paired plots, the median (±IQR) fuel consumption was 13.47 ± 10.52 g (Table 3).

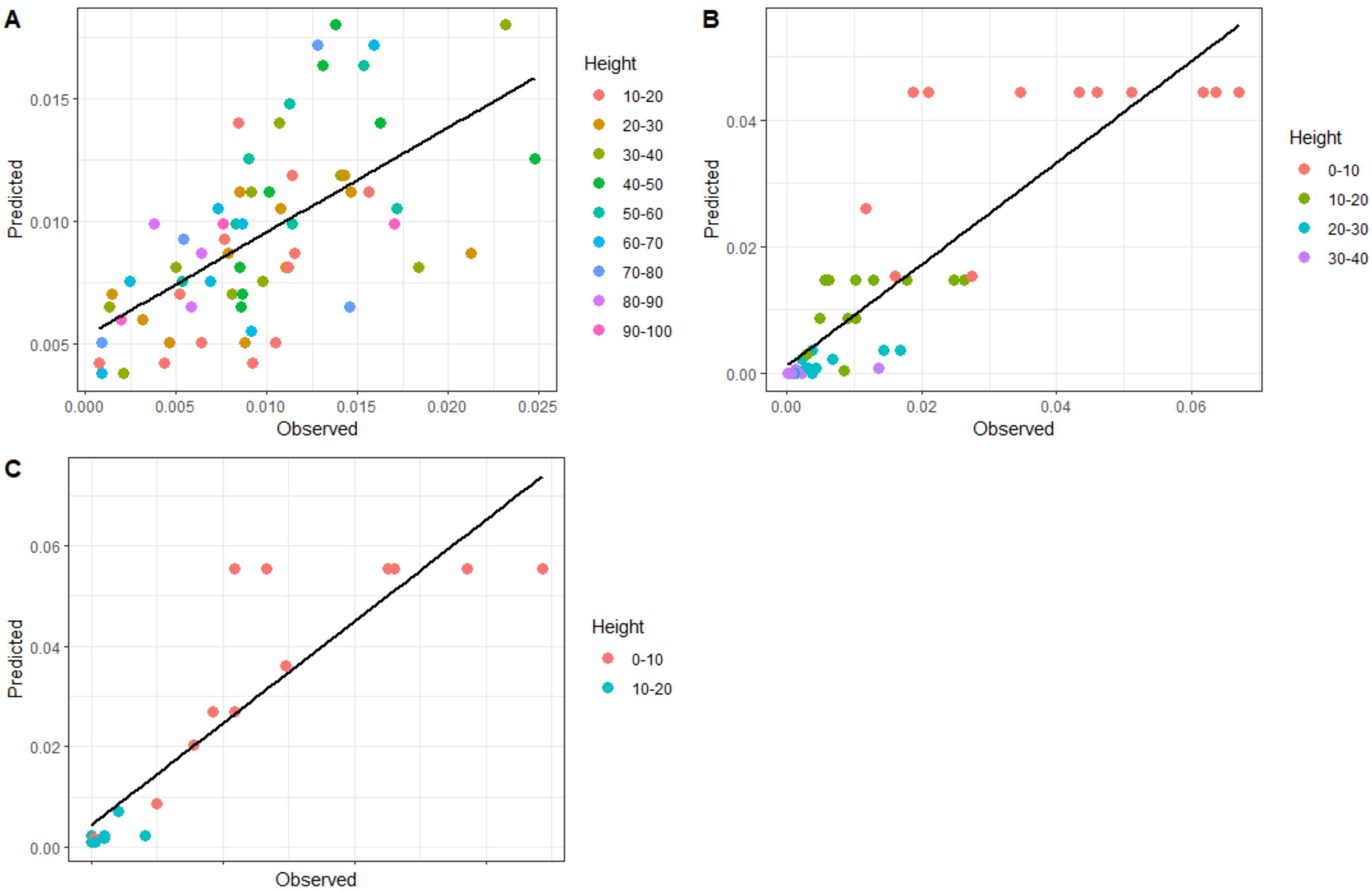

Figure 3. Predicted vs. actual plots for live woody material (**A**), herbaceous fuel (**B**), and woody litter (**C**). Lines represent linear regression with R^2 values of 0.37, 0.75, and 0.79 for A, B, and C respectively.

Table 3. Fuel consumption (g) in four plots for each fuel category. Before treatment application, pre-fire and post-fire plots were paired based on dominant fuel type. Fuel consumption in paired plots was calculated by subtracting biomass in post-fire plots from biomass in pre-fire plots within fuel categories. The regression equation for each fuel type was used to estimate biomass present in post-fire plots before the burn from voxel/volume data. Fuel consumption was then calculated by subtracting collected biomass in post-fire plots from estimated biomass in post-fire plots before the burn.

		Paired Plots		
Plot	**Type**	**Herbaceous**	**Live Woody**	**Woody Litter**
1	Shrub	26.29	14.9	28.8
2	Surface	73.95	−4.22	19.89
3	Shrub	83.96	12.03	21.77
4	Shrub	62.86	29.26	16.32
Median		68.41	13.47	20.83

Table 3. *Cont.*

		Regression Estimates		
Plot	**Type**	**Herbaceous**	**Live woody**	**Woody Litter**
1	Shrub	53.08	−22.47	28.93
2	Surface	59.00	2.95	19.64
3	Shrub	54.09	12.94	20.02
4	Shrub	62.92	29.25	14.05
Median		56.55	7.95	19.83

3.2. Herbaceous

There were significant differences in bulk density (H = 51.05, df = 9, $p < 0.001$; Table 1). Therefore, the height was used as a predictor in the nonlinear regression.

An exponential regression equation was used to predict the mass based on the volume and height (residual standard error (RSE) = 0.00911; Figure 4). The estimates for the nonlinear regression coefficients can be found in Table 2. The prediction vs. the actual plot showed a positive correlation between the predicted and observed data ($F(1,46) = 142.5$, $p < 0.001$, $R^2 = 0.75$; Figure 3).

