

Article

Smoke Emissions and Buoyant Plumes above Prescribed Burns in the Pinelands National Reserve, New Jersey

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Abstract: Prescribed burning is a cost-effective method for reducing hazardous fuels in pine- and oak-dominated forests, but smoke emissions contribute to atmospheric pollutant loads, and the potential exists for exceeding federal air quality standards designed to protect human health. Fire behavior during prescribed burns influences above-canopy sensible heat flux and turbulent kinetic energy (TKE) in buoyant plumes, affecting the lofting and dispersion of smoke. A more comprehensive understanding of how enhanced energy fluxes and turbulence are related during the passage of flame fronts could improve efforts to mitigate the impacts of smoke emissions. Pre- and post-fire fuel loading measurements taken during 48 operational prescribed burns were used to estimate the combustion completeness factors (CC) and emissions of fine particulates (PM_{2.5}), carbon dioxide (CO₂), and carbon monoxide (CO) in pine- and oak-dominated stands in the Pinelands National Reserve of southern New Jersey. During 11 of the prescribed burns, sensible heat flux and turbulence statistics were measured by tower networks above the forest canopy. Fire behavior when fire fronts passed the towers ranged from low-intensity backing fires to high-intensity head fires with some crown torching. Consumption of forest-floor and understory vegetation was a near-linear function of pre-burn loading, and combustion of fine litter on the forest floor was the predominant source of emissions, even during head fires with some crowning activity. Tower measurements indicated that above-canopy sensible heat flux and TKE calculated at 1 min intervals during the passage of fire fronts were strongly influenced by fire behavior. Low-intensity backing fires, regardless of forest type, had weaker enhancement of above-canopy air temperature, vertical and horizontal wind velocities, sensible heat fluxes, and TKE compared to higher-intensity head and flanking fires. Sensible heat flux and TKE in buoyant plumes were unrelated during low-intensity burns but more tightly coupled during higher-intensity burns. The weak coupling during low-intensity backing fires resulted in reduced rates of smoke transport and dispersion, and likely in more prolonged periods of elevated surface concentrations. This research facilitates more accurate estimates of PM_{2.5}, CO, and CO₂ emissions from prescribed burns in the Pinelands, and it provides a better understanding of the relationships among fire behavior, sensible heat fluxes and turbulence, and smoke dispersion in pine- and oak-dominated forests.

Keywords: prescribed burning; PM_{2.5}; wildland fire emissions; air quality; available fuels; fuel consumption; emission factors



Citation: Clark, K.L.; Gallagher, M.R.; Skowronski, N.; Heilman, W.E.; Charney, J.; Patterson, M.; Cole, J.; Mueller, E.; Hadden, R. Smoke Emissions and Buoyant Plumes above Prescribed Burns in the Pinelands National Reserve, New Jersey. *Fire* **2024**, *7*, 330. <https://doi.org/10.3390/fire7090330>

Academic Editor: Grant Williamson

Received: 17 July 2024

Revised: 11 September 2024

Accepted: 18 September 2024

Published: 21 September 2024



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1. Introduction

Prescribed burning is one of the most cost-effective methods for mitigating the impact of wildfires because it consumes fine and woody fuels on the forest floor, influencing surface fire behavior, and reduces dense understory and sub-canopy vegetation, which can facilitate the transition of surface fires to the canopy [1–4]. Prescribed burning can also alter the trajectory of vegetation changes in forests, affecting fuel types and structure, and influencing longer-term wildfire behavior. In forests of the mid-Atlantic region, USA, the use of prescribed burning to maintain and enhance fire-adapted ecosystems dominated by pines and oaks is well documented [5–8]. By modifying the forest structure, composition, and ecosystem functioning, prescribed burns can also enhance forests' resilience to other disturbances such as insect infestations [9], contribute to the recovery of forest productivity in insect-damaged stands [10], and decrease tick populations and reduce the incidence of tick-borne disease transmission to humans [11]. However, smoke emissions from prescribed burns contribute to atmospheric pollutant loads and the degradation of local–regional air quality, and they impair public health and safety. Emissions from wildland fires contain fine particulate matter <2.5 μm diameter ($\text{PM}_{2.5}$), carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic carbon compounds, which contribute to the formation of surface-level ozone (O_3) [4,12–14]. When prescribed burns are conducted near residential communities, urban centers, or non-attainment areas, the potential exists for exceeding the US Clean Air Act's National Ambient Air Quality Standards (NAAQS) for regulated pollutants [15,16]. In addition, impairment of visibility on roads and highways by smoke is a significant safety hazard [17].

Smoke dispersion on the relatively level forested landscapes of the mid-Atlantic coastal plain is strongly influenced by atmospheric conditions (including sea breeze fronts), and some constraints to atmospheric stability and related meteorological conditions are dictated by prescription to appropriate burn days [New Jersey Forest Fire Service, pers. com.]. When appropriate conditions do occur, understanding how fire behavior affects the lofting and dispersion of smoke can be essential for mitigating the impacts of prescribed burning on public health and safety in nearby communities, as well as on fire management personnel. During the passage of fire fronts, turbulent mixing of heat, momentum, $\text{PM}_{2.5}$, and other components of smoke is dependent on the distribution of energy among vertical and horizontal components of the turbulent kinetic energy (TKE) field [18–20]. Research efforts have documented patterns of TKE and canopy–atmosphere coupling within and above forest canopies as being influenced by relatively low-intensity prescribed burns, and they have demonstrated that TKE in buoyant plumes is often much greater near or immediately above the top of the canopy compared to near the surface and in mid-canopy locations [18,20–23]. TKE is typically anisotropic, and although buoyant plumes can strongly enhance vertical wind velocity fluctuations at the top of the canopy, horizontal components of TKE are often much greater than vertical components during fire front passage [19,21–23]. Enhanced turbulence during fire front passage results in greater rates of smoke transport through the canopy and dispersion into the atmospheric boundary layer, reducing surface concentrations rapidly [24,25].

Fire behavior and fireline intensity control the production rate and near-fire dynamics of buoyant plumes, influencing TKE, canopy–atmosphere coupling, and the dispersion of smoke. Sensible heat flux in buoyant plumes is the main pathway for the dissipation of convective energy generated by combustion [26,27]. However, it has been quantified less frequently during operational prescribed burns, and the linkages among fire behavior, sensible heat flux, and TKE within and above the canopy during prescribed burns of varying intensity have been investigated in fewer studies [18,19,28–31]. Repeated fireline measurements in stands of similar structure and pre-burn fuel loading but contrasting fire behaviors could aid in developing the concept of “escape velocities” for smoke as a function of fire behavior and convective (sensible) heat fluxes during prescribed burns, but this approach has been explored and refined in only a limited number of forests.

The nearly continuous fire-adapted forests of the Pinelands National Reserve in southern New Jersey (hereafter “Pinelands”) are a major concern for the New Jersey Forest Fire Service (NJFFS) and federal wildland fire managers [32,33]. Forests dominated by pitch pine (*Pinus rigida* Mill.) in this region have some of the highest incidences of wildfires in the Northeastern US, and they are located adjacent to large suburban residential developments, commercial property, and transportation corridors. To reduce the impact of wildfires on property and infrastructure within and along the margins of the Pinelands, numerous stands have been treated using prescribed fires, often at 5- to 8-year intervals, and many since the late 1950s [32]. Remotely sensed measurements of fuel density and loading in the canopy and understory of forests in the Pinelands demonstrate the effectiveness of prescribed burns in altering forest structure and reducing ladder fuels in the sub-canopy and understory [2,34,35]. However, prescribed burns typically consume large amounts of fine litter and small-diameter woody fuels on the forest floor, indicating that surface fuels are a major contributor to the emissions of PM_{2.5}, carbon dioxide (CO₂), CO, and other pollutants [3,30,36–39]. Fuels on the forest floor are not sampled as effectively using remotely sensing techniques, but integrating biometric measurements with remotely sensed LiDAR data can provide valuable information for state, federal, and private wildland fire managers regarding fuel consumption and smoke emissions. Studies of fireline heat flux and turbulence during prescribed burns in forested environments, coupled with accurate emission estimates, can also facilitate the development and evaluation of process-based simulation tools that predict smoke dispersion during wildland fires, e.g., [24,25,40].

Our objectives were (1) to provide accurate estimates of pre- and post-burn fuel loading and calculate appropriate combustion completeness factors for fine litter, small-diameter woody fuels, and understory vegetation in the Pinelands so that emissions of PM_{2.5}, CO, and CO₂ could be predicted accurately using pre-burn fuel loading estimates, and (2) to relate emission estimates to above-canopy sensible heat fluxes and turbulence statistics measured in buoyant plumes across a range of prescribed burns to provide a better understanding of how contrasting fire behavior potentially affects the lofting and dispersion of smoke.

2. Materials and Methods

2.1. Site Description

Our research sites were located in Burlington and Ocean Co. in the Pinelands National Reserve in southern New Jersey, USA. The Pinelands is the largest continuous forested landscape on the northeastern coastal plain. The climate is cool and temperate, with mean monthly temperatures of 0.3 and 23.8 °C in January and June, respectively (1990–2020; [41]). The mean annual precipitation is 1123 ± 182 mm. The soils are derived from the Cohansey and Kirkwood formations and are sandy, coarse-grained, and low in available nutrients [42].

Upland forests are the main focus of fuel management treatments in the Pinelands. These comprise approximately 62% of the forested areas in the Pinelands and are composed of three major forest communities: (1) pitch pine–scrub oak, dominated by pitch pine (*Pinus rigida* Mill.), with scattered post oak (*Q. stellata* Wangenh.) and white oak (*Q. alba* L.) in the overstory, and scrub oak (*Quercus ilicifolia* Wang.) and blackjack oak (*Q. marlandica* Muechh.) in the understory; (2) mixed pine–oak, consisting of pitch and shortleaf pine (*P. echinata* Mill.), with mixed oaks in the overstory; and (3) oak–pine, consisting of chestnut oak (*Quercus prinus* L.), white oak, black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), and scattered pitch and shortleaf pines [43–45] in the overstory. Most stands have ericaceous shrubs in the understory, primarily huckleberry (*Gaylussacia baccata* (Wang.) K. Koch, *G. frondosa* (L.) Torr. and *A. Gray* ex Torr.) and blueberry (*Vaccinium* spp.). Sedges (*Carex pensylvanica* Lam.), herbs, ferns, mosses, and lichens can also be present [46,47].

Most upland forest stands in the Pinelands have regenerated naturally following the cessation of logging and charcoaling activities in the late 1800s. Wildfires occur more frequently in pitch pine–scrub oak stands [5,48,49], and among mature upland forests of approximately the same age, the canopy height is lower and understory and sub-canopy

vegetation is typically denser in pine–scrub oak and pine–oak stands compared to oak-dominated stands [2,44]. In more mesic areas, forest composition has changed over time, with succession in combination with wildfire suppression favoring the regeneration of oaks and other mesic hardwoods in upland sites, and of red maple and black gum in lowland sites [50]. In contrast, oak mortality following extensive spongy moth infestations has encouraged pine regeneration in the understory and sub-canopy of heavily infested areas, resulting in mixed-composition stands [10].

The New Jersey Forest Fire Service (NJFFS), federal agencies, and private landowners in the Pinelands typically conduct prescribed burns on approximately 5000 ha to 10,000 ha of forest land per year. Over the last decade, the area burned in prescribed fires has exceeded that burned in wildfires twofold, with prescribed fires conducted on 63,721 ha and accounting for 66% of the total burned area of 98,000 ha from 2006 to 2015 [49]. Recent large wildfires include the Spring Hill fire (2019; 4710 ha) and the Mullica River fire (2022; 6070 ha).

2.2. Fuel Loading and Consumption Estimates

Fine litter and 1 h (<0.64 cm diameter), 10 h (≥ 0.64 to <2.54 cm diameter), and 100 h (≥ 2.54 to 7.60 cm diameter) woody fuels on the forest floor, along with herbs, shrubs, and understory oaks ≤ 2 m tall, were sampled in 48 stands located in Brendan T. Byrne State Forest, Greenwood and Stafford Wildlife Management Areas, Joint Base McGuire–Dix–Lakehurst (JBMDL), and Wharton State Forest in and adjacent to the Pinelands National Reserve. Sampled stands encompassed all three forest communities, although we focused our efforts on pitch pine–scrub oak and pine–oak stands. The pre-burn measurements consisted of 5 to 36 0.5 m² or 1.0 m² circular subplots located at random points within each stand. Understory vegetation was cut at ground level in each subplot, and then fine litter and small-diameter woody fuels in the litter layer (L horizon) were collected. The humus layer (O horizon), consisting of undifferentiated organic matter, was not collected, because it was rarely consumed during prescribed burns conducted during the typical prescribed burn window between early February and late March (NJFFS, pers. com). In the laboratory, samples were separated into foliage and live and dead 1 h, 10 h, and 100 h fuels, dried at 70 °C until dry, and then weighed.