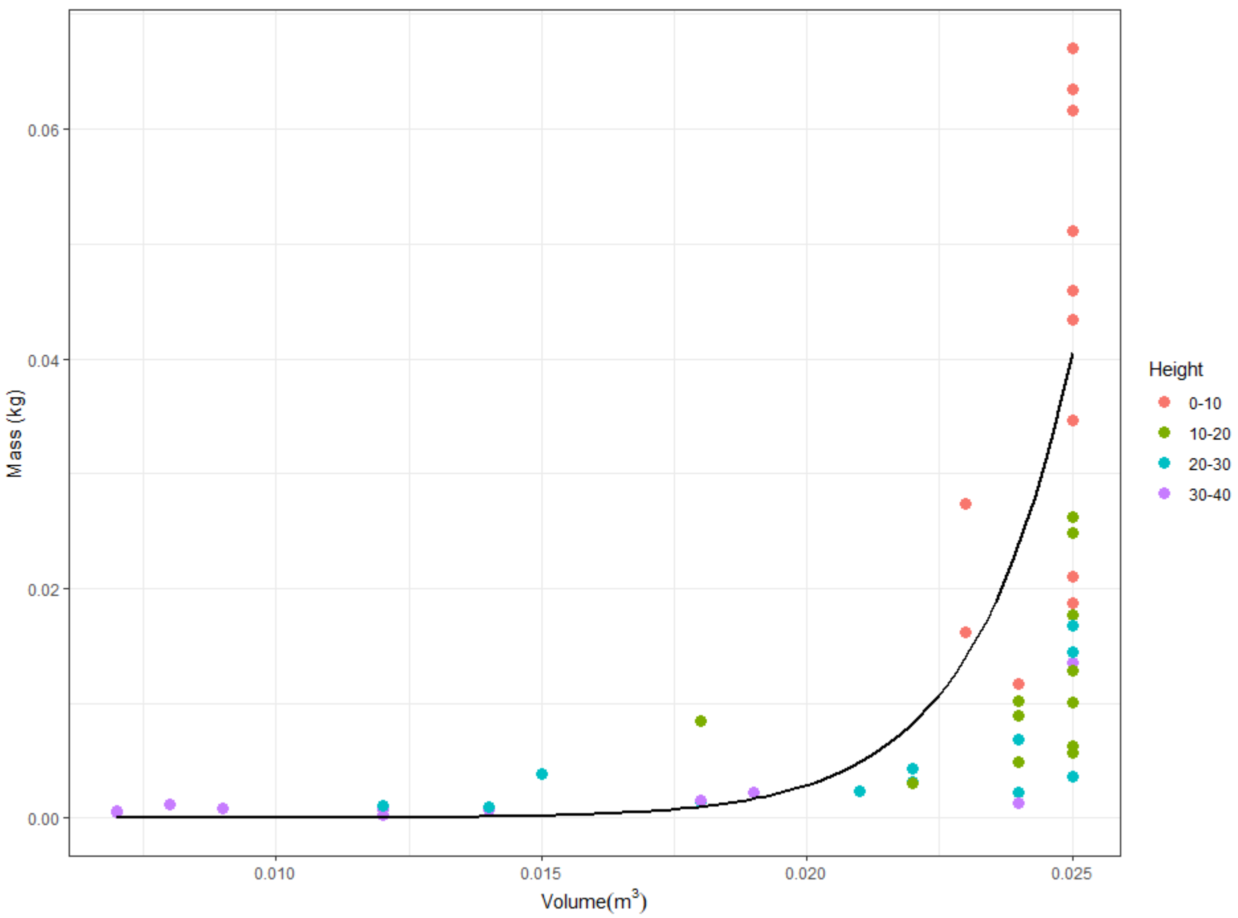

Figure 4. Exponential, nonlinear regression for herbaceous fuel material with both volume and height as predictors of mass. Only mass and volume observations associated with the strata between 0 and 70 cm were included. Using this equation, loading was calculated for each plot pre-fire using the voxelized volume and height (Figure 3). The median (±IQR) fuel consumption was 56.55 ± 10.52 g (Table 3). For the paired plots, the median (±IQR) fuel consumption was 68.41 ± 22.74 g (Table 3).

3.3. Woody Litter

There were significant differences in bulk density (W= 88.05, p = 0.0011; Table 1) between two height increments (0–10 cm and 10–20 cm). Therefore, the height was used as a predictor in the nonlinear regression.

An exponential regression equation was used to predict the mass based on the volume and height (RSE = 0.01229; Figure 5). The estimates for the nonlinear regression coefficients can be found in Table 2. The prediction vs. the actual plot showed a positive correlation between the predicted and observed data ($F(1,18) = 72.57$, $p < 0.001$, $R^2 = 0.79$; Figure 3).

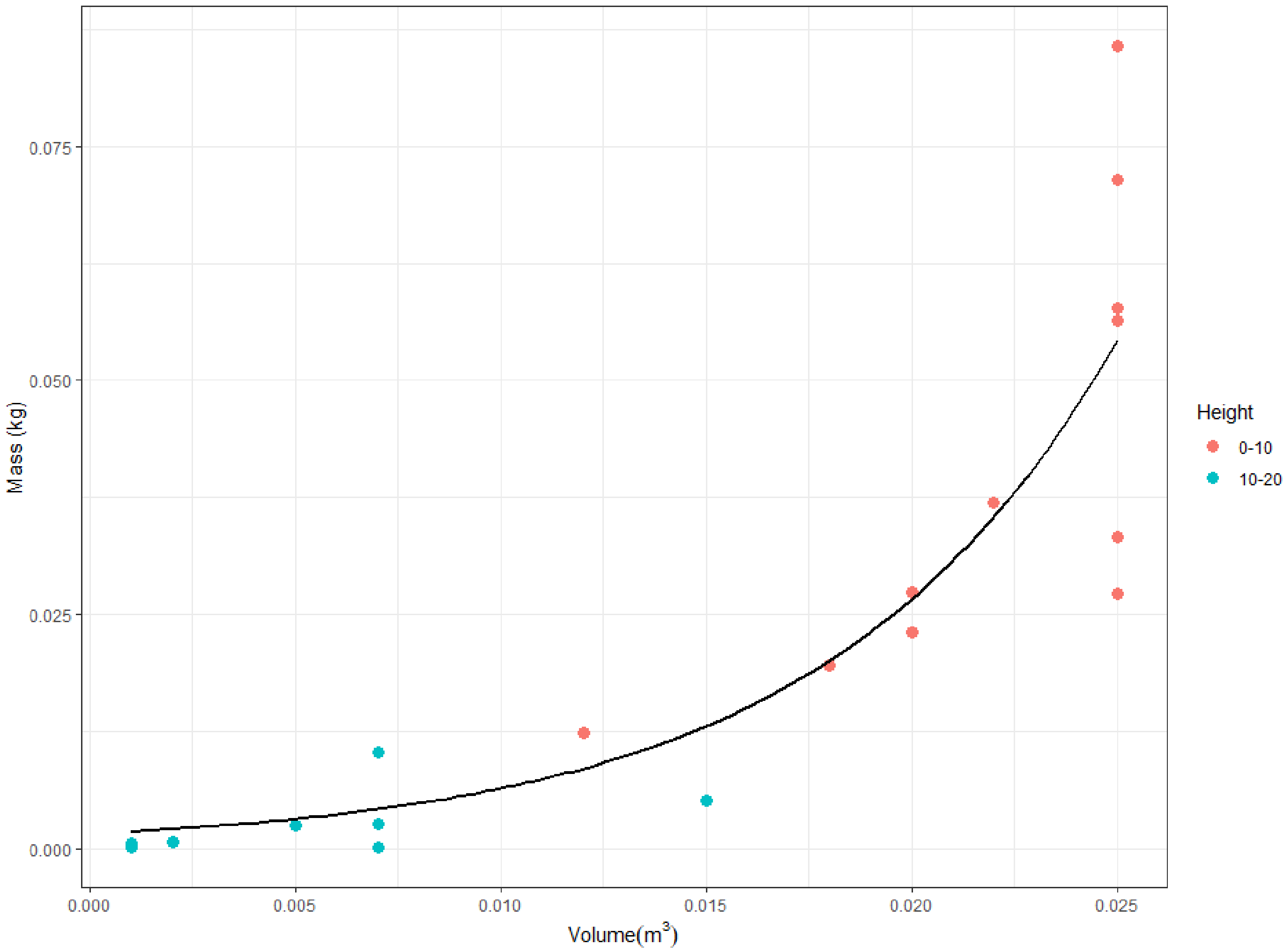

Figure 5. Exponential, nonlinear regression for woody litter fuel material with both volume and height as predictors of mass. Only mass and volume observations associated with the strata between 0 and 20 cm were included. Using this equation, loading was calculated for each plot pre-fire using both the voxelized volume and height (Figure 3). The median (±IQR) fuel consumption was 19.83 ± 4.01 g (Table 3). For the paired plots, the median (±IQR) fuel consumption was 20.83 ± 4.53 g (Table 3).

4. Discussion

This study illustrates an effective way to calculate biomass across vertical volume distributions and fuel types at the scales required to characterize complex fuelbeds common in low-intensity fires that shape many frequently burned ecosystems. There were distinct volume-to-mass relationships among these three common fuel types—live woody material, herbaceous material, and woody litter—that have, in the past, mainly been represented as average stand-level mass and bulk density values [31]. These results indicate that the height distribution of mass was significant for the herbaceous and woody litter fuel types, but not for live woody material (Table 1). This vertical evenness of bulk density for live woody material is consistent with previous work characterizing shrubs of similar (<1 m) stature [22]. However, the bulk density of herbaceous fuel varied, particularly in the 0–30 cm height range.

Wiregrass, the dominant herbaceous component in this ecosystem, has a dense crown closer to the forest floor and accumulates senesced material around the crown [40–42]. Given that these plots had two years of growth since the last fire and a long history of frequent fire (40 years) [39], our results corroborated that the crown was dense enough to have a different bulk density than the upper portions of the plant [42]. As such, applying a height metric for herbaceous fuel estimates is required to accurately represent the vertical distribution of a major component of the fuelbed.

While woody litter was present in multiple strata, most of the mass (>99%) was found in the first two strata (0–10 cm and 10–20 cm). In longleaf pine ecosystems, leaf litter in general often becomes suspended in wiregrass and shrubs [43]. It increases the vertical heterogeneity of the fuel bed [17] while also influencing fire behavior [19]. We showed that this suspended litter is less compact (1.35 kg/m^3 in the 0–10 cm layer vs. 0.38 kg/m^3 in the 10–20 cm layer), and in combination with the fact that it dries out quicker than the litter layer found near mineral soil, this vertical variability within the herbaceous fuels is important to consider in fuelbed dynamics [37]. These distinctions of mass distribution between and within fuel types contribute to the heterogeneity of fine-scale fuels found in these ecosystems, which have not been examined in this detail before.

These fine-scale bulk density estimations could provide a common link between ecosystems with similar fuel components. For instance, the structure and size of mature wiregrass (bunchgrass) tussocks are similar among southern pine ecosystems when present. Still, their growth rates, particularly after a fire, and flowering are partially dependent on regional climate and soil characteristics, at the site or stand level, by history of land use, fire, and soil disturbance, and continuously by competition with the overstory and midstory [44]. However, the bulk density of these mature individuals at the 1000 cm^3 scale is likely very similar among these sites and could be represented using these equations.