Prescribed burns were conducted by federal wildland fire managers at JBMDL or New Jersey Forest Fire Service personnel (all other stands). All burns were conducted within the prescription window for prescribed burns in the Pinelands, with cool air temperatures (0 to 16 °C), relative humidity between 20% and 60%, and low-to-moderate mean ambient wind speeds (1 to 5 m s^{−1}). Following each burn, the stands were re-sampled for unconsumed understory stems, fine litter, and 1 h, 10 h, and 100 h woody fuels within two weeks of burning, using the same protocols as for pre-burn fuel sampling. On the days on which the instrumented prescribed burns were conducted, fire behavior was observed throughout each stand, and the fuel moisture contents of live foliage and stems, fine litter, and 1 h and 10 h woody fuels were estimated using samples collected and sealed in plastic bags, weighed wet, and then dried and weighed again (see [30] for detailed sampling protocols). The available canopy fuels in pitch pine canopies were estimated for the three high-intensity prescribed burns using pre- and post-burn light detection and ranging (LiDAR) acquisitions calibrated to estimate canopy bulk density (kg m^{−3}) in 1 m thick layers [1,39].

2.3. Emissions from Prescribed Burns

Wildland fire emissions of pollutants (E_x) per unit area were estimated as the product of pre-burn loading of available fuels, a combustion completeness factor, and a specific emission factor [4,12]:

$$E_x = FL_{\text{preburn}} * CC_x * EF_x \quad (1)$$

where E_x is the emission of compound x , FL_{preburn} is the pre-burn fuel loading, CC_x is a combustion completeness factor for the specific fuel type, and EF_x is the specific emission factor for compound x . Using pre- and post-burn measurements to estimate the

consumption of available fuels (as we have done here) simplifies Equation (1) to become the product of the fuel consumed per unit area and a specific emission factor:

$$E_x = F_{\text{area}} * EF_x \quad (2)$$

where F_{area} is the amount of fuel consumed per unit area during the burn, and EF_x is the specific emission factor for compound x . Equation (3) approximates a combustion completeness factor for fuels:

$$CC_x = (FL_{\text{preburn}} - FL_{\text{postburn}}) / FL_{\text{preburn}} \quad (3)$$

where FL_{preburn} and FL_{postburn} are the pre- and post-burn loading of specific fuel components, respectively. The CC_x values are influenced by fuel conditions (e.g., fuel moisture content and density), meteorological conditions during the burn, patterns of ignition, and fire behavior.

The Smoke Emissions Repository Application database [51], a compilation of field and laboratory emission factors derived from wildland fires across the United States and Canada, was used to estimate emissions (Table 1). Appropriate emission factors for fuels in the Pinelands are also summarized in [4,12]. Mean understory and forest-floor consumption values, estimated from pre- and post-burn measurements or calculated CC_x values and emission factors in Table 1, were used to calculate emissions from prescribed burns in the Pinelands. For the instrumented prescribed burns, emissions from low-intensity fires were calculated assuming that approximately half of the fuel consumed was characterized by flaming combustion, and the other half by smoldering combustion (equivalent to the “combined values” in Table 1), while emissions from high-intensity fires were assumed to result from 75% flaming combustion and 25% smoldering combustion, consistent with observed fire behavior [4,52].

Table 1. Mean emissions of fine particulates ($PM_{2.5}$), carbon dioxide (CO_2), and carbon monoxide (CO) during prescribed burns for flaming and smoldering combustion in conifer, mixed, and deciduous forests in the Eastern US. Data are summarized from the Smoke Emissions Repository Application (SERA; [51]).

Combustion Type	$PM_{2.5}$	CO_2	CO
kg Emitted per Ton Fuel Consumed ($kg\ ton^{-1} \pm 1\ SD$)			
Flaming	20.9 ± 11.0	1691.8 ± 51.8	78.9 ± 21.5
Smoldering	29.4 ± 18.2	1462.0 ± 170.1	165.9 ± 38.1
Combined values	25.3 ± 16.0	1576.0 ± 248.0	122.4 ± 43.1

2.4. Tower Measurements during Instrumented Prescribed Burns

Networks of instrumented towers in burn and control areas were used to measure atmospheric turbulence and sensible heat fluxes during 11 of the 48 prescribed burns. Seven of the instrumented prescribed burns were conducted in pitch pine–scrub oak stands, two were conducted in pine–oak stands, and two were conducted in oak–pine stands (Table 2). All fires were ignited using drip torches, and linear ignitions were used to produce either low-intensity, predominantly backing fires or higher-intensity head or flanking fires when the fire fronts approached and passed each tower. In the pitch pine–scrub oak stands, five backing and mixed-behavior fires and two head fires characterized the predominant fire behavior when flame fronts passed by the towers in each burn area. One low-intensity backing fire and one higher-intensity flanking fire were conducted in pine–oak stands, and two low-intensity backing or mixed-behavior fires were conducted in oak–pine stands (Table 2). Overall, 14 towers recorded data in burn areas during low-intensity backing or mixed-behavior fires, and 7 towers recorded data in burn areas during high-intensity head or flanking fires.

Table 2. Location, forest type, date of burn, predominant ignition pattern and fire behavior, and number of towers in burn (B) and control (C) areas for the 11 instrumented prescribed burns conducted with above-canopy flux towers in the Pinelands National Reserve.

Location	Forest Type	Date	Ignition/ Behavior	Towers (B,C)	Reference
Low-intensity prescribed burns					
Cedar Bridge 1	Pine–scrub oak	03/22/2008	Backing	1, 2	[30]
Cedar Bridge 2	Pine–scrub oak	03/15/2013	Backing	1, 2	[30]
Warren Grove 1	Pine–scrub oak	03/09/2015	Mixed	3, 1	[30]
Cedar Bridge 3	Pine–scrub oak	02/29/2020	Backing	1, 1	This study
Cedar Bridge 4	Pine–scrub oak	02/29/2020	Mixed	1, 1	This study
Joint Base MDL	Pine–oak	02/09/2006	Backing	1, 2	[30]
Silas Little EF 1	Oak–pine	03/06/2012	Backing	1, 2	[22]
Silas Little EF 2	Oak–pine	03/13/2019	Mixed	5, 1	[21]
High-intensity prescribed burns					
Warren Grove 2	Pine–scrub oak	03/05/2013	Head	3, 1	[39]
Warren Grove 3	Pine–scrub oak	03/11/2014	Head	3, 1	[39]
Brendan Byrne 1	Pine–oak	03/20/2011	Mixed	1, 2	[22]

Sonic anemometers (R. M. Young 81000v, R. M. Young, Inc., Traverse City, MI, USA) mounted on antenna towers were used to measure air temperature and 3-dimensional wind velocity 2 m to 4 m above the forest canopy in burn and control areas during the instrumented prescribed burns. The sonic anemometers were operated at 10 Hz and a 38,400 baud rate and logged using either laptop computers in insulated meteorological boxes on towers or Campbell Scientific CR-3000 data loggers (Campbell Scientific, Inc., Logan, UT, USA) on SDI channels in burst mode in insulated meteorological boxes on towers or buried beneath towers, and all cables were protected with fireproof insulation. The sonic anemometers were used with factory calibrations, with average reported accuracies of 0.05 m s^{-1} for 3-dimensional wind velocities, ± 2 degrees for horizontal wind direction, and $\pm 0.01 \text{ m s}^{-1}$ for sonic speed of sound, resulting in a temperature accuracy of ± 2 °C up to 50 °C. The temperature response above 50 °C was nearly linear up to approximately 120 °C. However, there was a reasonably good correspondence between the sonic anemometer data and adjacent thermocouples during small-scale field experiments, e.g., [49], and values ≤ 125 °C were retained in the sonic anemometer datasets. Dynamic source areas that contributed to the measured fluxes, or “footprints”, during non-fire periods are well characterized for three of the prescribed burn sites (Cedar Bridge, Silas Little EF, and JBMDL, [53]), and seven of the eleven prescribed burns were conducted at or adjacent to these stands (Table 2).

Fine-wire thermocouples (Omega SSRTC-GG-K-36, Omega Engineering, Inc., Stamford, CT, USA) arranged in vertical profiles were used to approximate the arrival times of fire fronts. The thermocouples were mounted at intervals along each tower (1 m height intervals up to 10 m, and then every 2.5 m interval to 20 m height for burns conducted in 2011 and 2012, and at 0.25 m, 0.5 m, 1.0 m, 2.5 m, 5.0 m, 10.0 m, and 15.0 m heights for burns conducted in 2013–2020). All thermocouples were logged at 10 Hz using CR-3000 data loggers. Near-surface thermocouple temperatures ≥ 50 °C were assumed to indicate the presence of fire fronts, and temperatures ≥ 300 °C were assumed to characterize flaming combustion. All control towers and some burn area towers were instrumented with additional meteorological sensors for wind speed, air temperature, relative humidity, and 10 h fuel moisture and temperature measurements. Meteorological data, 10 h fuel moisture contents and temperatures, and other ancillary data were recorded at 1 s intervals using CR-23x, CR-3000, or CR-1000 data loggers and then integrated to half-hourly measurements. A complete list of the meteorological and eddy flux equipment can be found in Table A1.

Air temperature and vertical and horizontal wind velocity values measured at 10 Hz at each burn area and control tower were then integrated over 1 s and 1 min time periods.

The maximum differences between burn area and control towers (Δ values) were calculated by subtracting the appropriate control tower data from burn area tower data for each value for the identical time period. Sensible heat flux (H , kW m^{-2}) and friction velocity (u^* , m s^{-1}) were calculated at 1 min intervals from tilt-corrected and coordinate-rotated wind velocities and sonic temperature data using instantaneous (10 Hz) deviations from 1 min block averages with EdiRe software Version 1.5.0.32 [54]. Any 10 Hz data that exceeded 6 SD of the 1 min block averages were assumed to be spikes and were omitted. Sensible heat fluxes were calculated as follows:

$$H = \rho_{\text{air}} c_p \overline{w' T'} \quad (4)$$

where σ_{air} is the average density of air at the top of the canopy, c_p is the heat capacity of air, w' represents the instantaneous deviations of the coordinate-rotated vertical wind velocity from the 1 min block average, T' represents the instantaneous deviations of air temperature from the 1 min block average, and the overbar indicates time averages. Friction velocity was calculated as follows:

$$u^* = \left(\overline{u' w'^2} + \overline{v' w'^2} \right)^{1/4} \quad (5)$$

where u' , v' , and w' are the instantaneous (10 Hz) deviations of wind velocity from the 1 min block averages, following streamwise (u') and cross-stream (v') rotation. Turbulent kinetic energy (TKE; $\text{m}^2 \text{s}^{-2}$) was calculated at 1 min intervals for all sonic anemometer data collected at control towers:

$$\text{TKE} = \frac{1}{2} \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right) \quad (6)$$

where u' , v' , and w' are the instantaneous (10 Hz) deviations of wind velocity from the 1 min block averages during the pre- and post-fire periods. Based on analyses reported in [19–23], the half-hour pre-fire period was used to calculate the mean values of u , v , and w and then subtracted from instantaneous (10 Hz) values during the times of fire front passage to estimate the u' , v' , and w' turbulence statistics and the contribution of fire fronts to the above-canopy TKE. A complete description of the towers, instrumentation, and data processing for burns up through 2015 can be found in [30], and they are further described in [21,23].

2.5. Data and Statistical Analyses

The consumption of fine litter, woody fuels, and understory vegetation was estimated by subtracting post-burn from pre-burn dry weights for each fuel type for each prescribed burn. Fuel loading and estimated consumption data were first tested for normality using Shapiro–Wilk tests, and the homogeneity of variances among groups was tested using Levene’s test. Values were then compared using one-way ANOVA. Comparisons among groups were carried out with Tukey’s honestly significant difference (HSD) test, which adjusted significance levels for multiple comparisons. Pearson’s product–moment correlation coefficients were calculated for the relationship between pre-burn loading and the estimated consumption of each fuel type using SigmaPlot Version 12.5 (SYSTAT Software, Inc., San Jose, CA, USA). Combustion completeness factors (CC_x) were calculated for each fuel type using Equation (3). Emissions of $\text{PM}_{2.5}$, CO_2 , and CO were then calculated using Equation (1) or (2) and the emission factors in Table 1.

Heat release per unit area was calculated from the consumption estimates of each fuel type, using 18.7 kJ g^{-1} as the heat of combustion. The energy consumed during the preheating and pyrolysis of fuels was calculated as a function of the dry mass, moisture content, and initial ambient temperature of each fuel type consumed, using the equations in Appendix B. Following [26], it was assumed that radiant heat flux accounted for approximately 17% of the total heat of combustion of each fuel type. Latent heat flux from combusted fuels was calculated using the dry mass and moisture contents of each fuel type, assuming complete vaporization of the moisture in the consumed fuels. The remaining

heat flux was assumed to be convective heat, energy consumed in forest-floor and soil heating, and heat storage in the canopy airspace (Appendix B).