This study provides predictions on how biomass varies with fuel type, the volume occupied, and the height within the surface fuel layer, which can be used in fire behavior and fire effects studies that evaluate change in plant structure, mortality, reproduction, and composition patterns as well as fuel consumption at the same fine scale. In particular, when used in conjunction with fire, it is desirable to follow a plot from pre-fire levels of mass and vegetation composition to post-fire values. However, as pre-fire mass and fuel consumption have been notoriously difficult to measure directly [7,14,45], we developed a robust approach where volume and fuel type can be measured beforehand without destructive sampling and then link that to paired pre-fire plots of similar fuel types that were clipped, dried, and weighed. However, these results may only be paramount in respect to ecosystems that are depend on low-intensity, frequent surface fires.

Fuel consumption was then calculated by estimating pre-fire biomass with occupied volume using our linear and nonlinear regressions. Although a vastly different methodology from traditional methods, they both resulted in similar average fuel consumption for all but live woody material (Table 3). For the live woody material, one of the shrub plots did not burn well (Figure 6) and had an abnormally large amount of live biomass pre-fire (compared to the other shrub plots), resulting in an underestimation of mass. As noted earlier, this patchiness is common in these low-intensity fires where variability in consumption creates different sizes of shrubs within and across stands. A larger sample size with more varying shrubs sizes could provide more robust comparisons of average live woody consumption to the paired plots. Although our regressions were significant, a larger sample size could enhance the accuracy of the regressions and strength of the mass predictions. Future studies could expand mass and volume ranges across these and other fuel types, and in other frequently burned systems to increase their applicability. In the end, these regressions could be used to estimate biomass pre-fire more accurately and precisely without requiring destructive sampling, particularly in frequently burned southeastern U.S. pinelands.

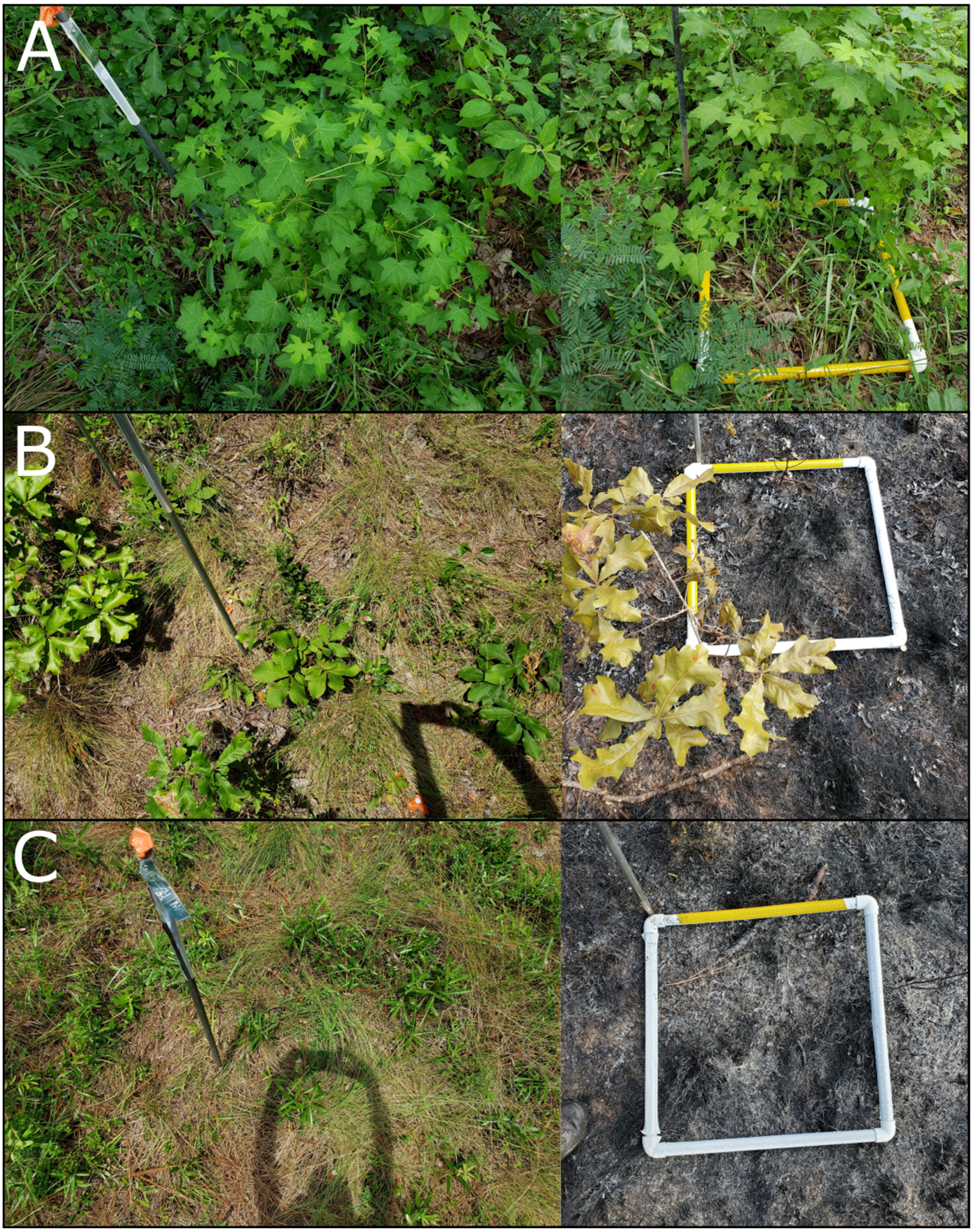

Figure 6. Fuel consumption in three plots. Photos on the left show pre-burn fuel and photos on the right show fuel remaining post-burn. (**A**) is a plot with no fuel consumption, (**B**) is a plot with moderate consumption, and (**C**) is a plot with complete consumption.

Volume in our sampling design is generalized down to the 1000 cm^3 or 0.001 m^3 scale. This is a substantial improvement considering that historically in order to estimate fuel volume, individual plants were represented as spheres and cylinders [46]. These oversimplified shapes greatly overestimate the actual volume [18], and by extension, greatly underestimate the bulk density. Furthermore, our method was likely the smallest realistic volume that can be measured by hand in the field. These fine-scale volume estimations are currently the best field method to categorize these fine, heterogeneous fuels.

One can obtain similar or even finer scale volumetric data from more precise methods, such as terrestrial-laser scanning (TLS), and pair these with our biomass collections. While TLS can provide the continuous fine-scale 3D structural data across a larger area [47], 3D manual sampling is still required to differentiate between interwoven fuel types and measure certain fuel aspects. These include fuel type distribution, mass, ground fuels such as compacted leaf litter and partially decomposed organic material [45]. In addition, the fine-scale volume from TLS has been successfully linked to laboratory and field measurements of biomass and leaf area [7,8,18]. Anecdotally, the difficulty with linking the two lies with achieving precise co-location and error associated with vegetation change or movement between data acquisition of each method caused by wind, fuel moisture, solar heating, and response to clipping as you move down the sampling frame. Additionally, TLS requires technology that may not be readily available and requires involved training, expertise, and processing skills. In comparison, the 3D fuels sampling protocol is inexpensive, follows similar presence/absence sampling protocols as other fuels methods, is adaptable across ecosystems, and accurately captures the fine-scale distribution of fuels, particularly biomass. In the end, this is the first known study to predict fine-scale fuel consumption of interwoven fuel types.

Previously, fine-scale homogeneity has been assumed because fuel load and fuel characterization methods were developed with coarse scale landscape processes in mind [16]. This study's 3D fuels methodology [27] used in recent studies [8,34] reveals the heterogeneity of the very same surface fuels that drive surface fire behavior and fire effects at the same scale [2,17,19,29]. These fine-scale studies have implications at broader scales by representing fine-scale bulk density and consumption estimates across a stand based on the known distribution of fuel types rather than average values.

5. Conclusions

This study is the first to evaluate bulk density estimations by only using field-based methods at such a fine scale. The predictions of mass across 10-cm height increments of fuel types illustrate the complex vertical heterogeneity in bulk density that varies at these fine scales. The results of this study could increase the accuracy of pre-fire biomass and fuel consumption estimates and reduce the need for destructive approaches of pre- and post-fire plot pairing of "similar" fuel types. Investigating bulk density, the interaction between volume, biomass, and height, is imperative to predicting fine-scale fuel consumption that can have implications for stand and landscape-level characterization of fuels and predictions of fire behavior and fire effects. These kinds of measurements will also be critical for refining inputs for coupled fire-atmosphere fire behavior models [3,4,15].

Author Contributions: This study was conceived and designed by E.L.L., C.M.H. (Christie M. Hawley), C.M.H. (Chad M. Hoffman), J.K.H., S.P. and J.J.O. The experiment was established by E.L.L. and C.M.H. (Christie M. Hawley). Field data collected by C.M.H. (Christie M. Hawley), Q.A.H. and E.L.L., and lab data was processed by C.M.H. (Christie M. Hawley) and Q.A.H. Q.A.H. conducted all statistical analyses, and Q.A.H. and E.L.L. wrote significant portions of the paper. All authors provided critical input and feedback on the research, analyses, and manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: Strategic Environmental Research and Development Program RC19-1119.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the Appendix A, Table A1.

Acknowledgments: Thanks to Pebble Hill Plantation, Tall Timbers Fire Ecology Program, and Kevin Robertson, whose long-term study site was made available for this work. We thank several for field and laboratory technical support, including D. Wallace, L. Stiles, N. Spencer, M. Johnson, M. Nolasco, and A. Wilson from Tall Timbers Research Station as well as C. Beasley, A. Coates, and A. McClure from Virginia Polytechnic Institute and State University. We acknowledge the USDA Forest Service, Southern Research Station, the Center for Forest Disturbance Science and the Athens Fire Lab, Athens, GA, for their support.

Conflicts of Interest: The authors declare that there is no conflict of interest.

Appendix A

Plot #:________________ Collectors:____ Date:________________

Voxel	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	Height:
10 hour fuel																										10-20 cm
100-1000 hr fuel																										
Pine Litter																										Random
Pine Needles																										Voxels:
Wiregrass/Bunchgrass																										
Other Graminoids																										
Forbs (and Forb Litter)																										
Vines (and Vine Litter)																										
Woody Species (Live) (O, N, B)																										
Woody Species (Leaves/Litter) (O, N, B)																										
Woody Species (Dead, Standing)																										
Other (state)																										
Empty Voxel																										
Voxel	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**Height:**
10 hour fuel																										0-10 cm
100-1000 hr fuel																										
Pine Litter																										
Pine Needles																										
Wiregrass/Bunchgrass																										
Other Graminoids																										
Forbs (and Forb Litter)																										
Vines (and Vine Litter)																										
Woody Species (Live) (O, N, B)																										
Woody Species (Leaves/Litter) (O, N, B)																										
Woody Species (Dead, Standing)																										
Other (state)																										
Empty Voxel																										
Fuel Height (0-10 stratum only)																										

Notes:____

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Plot No:________________ Collectors:____ Date:________________

Figure A1. Example of data sheet used to collect voxel data for fuel types. Wiregrass/Bunchgrass, Other Graminoids, Forbs, and Vines were aggregated into the herbaceous fuel category. Woody Species (Leaves/Litter) represented the woody litter category. Woody Species (Live) represented the live woody category.

Table A1. Data used in this study. Burn Number represents which arbitrary burn unit was sampled while Plot represents an individual clip plot in each burn unit. The "Pre" preceding the plot number indicates a Preburn plot while "Post" preceding the plot number represents a Postburn plot. The number in Plot represents paired plots. For example, within the same Burn Number, Pre2 and Post2 are paired plots. Burn Status describes when the data was taken, where Pre = before burn and Post = after burn. Therefore, Mass and Volume were collected before the burn for every preburn plot. While mass was only recorded after the burn for postburn plots, volume was recorded both before and after the burn. Height describes at which height stratum the data was collected. For Mass and Volume, H = Herbaceous, LW = Live Woody, and WL = Woody Litter. Further descriptions of the methodology are in the main text.