Short gaps (≤ 0.5 s) that occurred in the 10 Hz sonic anemometer wind velocity and air temperature data streams were filled using linear interpolation. At one of the towers in a high-intensity burn in a pitch pine–scrub oak stand in 2013, longer missing gaps were filled with temperature values from the adjacent uppermost thermocouple until the sonic temperatures decreased to ≤ 125 °C. Much longer gaps occurred on a second sonic anemometer, and a third sonic anemometer was damaged by heat. When the gaps from sonic anemometers on these two towers became too long to fill, their data were omitted from further analyses. Non-parametric Spearman’s rank correlation coefficients were calculated for the relationship between sonic air temperature and vertical and horizontal wind velocities measured at 10 Hz for periods when air temperatures exceeded 5 °C above ambient, which typically occurred during fire fronts’ passage beneath each tower or when flame fronts were in close proximity to towers in burned areas. The values of slopes and correlation coefficients for the relationship between air temperature and vertical wind velocity for low- and high-intensity fires were compared using Mann–Whitney U tests. Sonic air temperature and vertical and horizontal wind velocities were then integrated from 10 Hz raw data to 1 s and 1 min intervals, and differences between burn area and control towers were designated as Δ values.

One-minute values of sensible heat flux and TKE were calculated for times of fire front passage at each tower, with arrival times and periods of fire front passage estimated from near-surface thermocouples. Spearman’s rank correlation coefficients were calculated for the relationships between 1 min sensible heat flux and TKE values for each tower. Differences in sensible heat flux and TKE calculated between burn area and control towers over the appropriate time periods were designated as Δ values. Spearman’s rank correlation coefficients were then calculated for the relationships between mean and maximum Δ sensible heat flux and Δ TKE values during fire front passage. Differences in sensible heat fluxes (in MJ m^{-2}) between burn area and control towers were then integrated over the period of each burn and compared with convective heat fluxes calculated from the sum of consumed fuels. Spearman’s rank correlation coefficients were also calculated for the relationships between estimated $\text{PM}_{2.5}$ emissions and Δ air temperature, Δ wind velocity, Δ 1 min sensible heat, and Δ 1 min TKE values.

3. Results

3.1. Fuel Loading and Consumption during Prescribed Burns

For all prescribed burns sampled from 2004 to 2020 in the Pinelands, the pre-burn loadings of surface and understory fuels were greater in pine–scrub oak stands than in oak-dominated stands (Figure 1a, Table 3). When separated by fuel type, the pre-burn loading of fine litter was not significantly different among forest types, but there was a trend towards greater 1 + 10 h woody fuels and understory vegetation in pine–scrub oak stands.

Table 3. Statistics for pre-burn loading and consumption of surface fuels composed of fine litter, 1 h + 10 h woody fuels, and understory vegetation in 48 upland forest stands sampled between 2004 and 2020 in the New Jersey Pinelands. PSO = pine–scrub oak, PO = pine–oak, OP = oak–pine.

Fuel Type	F Statistic	Significance	Contrasts
Pre-burn			
Fine litter	$F_{2,47} = 1.525$	$p = 0.229$	NS
1 + 10 h wood	$F_{2,47} = 2.870$	$p = 0.067$	PSO > OP
Understory vegetation	$F_{2,34} = 3.126$	$p = 0.057$	PSO > OP
All fuels	$F_{2,34} = 6.087$	$p < 0.01$	PSO > PO = OP

Table 3. Cont.

Fuel Type	F Statistic	Significance	Contrasts
Consumption			
Fine litter	$F_{2,47} = 4.033$	$p < 0.05$	PSO > OP
1 + 10 h wood	$F_{2,47} = 3.992$	$p < 0.05$	PSO > OP
Understory vegetation	$F_{2,34} = 3.298$	$p < 0.05$	PSO > OP
All fuels	$F_{2,34} = 7.362$	$p < 0.01$	PSO > PO = OP

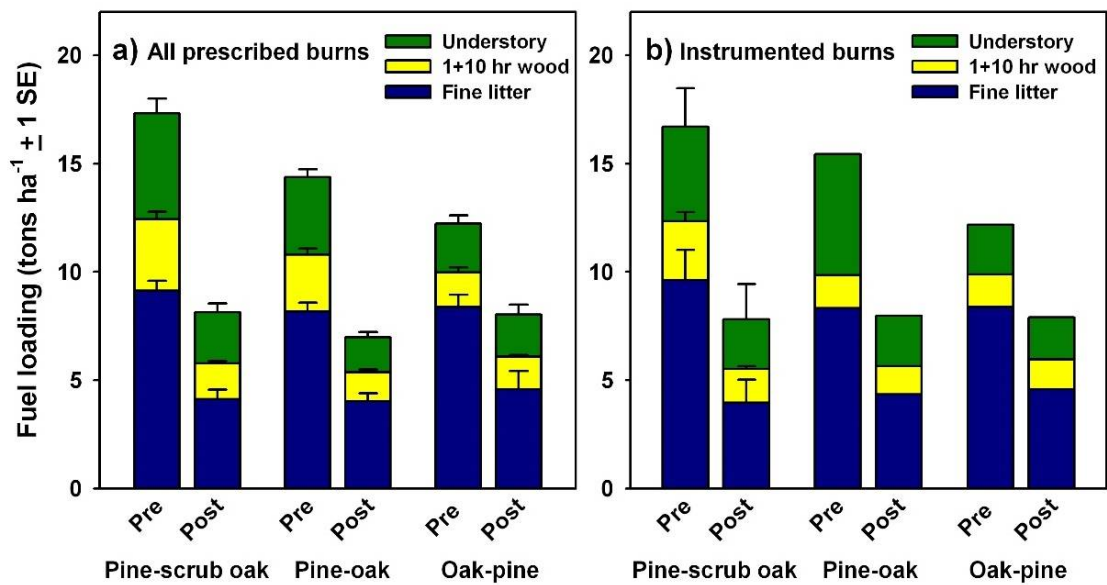


Figure 1. Pre- and post-burn fuel loading by forest type for prescribed burns: (a) 48 prescribed burns conducted in the Pinelands from 2004 to 2020, and (b) the 11 instrumented prescribed burns. Data are tons ha^{−1} ± 1 standard error for understory vegetation, 1 h + 10 h woody fuels, and fine litter.

Consumption of fuels during prescribed fires was a linear function of pre-burn fuel loading, which explained 67% and 86% of the variability in the consumption of understory vegetation and 1 h + 10 h fuels, respectively (Figure 2a,b). The relationship between pre-burn loading and consumption of fine litter composed of needles and leaves was more complex: two slopes occurred in this relationship, reflecting fire behavior during relatively low- vs. high-intensity burns; thus, overall pre-burn loading explained only 44% of fine litter consumption. When fine litter and 1 + 10 h woody fuels were combined, pre-burn loading explained approximately 65% of the variability in the consumption of forest-floor fuels (Figure 2c). Complete statistics for the relationships between pre-burn loading and estimated consumption can be found in Table A2.

When separated by forest type, the consumption of forest-floor and understory fuels was greater in pine–scrub oak stands than in oak-dominated stands, averaging 56 ± 10%, 49 ± 12%, and 39 ± 11% of total loading in pine–scrub oak, pine–oak, and oak–pine stands, respectively (Figure 1a, Table 3). Greater consumption of forest-floor and understory fuels in pitch pine–scrub oak stands resulted from both greater pre-burn fuel loading and greater proportional consumption losses compared to stands consisting of a greater co-dominance of overstory oaks and larger amounts of oak litter on the forest floor.

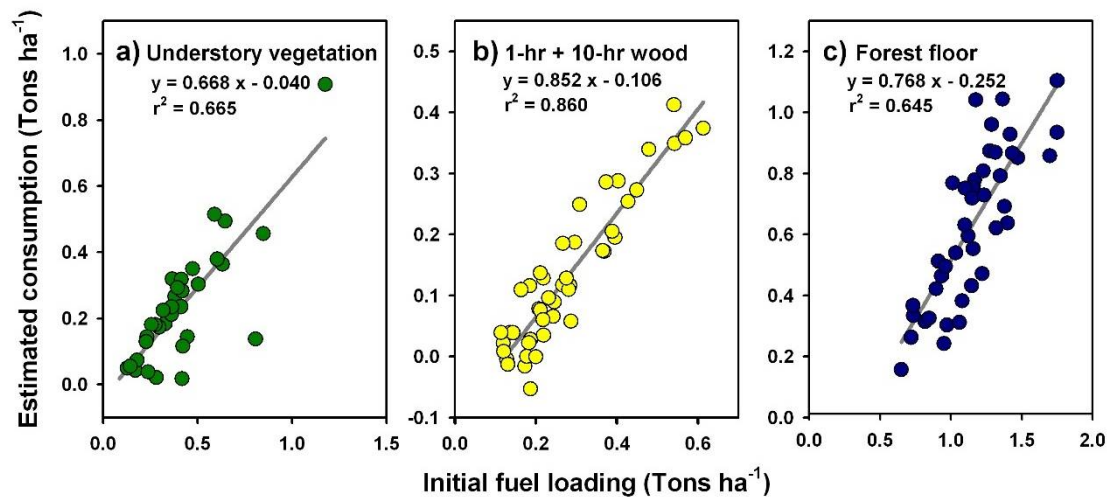


Figure 2. Pre-burn fuel loading and estimated consumption of (a) understory vegetation, (b) 1 h + 10 h woody fuels on the forest floor, and (c) fine litter and woody fuels on the forest floor during prescribed burns conducted in the Pinelands from 2004 to 2020. All values are tons ha^{−1}.

3.2. Combustion Completeness Factors

Combustion completeness factors for fine litter, 1 h + 10 h wood, understory vegetation, and average weighted values for the sum of all available fuels are shown in Table 4 and Figure A1. When separated by forest type, the consumption estimates calculated using CC factors averaged 57%, 51%, and 37% of total loading in pine–scrub oak, pine–oak, and oak–pine stands, respectively. Combustion completeness factors for understory vegetation and 1 h + 10 h wood, but not for fine litter, were greater for pine–scrub oak and pine–oak stands compared to oak–pine stands (Table 4). Although little relationship was apparent between pre-burn loading and estimated combustion completeness factors for understory vegetation and fine litter, pre-burn loading and combustion coefficients for 1 h + 10 h woody fuels were exponentially related (Figure A1b). There was also a trend towards a positive linear relationship between the sum of pre-burn fine litter and 1 h + 10 h fuels and forest-floor combustion coefficients (Figure A1d).

Table 4. Combustion completeness factors (CC) by forest and fuel type, calculated from biometric pre- and post-burn loading measurements of shrubs and scrub oaks in the understory, 1 h + 10 h woody fuels, and fine litter during prescribed burns in the Pinelands from 2004 to 2020. Values are means ± 1 standard error. “All fuels” is weighted by the amount of each fuel type consumed. Values with different superscripts are significantly different at $p < 0.05$.

Fuel Type	Pine–Scrub Oak	Pine–Oak	Oak–Pine
	(Mean ± 1 SE)		
Fine litter	0.618 ± 0.029	0.530 ± 0.036	0.457 ± 0.068
1 + 10 h wood	0.474 ± 0.047 ^a	0.394 ± 0.059 ^a	0.131 ± 0.127 ^b
Understory	0.534 ± 0.057 ^a	0.555 ± 0.040 ^a	0.205 ± 0.067 ^b
All fuels	0.567	0.511	0.369

3.3. Fuel Loading, Consumption, and Emissions during Instrumented Prescribed Burns

The pre-burn loading of understory and forest-floor fuels for the 11 instrumented prescribed burns averaged 16.7, 14.8, and 12.2 tons ha^{−1} in the pine–scrub oak, pine–oak, and oak–pine stands, respectively, and was similar to the larger prescribed burn dataset (Figure 1b and Table A3). The estimated consumption averaged 53%, 47%, and 35% of total loading in the pine–scrub oak, pine–oak, and oak–pine stands. Greater amounts of fine litter were consumed in all stand types, averaging 67 ± 16% of total consumption, while the consumption of understory and 1 h + 10 h woody fuels averaged 25% and 8% of total

consumption, respectively. During the highest-intensity burn, crown torching resulted in canopy fuel consumption of up to 1.9 tons ha^{-1} and 21% of total fuel consumption (see [39] for spatial estimates of crown fuel consumption).