Burn Number	Plot	Burn Status	Height	H Mass (g)	H Volume (m^3)	LW Mass (g)	LW Volume (m^3)	WL Mass (g)	WL Volume (m^3)
1	Pre1	Pre	0–10	18.7	0.025	7.45	0.012	36.93	0.022
1	Pre1	Pre	10–20	4.92	0.024	15.64	0.016	0.07	0.007
1	Pre1	Pre	20–30	2.38	0.021	21.28	0.012	0	0.003
1	Pre1	Pre	30–40	1.09	0.012	18.41	0.011	0	0
1	Pre1	Pre	40–50	0.32	0.01	24.77	0.018	0	0
1	Pre1	Pre	50–60	0.08	0.003	17.18	0.015	0	0
1	Pre1	Pre	60–70	0	0	9.13	0.006	0	0
1	Pre1	Pre	70–80	0	0	14.55	0.008	0	0
1	Pre1	Pre	80–90	0	0	5.82	0.008	0	0
1	Pre1	Pre	90–100	0	0	17.03	0.014	0	0
1	Pre2	Pre	0–10	67.07	0.025	12.41	0.006	19.53	0.018
1	Pre2	Pre	10–20	6.28	0.025	7.66	0.013	2.59	0.007
1	Pre2	Pre	20–30	1.45	0.018	1.45	0.009	0	0
1	Pre2	Pre	30–40	0.23	0.012	0	0	0	0
1	Pre2	Pre	40–50	0	0	0	0	0	0
1	Pre2	Pre	50–60	0	0	0	0	0	0
1	Pre2	Pre	60–70	0	0	0	0	0	0
1	Pre2	Pre	70–80	0	0	0	0	0	0
1	Pre2	Pre	80–90	0	0	0	0	0	0
1	Pre2	Pre	90–100	0	0	0	0	0	0
1	Pre3	Pre	0–10	61.68	0.025	6.29	0.001	27.33	0.02
1	Pre3	Pre	10–20	26.24	0.025	10.49	0.005	0.61	0
1	Pre3	Pre	20–30	6.79	0.024	11.08	0.011	0	0
1	Pre3	Pre	30–40	2.19	0.019	5.01	0.011	0	0
1	Pre3	Pre	40–50	1.13	0.019	8.57	0.008	0.23	0.002
1	Pre3	Pre	50–60	0.25	0.007	5.37	0.01	0	0.002
1	Pre3	Pre	60–70	0.09	0.003	6.9	0.01	0	0
1	Pre3	Pre	70–80	0	0	0.93	0.005	0	0
1	Pre3	Pre	80–90	0	0	0	0	0	0
1	Pre3	Pre	90–100	0	0	0	0	0	0
1	Pre4	Pre	0–10	34.64	0.025	8.38	0.008	23.13	0.02
1	Pre4	Pre	10–20	17.73	0.025	5.18	0.009	0.12	0.001
1	Pre4	Pre	20–30	16.73	0.025	7.89	0.012	0	0
1	Pre4	Pre	30–40	13.55	0.025	9.18	0.016	0	0
1	Pre4	Pre	40–50	8.88	0.025	16.27	0.02	0	0

Table A1. *Cont.*

Burn Number	Plot	Burn Status	Height	H Mass (g)	H Volume (m^3)	LW Mass (g)	LW Volume (m^3)	WL Mass (g)	WL Volume (m^3)
1	Pre4	Pre	50–60	3.56	0.025	11.41	0.014	0	0
1	Pre4	Pre	60–70	0.46	0.017	2.44	0.01	0	0
1	Pre4	Pre	70–80	0	0	0	0	0	0
1	Pre4	Pre	80–90	0	0	0	0	0	0
1	Pre4	Pre	90–100	0	0	0	0	0	0
1	Pre5	Pre	0–10	63.53	0.025	10.68	0.01	27.26	0.025
1	Pre5	Pre	10–20	10.1	0.025	8.45	0.02	0.78	0.002
1	Pre5	Pre	20–30	2.18	0.024	8.53	0.016	0	0
1	Pre5	Pre	30–40	0.55	0.007	1.35	0.008	0	0
1	Pre5	Pre	40–50	3.27	0.008	0	0	0	0
1	Pre5	Pre	50–60	0.01	0.003	0	0	0	0
1	Pre5	Pre	60–70	0	0	0	0	0	0
1	Pre5	Pre	70–80	0	0	0	0	0	0
1	Pre5	Pre	80–90	0	0	0	0	0	0
1	Pre5	Pre	90–100	0	0	0	0	0	0
1	Pre6	Pre	0–10	45.93	0.025	6.46	0.001	12.38	0.012
1	Pre6	Pre	10–20	12.83	0.025	6.41	0.005	5.13	0.015
1	Pre6	Pre	20–30	3.67	0.025	10.8	0.015	0	0
1	Pre6	Pre	30–40	0.79	0.014	8.13	0.009	0	0
1	Pre6	Pre	40–50	0.29	0.01	8.64	0.009	0	0
1	Pre6	Pre	50–60	0.05	0.001	8.33	0.014	0	0
1	Pre6	Pre	60–70	0	0	0.94	0.002	0	0
1	Pre6	Pre	70–80	0	0	0	0	0	0
1	Pre6	Pre	80–90	0	0	0	0	0	0
1	Pre6	Pre	90–100	0	0	0	0	0	0
3	Pre1	Pre	0–10	51.09	0.025	0.64	0.002	0.53	0.001
3	Pre1	Pre	10–20	24.85	0.025	0.79	0.003	0	0
3	Pre1	Pre	20–30	14.43	0.025	0	0.001	0	0
3	Pre1	Pre	30–40	1.34	0.024	0	0	0	0
3	Pre1	Pre	40–50	0.17	0.015	0	0	0	0
3	Pre1	Pre	50–60	0	0	0	0	0	0
3	Pre1	Pre	60–70	0	0	0	0	0	0
3	Pre1	Pre	70–80	0	0	0	0	0	0
3	Pre1	Pre	80–90	0	0	0	0	0	0
3	Pre1	Pre	90–100	0	0	0	0	0	0
3	Pre2	Pre	0–10	43.36	0.025	8.73	0.009	85.73	0.025
3	Pre2	Pre	10–20	10.2	0.024	11.22	0.011	2.49	0.005
3	Pre2	Pre	20–30	4.31	0.022	14.65	0.016	0.34	0.002
3	Pre2	Pre	30–40	1.57	0.018	9.78	0.01	0	0
3	Pre2	Pre	40–50	0.87	0.01	8.5	0.011	0	0

Table A1. *Cont.*

Burn Number	Plot	Burn Status	Height	H Mass (g)	H Volume (m^3)	LW Mass (g)	LW Volume (m^3)	WL Mass (g)	WL Volume (m^3)
3	Pre2	Pre	50–60	2.09	0.007	11.25	0.021	0	0
3	Pre2	Pre	60–70	1.68	0.004	7.32	0.015	0	0
3	Pre2	Pre	70–80	0.75	0.004	5.45	0.013	0	0
3	Pre2	Pre	80–90	2.68	0.004	6.43	0.012	0	0
3	Pre2	Pre	90–100	3.18	0.008	7.58	0.014	0	0
3	Pre3	Pre	0–10	27.42	0.023	27.55	0.004	71.39	0.025
3	Pre3	Pre	10–20	8.44	0.018	9.2	0.003	10.27	0.007
3	Pre3	Pre	20–30	3.82	0.015	3.13	0.007	0	0
3	Pre3	Pre	30–40	1.15	0.008	2.13	0.002	0	0
3	Pre3	Pre	40–50	0.38	0.004	0	0	0	0
3	Pre3	Pre	50–60	0	0	0	0	0	0
3	Pre3	Pre	60–70	0	0	0	0	0	0
3	Pre3	Pre	70–80	0	0	0	0	0	0
3	Pre3	Pre	80–90	0	0	0	0	0	0
3	Pre3	Pre	90–100	0	0	0	0	0	0
3	Pre4	Pre	0–10	21.03	0.025	6.01	0.006	57.74	0.025
3	Pre4	Pre	10–20	5.71	0.025	11.55	0.012	0.6	0.001
3	Pre4	Pre	20–30	3.13	0.022	8.78	0.005	0	0
3	Pre4	Pre	30–40	0.74	0.012	14.09	0.017	0	0
3	Pre4	Pre	40–50	0.22	0.005	13.82	0.025	0	0
3	Pre4	Pre	50–60	0.2	0.002	15.35	0.023	0	0
3	Pre4	Pre	60–70	0.08	0.002	15.9	0.024	0	0
3	Pre4	Pre	70–80	0.07	0.001	12.79	0.024	0	0
3	Pre4	Pre	80–90	0	0	3.79	0.014	0	0
3	Pre4	Pre	90–100	0	0	1.97	0.007	0	0
3	Pre5	Pre	0–10	11.71	0.024	0	0.002	56.43	0.025
3	Pre5	Pre	10–20	8.98	0.024	4.37	0.003	0	0
3	Pre5	Pre	20–30	1.13	0.012	4.66	0.005	0	0
3	Pre5	Pre	30–40	0.82	0.009	10.67	0.02	0	0
3	Pre5	Pre	40–50	0.44	0.008	10.14	0.016	0	0
3	Pre5	Pre	50–60	0.32	0.006	8.98	0.018	0	0
3	Pre5	Pre	60–70	0.2	0.005	8.64	0.014	0	0
3	Pre5	Pre	70–80	0	0	0	0	0	0
3	Pre5	Pre	80–90	0	0	0	0	0	0
3	Pre5	Pre	90–100	0	0	0	0	0	0
3	Pre6	Pre	0–10	16.14	0.023	13.07	0.014	33.3	0.025
3	Pre6	Pre	10–20	3.05	0.022	11.43	0.017	0	0.001
3	Pre6	Pre	20–30	1.02	0.014	14.29	0.017	0.15	0
3	Pre6	Pre	30–40	0.65	0.007	23.2	0.025	0	0
3	Pre6	Pre	40–50	0.64	0.009	13.11	0.023	0	0