The average $\text{PM}_{2.5}$ emissions estimated from consumed fuels during instrumented prescribed burns were 227 ± 59 , 189 ± 12 , and 112 ± 7 $\text{kg PM}_{2.5} \text{ ha}^{-1}$ for pine–scrub oak, pine–oak, and oak–pine stands, respectively. The values calculated using pre-burn loadings and the appropriate CC values in Table 4 were only slightly larger than those calculated using estimated consumption for each burn, differing by 9%, 7%, and 1% for prescribed burns conducted in the pine–scrub oak, pine–oak, and oak–pine stands. When $\text{PM}_{2.5}$ emissions were expressed as a function of predominant fire intensity, the estimates differed by 15% and 10% for low- and high-intensity fires, respectively (Figure 3a). The estimated emissions of CO_2 during instrumented prescribed burns corresponded more closely with fuel consumption because there was less variation in the release of CO_2 from smoldering vs. flaming consumption (Figure 3b). When separated by forest type, CO_2 emissions from pine–scrub oak stands were greater than those from oak–pine stands.

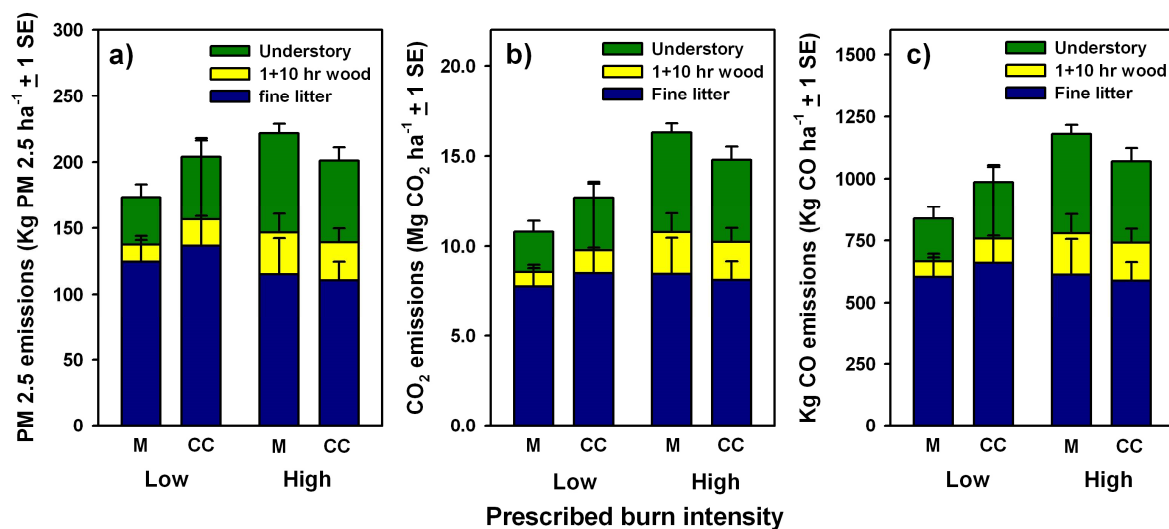


Figure 3. Estimated emissions of (a) $\text{PM}_{2.5}$, (b) CO_2 , and (c) CO during low- and high-intensity instrumented prescribed burns. Values are means ± 1 standard error calculated using field measurements of pre- and post-burn fuel loading (M) or by using pre-burn fuel loading and the appropriate combustion completeness factors (CC) in Table 4.

3.4. Above-Canopy Heating and Turbulence during Prescribed Burns

The ambient air temperature ranged from 0.9 to 16.7 °C, relative humidity from 20 to 39%, and above-canopy horizontal wind speed from 1.5 to 4.3 m s^{-1} during the 11 instrumented prescribed burns (Table 5). The maximum values of air temperature and vertical and horizontal wind velocities during the prescribed burns occurred at the time of flame front passage, or occasionally when fire fronts were in close proximity to towers in the burn areas. The time series in Figure 4 illustrates the differences in above-canopy heating and turbulence for a low-intensity backing fire and a high-intensity head fire in two pitch pine–scrub oak stands characterized by similar forest structure and estimated fuel consumption, and conducted under similar ambient air temperatures, RH levels, and wind speeds. The maximum 10 Hz air temperature and horizontal and vertical wind velocities were 3.2, 1.2, and 1.6 times greater during the high-intensity, predominately head fire with occasional crown torching than during the low-intensity backing fire, respectively (Figure 4a–c).

Table 5. Ambient meteorological conditions during prescribed burns conducted in stands with overstory flux towers in the Pinelands. Data are presented by predominant fire behavior, including the site location, forest type, date of prescribed burn, and mean $\pm$ 1 standard deviation half-hourly air temperature, relative humidity, and wind speed 2 m to 4 m above the mean canopy height at control towers during each burn. PSO = pine–scrub oak, PO = pine–oak, OP = oak–pine.

Fire Behavior/Location		Date	Air Temperature (°C)	RH (%)	Wind Speed (m s ^{−1})
Low-intensity prescribed burns					
Cedar Bridge 1	PSO	03/22/2008	9.0 $\pm$ 1.3	34.9 $\pm$ 7.1	2.2 $\pm$ 0.4
Cedar Bridge 2	PSO	03/15/2013	7.2 $\pm$ 1.2	34.3 $\pm$ 2.0	4.3 $\pm$ 0.6
Warren Grove 1	PSO	03/09/2015	3.7 $\pm$ 0.9	20.2 $\pm$ 1.1	2.7 $\pm$ 0.4
Cedar Bridge 3,4	PSO	02/29/2020	0.6 $\pm$ 0.5	33.1 $\pm$ 2.3	3.9 $\pm$ 0.3
Joint Base MDL 1	PO	02/09/2006	0.9 $\pm$ 0.9	31.1 $\pm$ 3.0	3.0 $\pm$ 0.3
Silas Little EF 1	OP	03/06/2012	5.8 $\pm$ 1.4	21.6 $\pm$ 2.2	2.2 $\pm$ 0.3
Silas Little EF 2	OP	03/13/2019	10.2 $\pm$ 2.2	32.2 $\pm$ 9.0	2.4 $\pm$ 0.5
High-intensity prescribed burns					
Warren Grove 2	PSO	03/05/2013	7.6 $\pm$ 1.0	38.6 $\pm$ 3.6	1.5 $\pm$ 0.3
Warren Grove 3	PSO	03/11/2014	16.7 $\pm$ 1.1	33.1 $\pm$ 4.5	2.9 $\pm$ 0.4
Brendan Byrne 1	PO	03/20/2011	8.6 $\pm$ 1.9	37.1 $\pm$ 8.4	2.1 $\pm$ 0.6

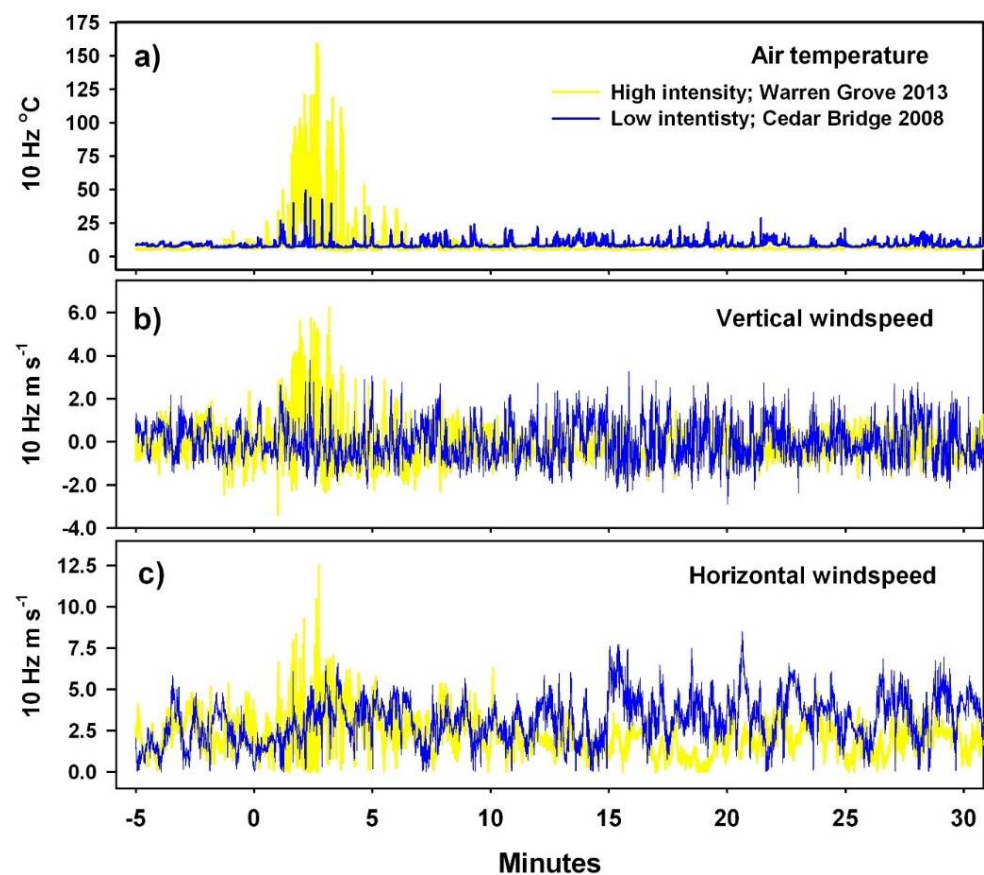


Figure 4. Time series of above-canopy (a) air temperature measured at 10 Hz, (b) vertical wind velocity measured at 10 Hz, and (c) horizontal wind velocity measured at 10 Hz during a low-intensity backing fire in a pitch pine–scrub oak stand at Cedar Bridge in 2008 (blue line) and a high-intensity head fire in a pitch pine–scrub oak stand near Warren Grove in 2013 (yellow line).

The maximum values of Δ air temperature and vertical and horizontal Δ wind velocities measured above the canopy at 10 Hz, at 1 s and 1 min intervals, for all 11 instrumented prescribed burns are shown in Figure 5. The average maximum 10 Hz values for Δ air temperature, Δ vertical wind velocity, and Δ horizontal wind velocity were 4.6, 9.5, and 45.7 times greater during high-intensity burns than low-intensity burns, respectively (Table A4). High-intensity prescribed burns were also characterized by enhanced negative 10 Hz vertical wind velocities compared to low-intensity burns (e.g., Figure 4b), indicating the presence of high-frequency turbulent eddies bringing either warm (negative heat flux) or cool (positive heat flux) air from above into the canopy airspace.

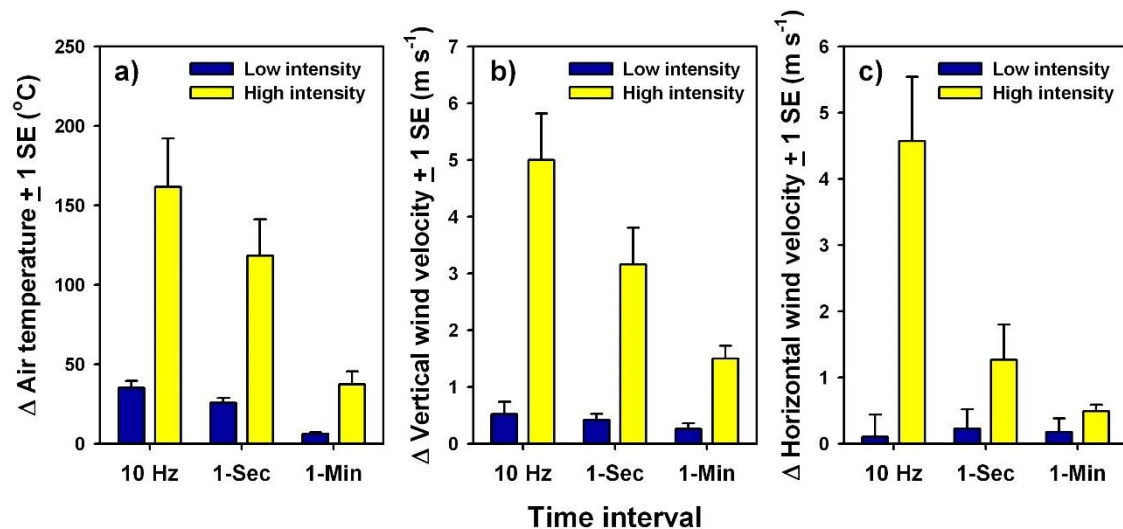


Figure 5. Maximum (a) Δ air temperature ($^{\circ}\text{C}$), (b) Δ vertical wind velocity (m s^{-1}), and (c) Δ horizontal wind velocity (m s^{-1}) measured at 10 Hz, at 1 s and 1 min intervals, measured above the canopy during low- and high-intensity prescribed burns. Values are means $\pm$ 1 standard error.