Table A1. *Cont.*

Burn Number	Plot	Burn Status	Height	H Mass (g)	H Volume (m^3)	LW Mass (g)	LW Volume (m^3)	WL Mass (g)	WL Volume (m^3)
3	Pre6	Pre	50–60	0	0.005	0	0	0	0
3	Pre6	Pre	60–70	0.06	0.004	0	0	0	0
3	Pre6	Pre	70–80	0	0	0	0	0	0
3	Pre6	Pre	80–90	0	0	0	0	0	0
3	Pre6	Pre	90–100	0	0	0	0	0	0
1	Post1	Post	0–10	1.01	0.009	22.52	0.004	8.13	0.011
1	Post1	Post	10–20	0.19	0.002	17.78	0.004	0	0
1	Post1	Post	20–30	0	0	16.86	0.009	0	0
1	Post1	Post	30–40	0	0	20.09	0.019	0	0
1	Post1	Post	40–50	0	0	16.79	0.014	0	0
1	Post1	Post	50–60	0	0	18.85	0.011	0	0
1	Post1	Post	60–70	0	0	11.53	0.006	0	0
1	Post1	Post	70–80	0	0	9.6	0.008	0	0
1	Post1	Post	80–90	0	0	18.38	0.01	0	0
1	Post1	Post	90–100	0	0	26.43	0.023	0	0
1	Post2	Post	0–10	0.91	0.009	2.31	0.003	2.23	0
1	Post2	Post	10–20	0.17	0.001	4.76	0.003	0	0
1	Post2	Post	20–30	0.02	0.002	6.24	0.006	0	0
1	Post2	Post	30–40	0	0	2.33	0.003	0	0
1	Post2	Post	40–50	0	0	0	0	0	0
1	Post2	Post	50–60	0	0	0	0	0	0
1	Post2	Post	60–70	0	0	0	0	0	0
1	Post2	Post	70–80	0	0	0	0	0	0
1	Post2	Post	80–90	0	0	0	0	0	0
1	Post2	Post	90–100	0	0	0	0	0	0
1	Post3	Post	0–10	5.24	0.022	2.39	0.003	6.17	0.025
1	Post3	Post	10–20	1.81	0.008	2.99	0.004	0	0
1	Post3	Post	20–30	0.8	0.006	2.39	0.003	0	0
1	Post3	Post	30–40	0.26	0.002	5.85	0.006	0	0
1	Post3	Post	40–50	0	0	16.15	0.013	0	0
1	Post3	Post	50–60	0	0	4.13	0.009	0	0
1	Post3	Post	60–70	0	0	3.38	0.007	0	0
1	Post3	Post	70–80	0	0	0	0	0	0
1	Post3	Post	80–90	0	0	0	0	0	0
1	Post3	Post	90–100	0	0	0	0	0	0
1	Post6	Post	0–10	0.76	0.013	5.28	0.004	1.19	0.004
1	Post6	Post	10–20	0	0.008	5.44	0.003	0	0
1	Post6	Post	20–30	0	0	2.25	0.001	0	0
1	Post6	Post	30–40	0	0	2.86	0.002	0	0
1	Post6	Post	40–50	0	0	2.46	0.006	0	0

Table A1. *Cont.*

Burn Number	Plot	Burn Status	Height	H Mass (g)	H Volume (m^3)	LW Mass (g)	LW Volume (m^3)	WL Mass (g)	WL Volume (m^3)
1	Post6	Post	50–60	0	0	0.99	0.005	0	0
1	Post6	Post	60–70	0	0	0	0	0	0
1	Post6	Post	70–80	0	0	0	0	0	0
1	Post6	Post	80–90	0	0	0	0	0	0
1	Post6	Post	90–100	0	0	0	0	0	0
1	Post1	Pre	0–10	NA	0.025	NA	0.016	NA	0.022
1	Post1	Pre	10–20	NA	0.023	NA	0.022	NA	0
1	Post1	Pre	20–30	NA	0.011	NA	0.014	NA	0
1	Post1	Pre	30–40	NA	0.002	NA	0.014	NA	0
1	Post1	Pre	40–50	NA	0	NA	0.014	NA	0
1	Post1	Pre	50–60	NA	0	NA	0.013	NA	0
1	Post1	Pre	60–70	NA	0	NA	0.009	NA	0
1	Post1	Pre	70–80	NA	0	NA	0.009	NA	0
1	Post1	Pre	80–90	NA	0	NA	0.007	NA	0
1	Post1	Pre	90–100	NA	0	NA	0.019	NA	0
1	Post2	Pre	0–10	NA	0.025	NA	0.002	NA	0.017
1	Post2	Pre	10–20	NA	0.024	NA	0.007	NA	0.005
1	Post2	Pre	20–30	NA	0.024	NA	0.008	NA	0.001
1	Post2	Pre	30–40	NA	0.02	NA	0.007	NA	0
1	Post2	Pre	40–50	NA	0.009	NA	0.001	NA	0
1	Post2	Pre	50–60	NA	0.001	NA	0.002	NA	0
1	Post2	Pre	60–70	NA	0	NA	0	NA	0
1	Post2	Pre	70–80	NA	0	NA	0	NA	0
1	Post2	Pre	80–90	NA	0	NA	0	NA	0
1	Post2	Pre	90–100	NA	0	NA	0	NA	0
1	Post3	Pre	0–10	NA	0.025	NA	0.003	NA	0.008
1	Post3	Pre	10–20	NA	0.025	NA	0.003	NA	0.007
1	Post3	Pre	20–30	NA	0.024	NA	0.001	NA	0.004
1	Post3	Pre	30–40	NA	0.012	NA	0.008	NA	0.004
1	Post3	Pre	40–50	NA	0.006	NA	0.007	NA	0.001
1	Post3	Pre	50–60	NA	0	NA	0.01	NA	0
1	Post3	Pre	60–70	NA	0	NA	0.006	NA	0
1	Post3	Pre	70–80	NA	0	NA	0	NA	0
1	Post3	Pre	80–90	NA	0	NA	0	NA	0
1	Post3	Pre	90–100	NA	0	NA	0	NA	0
1	Post6	Pre	0–10	NA	0.025	NA	0.001	NA	0.021
1	Post6	Pre	10–20	NA	0.025	NA	0.001	NA	0.008
1	Post6	Pre	20–30	NA	0.024	NA	0.003	NA	0.001
1	Post6	Pre	30–40	NA	0.023	NA	0.007	NA	0
1	Post6	Pre	40–50	NA	0.014	NA	0.022	NA	0

Table A1. *Cont.*

Burn Number	Plot	Burn Status	Height	H Mass (g)	H Volume (m^3)	LW Mass (g)	LW Volume (m^3)	WL Mass (g)	WL Volume (m^3)
1	Post6	Pre	50–60	NA	0.005	NA	0.019	NA	0
1	Post6	Pre	60–70	NA	0.001	NA	0.005	NA	0
1	Post6	Pre	70–80	NA	0	NA	0	NA	0
1	Post6	Pre	80–90	NA	0	NA	0	NA	0
1	Post6	Pre	90–100	NA	0	NA	0	NA	0

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