When low- and high-intensity burns were compared among pairs of pine-oak or pine-scrub oak stands with a similar forest structure, the relationships between above-canopy air temperature and vertical wind velocity measured at 10 Hz during fire front passage were stronger for high-intensity prescribed burns than for low-intensity, predominately backing prescribed burns (Figure 6). While the slopes of the linear relationship between air temperature $\geq 5^{\circ}\text{C}$ above ambient and vertical wind velocity measured at 10 Hz at the top of the canopy during fire front passage were greater for low-intensity burns than for high-intensity burns (Mann–Whitney $U = 6.5$, $n = 13,7$, $Z\text{-Score} = 1.960$, $p < 0.05$), Spearman's rank correlation coefficients were nearly greater for high-intensity burns compared to low-intensity burns (Mann–Whitney $U = 69$, $n = 13,7$, $Z\text{-score} = -1.862$, $p = 0.063$) (Figure 6; Table 6).

Table 6. Slopes and Spearman's rank correlation coefficients for the relationship between air temperature $\geq 5^{\circ}\text{C}$ above ambient and vertical wind velocity (w) measured at 10 Hz at the top of the canopy for all burn area towers during low- and high-intensity fires. Values are means $\pm$ 1 standard deviation, and values with different superscripts are significantly different at $p < 0.05$.

Fire Intensity	N	Slope	Intercept (Mean $\pm$ 1 SD)	Spearman's R_s
Low intensity	13	0.072 ± 0.020^a	0.148 ± 0.081	0.362 ± 0.096
High intensity	7	0.036 ± 0.006^b	0.263 ± 0.104	0.472 ± 0.120

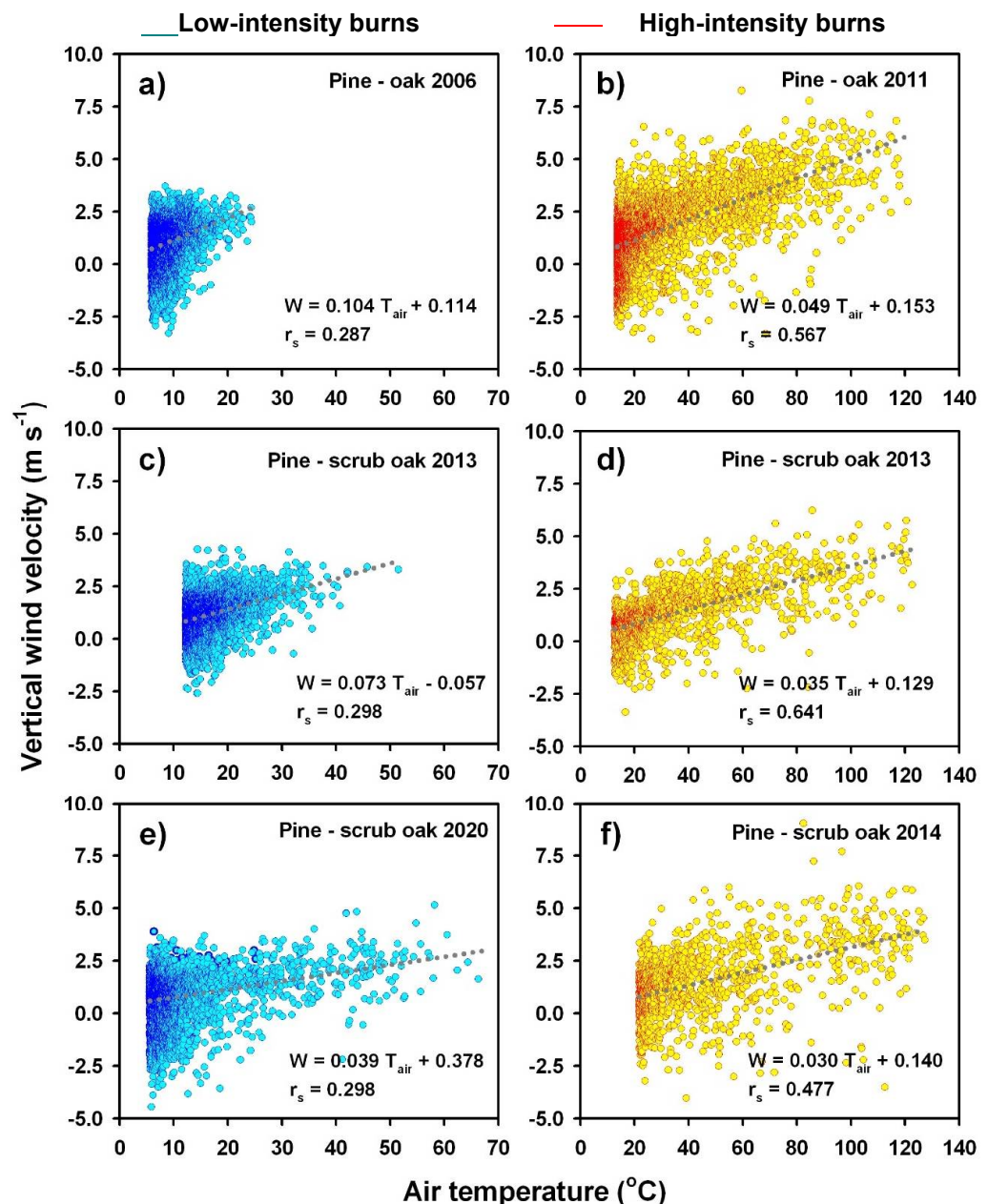


Figure 6. Relationships between above-canopy air temperature and vertical wind velocity measured at 10 Hz during low- and high-intensity prescribed burns in pine–oak and pine–scrub oak stands. Shown are (a) a backing fire at JBMDL in 2006 and (b) a flanking fire in Brendan Byrne SF in 2011, (c) a backing fire at Cedar Bridge in 2013 and (d) a head fire near Warren Grove in 2013, and (e) a mixed-behavior fire at Cedar Bridge in 2020 and (f) a head fire near Warren Grove in 2014. Blue dots indicate low-intensity burns and yellow dots indicate high-intensity burns.

3.5. Sensible Heat Flux and Turbulent Kinetic Energy during Prescribed Burns

Figure 7 shows time series for a low-intensity backing fire and a high-intensity head fire conducted in pitch pine–scrub oak stands characterized by a similar forest structure and estimated fuel consumption, and under similar ambient air temperatures, RH levels, and wind speeds, illustrating the differences in above-canopy 1 min sensible heat flux and TKE. The peak 1 min sensible heat flux, which reflected convective heating during fire front passage, was 12.6 times greater in the high-intensity burn than the low-intensity, predominately backing burn (46.4 vs. 3.7 kW m^{-2}), although the integrated sensible heat flux during each burn was more similar, with values of 6.5 MJ m^{-2} vs. 4.4 MJ m^{-2} for

the high- and low-intensity burns, respectively (Figure 7a). The maximum TKE values estimated at 1 min intervals during fire front passage were greater than the values measured at the appropriate control towers during each prescribed burn (Table A5), while the maximum TKE values measured at burn area towers during fire front passage were similar (Figure 7b).

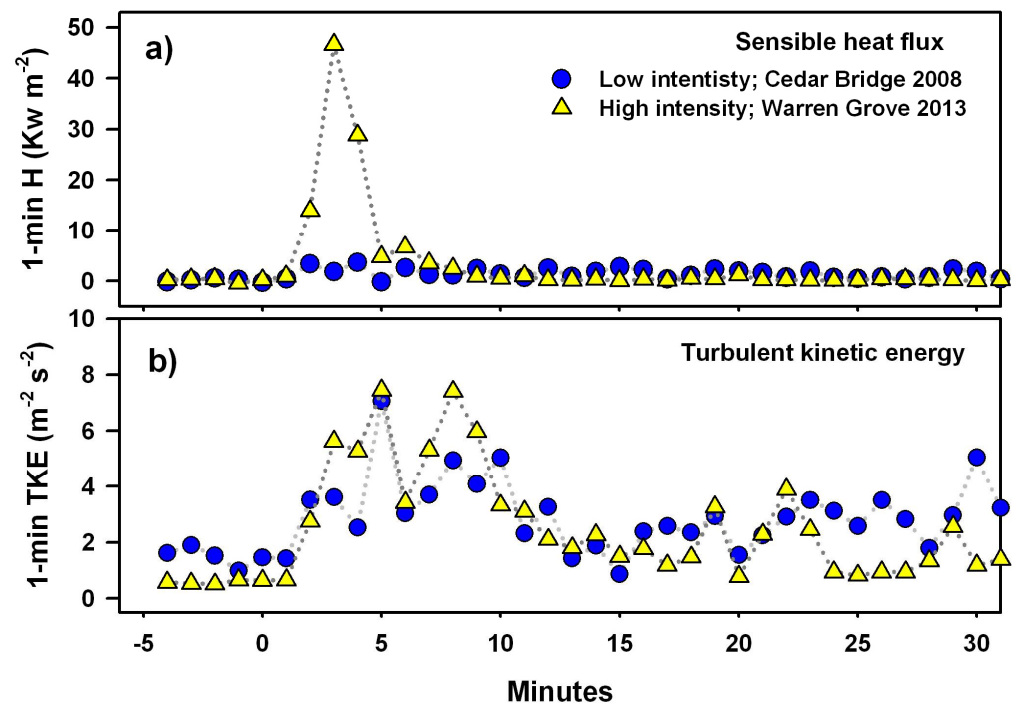


Figure 7. Time series of above-canopy (a) sensible heat flux calculated at 1 min intervals and (b) turbulent kinetic energy (TKE) at 1 min intervals measured during a low-intensity backing fire in a pitch pine–scrub oak stand at Cedar Bridge in 2008 (blue symbols) and a high-intensity head fire in a pitch pine–scrub oak stand near Warren Grove in 2013 (yellow symbols).

Figure 8 illustrates the relationships between the 1 min values of sensible heat flux and TKE measured during fire front passage during low-intensity and high-intensity burns in the same pairs of pine–oak and pitch pine–scrub oak stands shown in Figure 6. The relationship between the 1 min values of sensible heat flux and TKE during fire front passage for individual towers in burn areas was significant for only two of the low-intensity fires, and neither of these were predominately backing fires, indicating that buoyant plumes generated during low-intensity fires had little effect on the above-canopy TKE (Table 7). In contrast, the relationship between 1 min sensible heat flux and TKE was significant for the two high-intensity head fires and nearly significant for the flanking fire with nearby crown torching. Overall, the relationships between the 1 min values of sensible heat flux and TKE during fire front passage were stronger for high-intensity burns than for low-intensity burns.

The average and maximum values of Δ 1 min sensible heat fluxes during fire front passage were 4.2 and 3.0 times greater, respectively, during high-intensity burns compared to low-intensity burns (Mann–Whitney U test z-score = 3.421, $p < 0.01$ for mean ΔH values, and z-score = 3.333, $p < 0.01$ for maximum 1 min ΔH values) (Figure 9a,b). The average and maximum values of Δ 1 min TKE values were 1.3 and 2.3 times greater, respectively, during high-intensity burns compared to low-intensity burns (Mann–Whitney U test z-score = 3.368, $p < 0.01$ for mean ΔTKE values, and z-score = 3.209, $p < 0.01$ for maximum ΔTKE values) (Figure 9c,d). When the 1 min Δ sensible heat flux and Δ TKE values for all burn area towers were considered together, the maximum 1 min Δ sensible heat flux and

Δ TKE values were linearly related ($F_{1,17} = 10.5$, $p < 0.05$), while the relationship between mean values during fire front passage was weaker ($F_{1,17} = 4.6$, $p = 0.06$) (Figure 10).

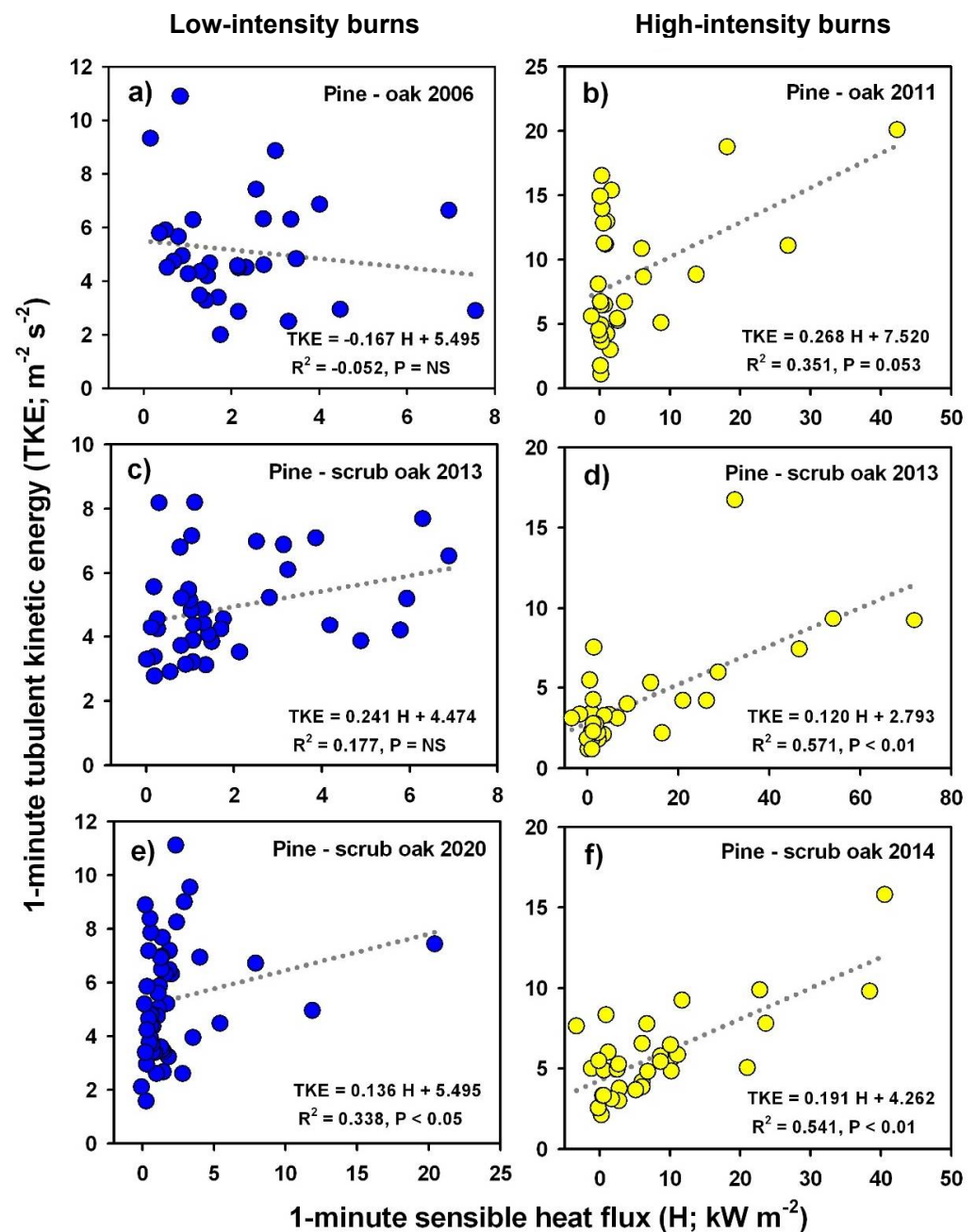


Figure 8. Examples of the relationship between 1 min values of sensible heat flux ($kW m^{-2} min^{-1}$) and TKE ($m^2 s^{-2}$) at the top of the canopy during fire front passage during low- and high-intensity prescribed burns in the same pine–oak and pitch pine–scrub oak stands shown in Figure 6. Panels represent (a) a low-intensity backing fire at Fort Dix in 2006 and (b) a high-intensity flanking fire in Brendan Byrne State Forest in 2011, (c) a backing fire at Cedar Bridge in 2013 and a (d) head fire at Warren Grove in 2013, and (e) a mixed-behavior fire at Cedar Bridge in 2020 and (f) a head fire near Warren Grove in 2014. Slopes and intercepts of the linear relationship between H and TKE are shown, along with values of Spearman’s rank correlation coefficients and significance levels.

Table 7. Relationships between 1 min values of sensible heat flux ($\text{kW m}^{-2} \text{min}^{-1}$) and turbulent kinetic energy ($\text{m}^{-2} \text{s}^{-2}$) measured at the top of the canopy during fire front passage for low-intensity and high-intensity prescribed burns. Values are slopes and intercepts, Spearman's rank correlation coefficients (R_s), Student's T and degrees of freedom (n-2), and significance levels for the linear relationship between sensible heat flux and TKE. Data from prescribed burns with multiple burn area towers were pooled.

Fire Behavior/Location	Slope	Intercept	R_s	T (n-2)	p-Value
Low-intensity burns					
Cedar Bridge 1	0.053	2.535	0.081	0.436 (29)	NS
Cedar Bridge 2	0.241	4.474	0.177	1.106 (38)	NS
Warren Grove 1	0.105	2.747	0.223	2.203 (78)	<0.05
Cedar Bridge 3,4	0.136	5.093	0.338	2.512 (49)	<0.05
Joint Base MDL	−0.167	5.495	−0.052	0.279 (29)	NS
Silas Little EF 1	−0.347	2.833	−0.071	0.383 (29)	NS
Silas Little EF 2	0.045	2.174	0.091	0.841 (81)	NS
High-intensity burns					
Warren Grove 2	0.120	2.793	0.571	3.745 (29)	<0.001
Warren Grove 3	0.191	4.262	0.541	3.468 (31)	<0.01
Brendan Byrne 1	0.268	7.520	0.351	2.017 (29)	0.053

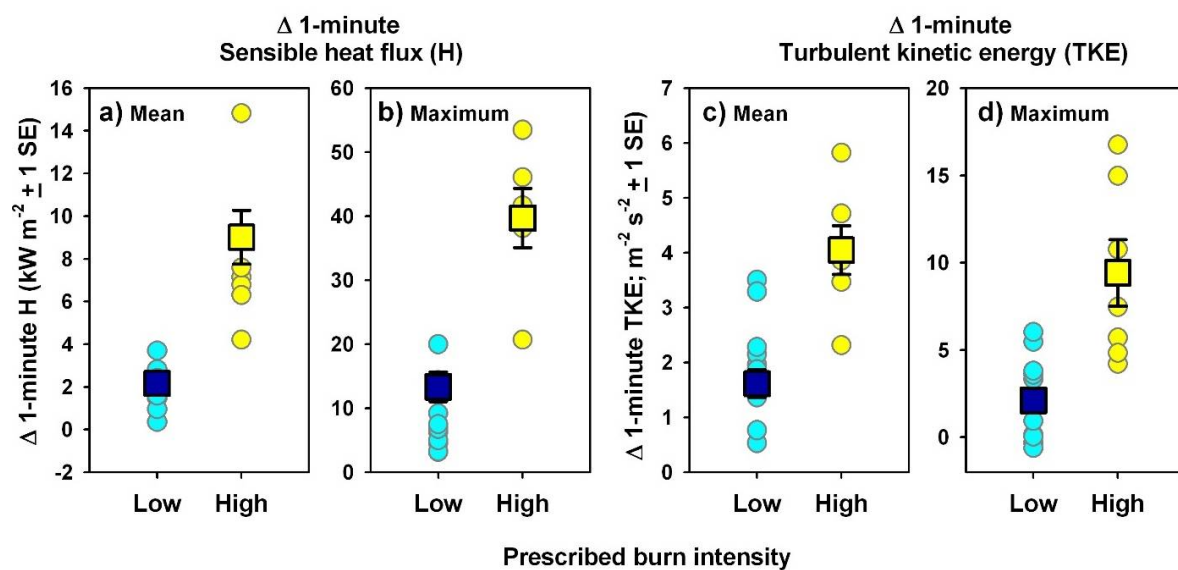


Figure 9. Mean and maximum 1 min Δ values of sensible heat flux (kW m^{-2}) and turbulent kinetic energy ($\text{m}^2 \text{s}^{-2}$) measured at the top of the canopy during fire front passage. Values are (a) mean and (b) maximum 1 min Δ sensible heat flux, and (c) mean and (d) maximum 1 min Δ turbulent kinetic energy. Colored squares and error bars are average Δ values ± 1 standard error, and colored circles are Δ values from individual towers in burn areas.

Convective heat flux and heat storage in the canopy airspace, calculated from fuel consumption estimates for the 11 instrumented prescribed burns, were nearly greater for high-intensity burns compared to low-intensity burns (Table 8). In contrast, the integrated Δ sensible heat flux at the top of the canopy during the times when fire fronts were in the vicinity of each tower was significantly greater for high-intensity burns than for low-intensity burns. Integrated Δ sensible heat flux accounted for only $48.4 \pm 9.4\%$ of the estimated convective heat flux and heat storage during low-intensity burns, compared to 66.8 ± 16.0 of the estimated convective heat flux and heat storage during high-intensity burns (Table 8).

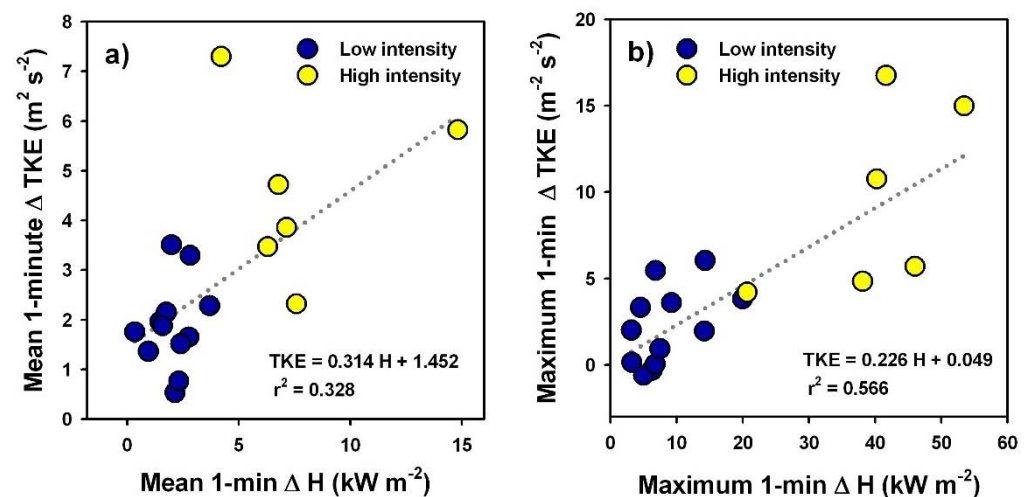


Figure 10. Relationships between Δ 1 min sensible heat flux (kW m^{-2}) and Δ 1 min turbulent kinetic energy ($\text{m}^2 \text{s}^{-2}$) measured above the canopy during fire front passage for all burn area towers. Values are (a) mean 1 min values of ΔH and ΔTKE , and (b) maximum 1 min values of ΔH and ΔTKE .

Table 8. Convective heat flux and storage in the canopy airspace, calculated from fuel consumption estimates and integrated sensible heat flux at the top of the canopy during fire front passage for the 11 instrumented prescribed burns, separated by burn intensity. Values are the mean $\text{MJ m}^{-2} \pm 1$ standard error, sample sizes, T statistics, and significance levels.

Low Intensity	High Intensity	n	$T_{1,9}$	p-Value
(Mean $\text{MJ m}^{-2} \pm 1$ SE)				
Convective heat flux + heat storage				
8.356 ± 1.175	13.732 ± 2.398	11	2.290	0.051
Integrated Δ sensible heat flux				
3.784 ± 0.617	8.470 ± 1.243	11	3.819	0.005

3.6. Relationships between Emissions and Heating and Turbulence Statistics

When all instrumented prescribed burns were considered together, the estimated $\text{PM}_{2.5}$ emissions calculated using fuel consumption values were either unrelated or only weakly related to above-canopy enhanced heating, sensible heat flux, or turbulence statistics (Table 9). The relationships between $\text{PM}_{2.5}$ emissions and maximum Δ air temperatures measured above the canopy at any timescale (10 Hz, 1 s, 1 min), or the maximum Δ vertical or horizontal wind velocities measured at 10 Hz, were insignificant. $\text{PM}_{2.5}$ emissions were also unrelated to average or maximum 1 min Δ sensible heat fluxes during fire front passage, total Δ sensible heat flux calculated from above-canopy measurements, or average or maximum 1 min Δ TKE values (Table 9). The lack of relationships between above-canopy heat fluxes and turbulence and the consumption of fuels on the forest floor and understory indicate that $\text{PM}_{2.5}$, along with CO_2 , CO, and other compounds emitted during the combustion process, likely remained near the ground and within the canopy airspace for longer periods of time during low-intensity burns than during high-intensity head and mixed-behavior burns.

Table 9. Relationships between maximum values of Δ air temperature, Δ vertical and horizontal wind velocities, Δ 1 min mean and peak sensible heat fluxes, Δ 1 min mean and peak turbulent kinetic energy, and estimated PM_{2.5} emissions during instrumented prescribed burns.

Fire Behavior/Location	Slope	Intercept	R _s	T _{1,9}	p-Value
Δ 10 Hz air temperature (°C)	0.498	154.3	0.378	1.225	0.252
Δ 1 s air temperature (°C)	0.608	157.7	0.424	1.404	0.194
Δ 1 min air temperature (°C)	1.169	170.8	0.032	0.096	0.926
Δ 10 Hz vertical wind speed (m s ^{−1})	9.551	172.4	0.287	0.899	0.392
Δ 10 Hz horizontal wind speed (m s ^{−1})	8.243	153.8	−0.005	0.000	0.989
Δ 1 min mean H (W m ^{−2})	8.196	159.0	0.228	0.703	0.501
Δ 1 min peak H (W m ^{−2})	0.957	170.7	0.055	0.165	0.873
Δ Total sensible heat (MJ m ^{−2})	9.942	138.3	0.358	1.150	0.310
Δ 1 min mean TKE (m ² s ^{−2})	8.800	163.5	0.465	1.576	0.150
Δ 1 min peak TKE (m ² s ^{−2})	1.818	179.1	0.223	0.686	0.509

4. Discussion

Pre- and post-burn fuel loading measurements were used to estimate fuel consumption, combustion completeness factors, and PM_{2.5} emissions during prescribed burns conducted in the three major upland forest types in the Pinelands of southern New Jersey. Biometric fuel estimates were then integrated with above-canopy heat flux and turbulence measurements to compare low- and high-intensity burns. Greater amounts of fine litter on the forest floor were consumed compared to understory vegetation or 1 h + 10 h fuels in all three forest types during most prescribed burns, indicating that the combustion of fine litter is typically the predominant source of emissions of PM_{2.5}, CO₂, and other compounds during prescribed burns in the Pinelands. Our findings further indicated that low-intensity backing fires, regardless of forest type, had weaker relationships between above-canopy sensible heat flux and turbulence statistics than high-intensity fires. Heat flux in buoyant plumes, here approximated as Δ sensible heat flux, is the main pathway of heat dissipation from combustion during prescribed burns [26,27,30]. Above-canopy sensible heat flux during high-intensity burns accounted for a greater proportion of estimated convective heat flux and heat storage during the combustion of forest floor and understory fuels than during low-intensity burns. Because emissions of PM_{2.5}, CO₂, and CO were not strongly coupled with above-canopy turbulence during low-intensity burns under the low-to-moderate ambient wind speeds characterizing prescription burn days, relatively high concentrations likely occurred near the surface for longer periods of time [25,55]. Overall, the lack of enhanced above-canopy sensible heat fluxes, vertical and horizontal wind velocities, and TKE values during low-intensity burns limited the movement of smoke (and embers) above the canopy, where dispersion occurs with greater efficiency [19,21,22].

4.1. Fuel Loading and Consumption during Prescribed Burns

We sampled a wide range of surface fuel loadings in the three upland forest communities to calculate combustion completeness factors, with the time since the last prescribed burn or wildfire ranging from two years in a re-burned pine–scrub oak stand to over four decades in oak- and pitch-pine-dominated stands [47]. Fine litter on the forest floor comprised the largest proportion of available fuels consumed during prescribed burns in nearly all stands. Our field sampling also indicated that, of the three major surface fuel types, the spatial variation within stands was the least for fine litter. When expressed as a coefficient of variation (CV; standard deviation/mean), the values for fine litter averaged $26 \pm 8\%$, while the CVs for understory vegetation and 1 h + 10 h fuels averaged $50 \pm 22\%$ and $63 \pm 12\%$, respectively. Field sampling further indicated that, when the time since the last fire is accounted for, the fine litter loading is similar between forest types, reflecting similar rates of production and decomposition of fine litter in intermediate-age pine–scrub oak, pine–oak, and oak–pine stands in the Pinelands [56].

Quantifying surface fuels in small (0.5 and 1.0 m²) plots is relatively straightforward, but scaling randomly located plots to the stand level introduces greater uncertainty into fuel loading estimates. Similarly, post-burn measurements made in an identical manner but not in the exact same spatial location as the pre-burn measurements can further introduce error into consumption estimates, including apparent net increases in 1 h + 10 h woody fuels. Canopy and understory fuels can be estimated accurately over large spatial extents using terrestrial or airborne LiDAR scanning systems, and these approaches have been used extensively in the Pinelands, e.g., [1,2,34,35,44]. However, remote sensing approaches are less effective at quantifying available fuels on the forest floor and their consumption during prescribed burns. A variety of hybrid approaches integrating field sampling and simulation models to estimate fine fuel accumulation over time, along with the use of CC_x factors, could provide more accurate estimates of PM_{2.5} emissions during prescribed burns. For example, litter layer accumulation is a near-linear function of the time since the last prescribed burn in Pinelands forests, and the accumulation rates of fine litter and 1 h + 10 h wood are consistent with woody biomass accumulation by understory shrubs and oaks [10,47]. Thus, an estimate of the time since the last fire, coupled with LiDAR data to link shrub height to accumulated litter mass, can be used to approximate the available surface fuels. A second potential approach is to employ process-based forest productivity models such as PnET CN or LANDIS II, which have been used extensively to simulate forest productivity throughout the Atlantic coastal plain [57–61], to predict foliage and fine wood production, and to link litterfall production to the time since the last fire in order to provide an estimate of accumulated fuels on the forest floor. A third approach is to use remotely sensed estimates of leaf area from Landsat or MODIS satellite products for the appropriate forest types, and then couple simulated litterfall with decomposition rates for specific litter types to estimate the forest floor dynamics. Remotely sensed NDVI has been used extensively to estimate burn severity in the Pinelands [35,49], and the decomposition of major litter types is well constrained in many forests on the Atlantic coastal plain, e.g., [56].

Over the range of operational prescribed burns that were quantified from 2004 to 2020, pre-burn fuel loading had an overriding effect on the amount of fuel consumed, and consumption was generally linearly related to pre-burn loading [47,49]. The linear relationships between pre-burn fuel loading and consumption observed in pine- and oak-dominated stands in the Pinelands are consistent with extensive pre- and post-burn sampling in mixed southern pine stands dominated by longleaf pine (*P. palustris* Mill.), loblolly pine (*P. taeda* L.), slash pine (*P. elliotii* Engelm.), and sand pine (*P. clausa* (Chapm. Ex Engelm.) (Vasey ex Sarg.) in the Southeastern US [3,37]. In their studies, correlation coefficients ≥ 0.8 characterized the linear relationships between pre-burn loading and consumption for the majority of surface fuels. However, a number of points are notable in our study: (1) when separated by forest type, CC factors were generally lower for oak–pine stands than for stands with a greater dominance of pines; (2) there was a trend towards greater fine litter consumption at higher fire intensities, and the weakest linear relationship occurred for fine litter in our analyses of pre-burn loading and consumption; and (3) a non-linear relationship emerged when combustion completeness factors were calculated for 1 h + 10 h fuels. Differences in CC factors among stand types and fire intensity are likely related to the fact that fine litter composed predominantly of oak or pine litter differs in particle size and compaction, affecting porosity and airflow during preheating and combustion processes [62–64]. Although oak-dominated stands have lower leaf area during the dormant season—which affects the microclimate by allowing greater penetration of solar radiation and ambient wind velocities near the surface, and contributes to enhanced rates of evaporation from litter surfaces—particles of oak litter tend to be larger than those of pine litter; thus, the fuel moisture dynamics in accumulated litter beds can differ [65,66]. The litter layer in pitch pine–scrub oak stands consisted of a larger proportion of pine needles compared to oak-dominated stands, and at higher fire intensities, a trend towards increased proportional consumption of fine litter was noted. During crowning wildfires in the Pinelands, a large proportion to nearly all of the fine litter

is consumed [49]. For 1 h + 10 h woody fuels, non-linearity in the relationship between loading and consumption was reflected in an increase in the value of the CC factor with increased loading for 1 h + 10 h fuels; this pattern also occurred to a lesser extent for the CC for total forest floor consumption. Overall, these relationships suggest that some caution should be exercised when emissions are calculated from CC factors averaged across forest types in the Pinelands. It would be more accurate to use the appropriate values for each forest type, and scaled combustion completeness factors may be more appropriate for calculating emissions during the combustion of 1 h + 10 h wood.

4.2. Tower Measurements of Heating and Turbulence during Prescribed Burns

Atmospheric turbulence generated by buoyant plumes above fire fronts plays the leading role in the lofting and dispersion of smoke during prescribed burns [67]. Observations indicate that sensible heat flux (ΔH) and turbulent kinetic energy (ΔTKE) are enhanced to a greater extent during high-intensity head and flanking burns than during low-intensity backing burns, and the relationship between sensible heat flux and TKE is stronger during high-intensity burns than during low-intensity burns. The enhanced turbulence at the top of the canopy, driven by greater rates of convective heat production and stronger buoyant plumes during the passage of higher-intensity fire fronts, results in increased lofting and dispersion of smoke, likely reducing the concentrations of $PM_{2.5}$, CO_2 , CO , and other pollutants near the surface more rapidly [24,25,55].

A number of sources of error may have influenced our estimates of sensible heat flux and turbulence statistics. We must acknowledge that the sonic anemometers were operated beyond their factory specifications, although the large majority of data recorded at air temperatures between 50 °C and ≈ 125 °C were not associated with sonic anemometer diagnostic error codes, indicating that sensor pairs were functioning normally. However, during the more intense head fires, extreme turbulence and rapidly fluctuating air temperatures in buoyant plumes and downdrafts may not have been captured accurately at a 10 Hz sampling speed. In addition, the variability in the 1 min values of sensible heat flux was greater during high-intensity burns than low-intensity burns, due in part to intermittent negative vertical wind velocities associated with cooler ambient air just before and sometimes after fire fronts' passage, which occasionally resulted in large negative 1 min sensible heat flux values. Linear gap filling of short intervals (≤ 0.5 s) and the limited use of thermocouple data to fill gaps in high-temperature data at some of the towers in high-intensity burns may also have affected our results. In addition, data were incomplete for the latter part of fire front passage at two of the six burn area towers in high-intensity head fires because the sonic anemometers were damaged.

Our estimates of TKE during the passage of fire fronts were also influenced by the choice of averaging times for the mean vertical and horizontal wind velocities. We followed the approach used in previous analyses [19,21–23] and used the half-hour period immediately before the fires were in close proximity to or under the towers to calculate the mean u , v , and w . In a previous set of analyses that included the instrumented burns up to 2015, 1 min averaging times were used to calculate TKE, and this approach resulted in lower TKE values because turbulence produced by buoyant plumes was included in the 1 min averages of u , v , and w [30]. Despite any methodological limitations, the values for sensible heat fluxes and TKE during fire front passage were consistent with measurements reported for other tower-based studies during prescribed burns. Seto et al. [19] reported a maximum air temperature of 202.5 °C and estimated that summed 1 min sensible heat flux totaled 50.2 kW m^{-2} for above-canopy measurements in a prescribed burn in a longleaf pine–turkey oak stand in North Carolina, USA. Clements et al. [29] reported that the peak 1 min sensible heat flux and TKE in a head fire during the RxCadre experiments was 15.2 kW m^{-2} and $\approx 3 \text{ m}^2 \text{ s}^{-2}$, respectively, in Florida, USA, within the range of our measurements for high-intensity burns. Much higher values were reported for a head fire in grasslands during “red flag” conditions in Texas, USA; the maximum sensible heat flux was $\approx 300 \text{ kW m}^{-2}$, and the TKE ranged up to $40 \text{ m}^2 \text{ s}^{-2}$ [31,68].

Using sonic anemometer data from three heights through the canopy during the prescribed burn conducted in a pine–oak stand in 2011, Heilman et al. [20,22] showed that increases in fire-induced TKE can be much larger at or near the top of the canopy than at levels near the ground, strongly influencing the diffusion and dispersion of smoke as it exits the top of the canopy. They also calculated the relative contributions of the horizontal and vertical components of the total TKE field (a measure of turbulence anisotropy) and indicated that the vertical component of TKE comprised less than 22% of the total TKE field, with the horizontal component of above-canopy TKE dominating the vertical component primarily at large eddy sizes occurring at low frequencies [21–23]. In further analyses, the presence of fire fronts was shown to cause substantial changes in the turbulence regimes compared to ambient conditions. During the passage of fire fronts, upward flux of high-horizontal-momentum air from below, termed outward interactions, and sweeps, defined as the downward flux of high-horizontal-momentum air from aloft, dominated the period characterized by the production of buoyant plumes and the largest sensible heat fluxes. The oscillatory behavior of sweeps and outward interactions differed from the behavior that occurred before and after fire fronts' passage, which was characterized by a larger proportion of ejections—defined as the upward flux of low-horizontal-momentum air from below—and sweeps. Overall, greater fireline intensity resulted in hotter buoyant plumes that were associated with enhanced sensible heat flux and turbulence within and above the canopy during the instrumented prescribed fires, and this contributed to a more rapid dispersion of smoke near the surface.

4.3. $PM_{2.5}$ in the Pinelands National Reserve

Atmospheric $PM_{2.5}$ concentrations measured adjacent to the Pinelands National Reserve at the Brigantine Wilderness Area IMPROVE site indicate that the annual mean and maximum 24 h $PM_{2.5}$ concentrations have slowly declined by approximately -0.24 and $-0.90 \mu\text{g m}^{-3} \text{yr}^{-1}$ over the last two decades, respectively, and in 2020 the average annual and maximum values over 24 h periods were 5.6 and $20.2 \mu\text{g m}^{-3}$, respectively, below the current annual and 24 h US EPA standards [69,70]. The overall trend of declining $PM_{2.5}$ concentrations is a result of existing state and federal emission controls, especially those regulating the $PM_{2.5}$ precursors SO_2 and NO_x from power plants, motor vehicles, heating oil, and off-road vehicles and equipment, and is consistent with the regional-scale reduction in $PM_{2.5}$ concentrations throughout the Eastern USA [71]. Although a regional analysis of the impacts of prescribed burning on $PM_{2.5}$ concentrations is beyond the scope of this research, it is instructive to consider patterns of $PM_{2.5}$ emission reductions across the state over the last decade, as prescribed burning now contributes a proportionally greater amount of $PM_{2.5}$ to the atmosphere. Total $PM_{2.5}$ emissions were estimated at 27,658 tons in 2007 and 19,965 tons in 2017 [72]. Reductions were greatest in the non-mobile point source category (53% reduction from 2007 to 2017) and least in the area-based category (4% reduction from 2007 to 2017). This latter category includes $PM_{2.5}$ emissions from prescribed burning and wildfires, which are lower than emissions from residential wood use (31% of total statewide $PM_{2.5}$ emissions in 2017) and other area-based emissions (26% of total statewide $PM_{2.5}$ emissions in 2017) [72]. However, because of significant reductions in $PM_{2.5}$ emissions from the point source, on-road mobile, and off-road mobile categories, the proportion of statewide emissions that can be attributed to prescribed burning and wildfires has increased over time.

Previous estimates of $PM_{2.5}$ from prescribed burns conducted by the NJFFS in the Pinelands suggest that they contributed an estimated 1.3%, with a range of 0.9 to 2.1%, of the total $PM_{2.5}$ emissions in the state in 2007 [55]. Their analyses also indicated that annual emissions of $PM_{2.5}$ from prescribed burning would be less than from wildfires when approximately <5000 ha a year was subjected to prescribed burning in the Pinelands. These estimates are only approximate, and factors affecting the actual release rates of $PM_{2.5}$ and other criterion pollutants include fuel moisture contents, the efficiency of fuel combustion, and the balance between flaming and smoldering combustion. However, the NJDEP anti-

pates additional reductions in the emission of PM_{2.5} and its precursors (SO₂, NO_x, VOCs, and ammonia) in the future due to state and federal controls that have been adopted, fleet replacement with newer, lower-emission vehicles, and equipment turnover [72,73]. Any increase in prescribed burning across the state would no doubt increase the proportions of PM_{2.5}, CO, and potentially other pollutants attributed to wildland fires. In addition, uncertainties exist for future trends in regional PM_{2.5} concentrations throughout the Eastern USA because of predicted increases in climate-driven wildfire activity and subsequent downwind transport throughout North America, potentially increasing surface concentrations in the Northeastern and mid-Atlantic regions [74,75].

5. Summary

Our research combined fuel consumption and emission estimates of PM_{2.5}, CO₂, and CO with observations of above-canopy sensible heat flux and turbulence during operational prescribed burns of varying intensity in the Pinelands National Reserve, New Jersey. Fine litter typically had the greatest pre-burn loading but the least spatial variability of the three major surface fuel types, and it contributed the most to PM_{2.5} emissions during prescribed burns. Estimated PM_{2.5} emissions were greater in pitch pine–scrub oak stands than in stands with a greater density of overstory oaks because of greater fuel loading and greater proportional consumption, although increased flaming combustion during high-intensity burns also influenced emissions. Tower measurements indicate that above-canopy sensible heat flux and turbulent kinetic energy (TKE) calculated at 1 min intervals during the passage of fire fronts were strongly influenced by fire behavior. Low-intensity backing burns, regardless of forest type, had weaker enhancement of above-canopy air temperature, vertical and horizontal wind velocities, sensible heat fluxes, and TKE compared to higher-intensity head and flanking burns. Sensible heat flux and TKE in buoyant plumes were unrelated during a majority of the low-intensity burns but more tightly coupled during high-intensity burns. The relatively low values and weak coupling that occurred during low-intensity backing burns likely resulted in reduced rates of smoke transport and dispersion, as well as more prolonged periods of elevated surface concentrations of PM_{2.5}, CO, and other compounds.

The development of combustion completeness factors by fuel and forest type can assist state and federal wildland fire managers in estimating smoke emissions during operational prescribed burns in the Pinelands more accurately, and it can be based on knowledge of pre-burn fuel loading or time since the last burn. Furthermore, information regarding forest floor and understory loading and consumption in Pinelands forests complements remotely sensed products used to characterize the effects of prescribed burning on forest structure. Overall, this comparative observational study provides a better understanding of the linkage between convective (sensible) heat flux and turbulence in buoyant plumes, and it contributes to the development of predictive tools that more completely account for the impacts of the forest overstory and fire intensity on smoke lofting and dispersion.

Author Contributions: Conceptualization, K.L.C., W.E.H., N.S., M.R.G. and R.H.; formal analysis, K.L.C., W.E.H. and M.R.G.; investigation, K.L.C., M.R.G., N.S., W.E.H., N.S., J.C. (Joseph Charney), M.P., E.M. and R.H.; data curation, K.L.C., J.C. (Jason Cole) and M.P.; writing—original draft preparation, K.L.C.; writing—review and editing, K.L.C., W.E.H., M.R.G. and N.S.; supervision, W.E.H., N.S. and R.H.; project administration, W.E.H., N.S., K.L.C., M.R.G. and R.H.; funding acquisition, W.E.H., N.S., K.L.C., M.R.G., E.M. and R.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the USDA Northern Research Station, the Joint Fire Science Program, grant numbers 09-1-04-1 and 12-1-03-11, and the Department of Defense Strategic Research and Development Program (SERDP), project number RC-2461.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Most of the original data presented in the study are openly available in the USDA Forest Service data repository [76,77]. Additional heat flux and turbulence data for the Cedar Bridge stand is in AmeriFlux data archive [78].

Acknowledgments: We thank the staff of the New Jersey Forest Fire Service for their continued support.

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

Appendix A

Table A1. Meteorological sensors and eddy covariance equipment used to measure turbulence and heat fluxes at all burn area towers, as well as additional meteorological variables at selected burn area towers and all control towers.

Variable	Instrument/Sensor	Vendor/Model	Height(s)
Turbulence	Sonic anemometer	R.M. Young 81000v, Gill Windmaster Pro	19.5 m or 16 m
CO ₂ and H ₂ O	LiCor 7000		19.5 m or 16 m
Solar radiation	LiCor 200	LiCor, Inc.	19.5 m or 16 m, 2 m
Net radiation	NRLite, CNR1	Kipp and Zonen	19.5 m or 16 m, 2m
Air temperature	HMP45c	Vaisala	18.5 m or 15 m, 2 m
Relative humidity	HMP45c	Vaisala	18.5 m or 15 m, 2 m
Precipitation	TE525	Texas Electronics	18.0 m or 15 m
Wind velocity	05013	R.M. Young	19.5 m or 15 m, 2m
Wind direction	05013	R.M. Young	19.5 m or 15 m, 2m
Soil temperature	CS-107, 109	Campbell Scientific	5 cm depth
Soil heat flux	HFT-3.1	REBS, Inc.	10 cm depth

Appendix B. Heat and Energy Release from Consumed Fuels

Heat release per unit area was calculated from consumption estimates of each fuel type, using 18.7 KJ g^{-1} as the estimated heat of combustion. Energy consumed during preheating and pyrolysis of fuels was calculated as a function of the mass, moisture content, and initial ambient temperature of each fuel type [26]:

$$E_{pp} = \text{Mass} \left(0.7 \text{ kJ g}^{-1} + \left(0.0042 \text{ kJ g}^{-1} \text{H}_2\text{O} \times M_c (100 - T_{\text{air}}) \right) \right)$$

where E_{pp} is the energy consumed in preheating and pyrolysis, Mass is the amount of each fuel type consumed, M_c is the moisture content of each fuel type, and T_{air} is the ambient air temperature. Based on the work of Kremens et al. [26], it was assumed that radiant heat flux accounted for approximately 17% of the total heat of combustion of each type:

$$E_R = E_{pp} * 0.17 \text{ kJ g}^{-1}$$

where E_R is the radiant heat flux. The latent heat flux from combusted fuels was calculated using the mass and moisture content of each fuel type, assuming complete vaporization of the moisture in consumed fuels:

$$E_L = \text{Mass} * (M_c * Q_v + Q_C)$$

where E_L is the latent heat flux, Q_v is the latent heat of vaporization (2.25 kJ g^{-1}), and Q_C is the heat due to moisture released by combustion (1.40 kJ g^{-1}). The remaining heat flux was assumed to be convective heat and energy consumed in the litter layer and soil heating [26].

Table A2. Summary of equations and statistics for the relationship between pre-burn fuel loading and consumption estimated from post-burn measurements for understory vegetation, 1 h + 10 h woody fuels, fine litter, and litter and woody fuels on the forest floor. Units are mean tons ha⁻¹, and data were fitted to linear equations with the following form: Consumption = α (fuel loading) – β .

Fuel Type	n	Slope	Intercept	r ²	F	p
Understory (Figure 3a)	35	0.668	−0.040	0.665	66.4	<0.001
1 + 10 h wood (Figure 3b)	46	0.852	−0.106	0.860	276.9	<0.001
Fine litter	46	0.553	−0.005	0.440	34.0	<0.01
Forest floor (Figure 3c)	46	0.768	−0.252	0.645	77.4	<0.001

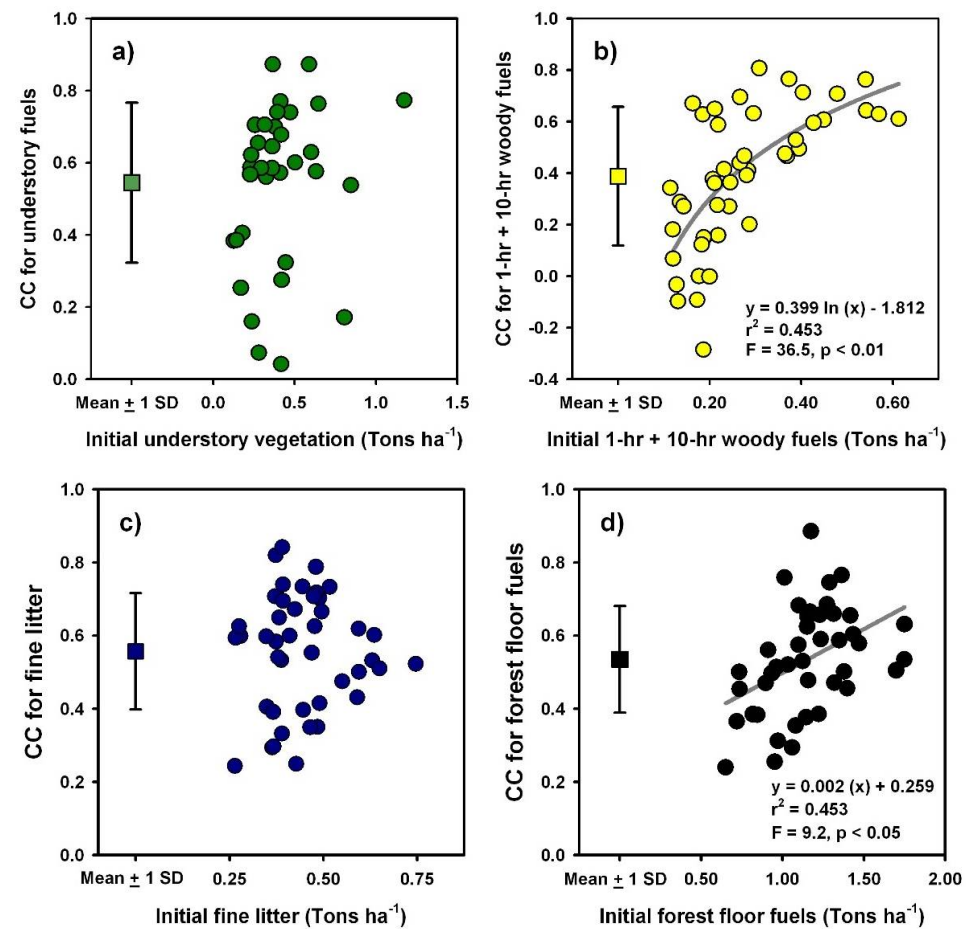


Figure A1. The relationship between pre-burn loading and calculated combustion completeness factor (CC_x) for (a) understory vegetation, (b) 1 h + 10 h woody fuels, (c) fine litter, and (d) total forest floor material. Pre-burn fuel loading is in g m⁻², and mean $\pm$ 1 SD values for each coefficient are shown to the left of each scatterplot.

Table A3. Pre- and post-burn fuel loading and estimated consumption during the 11 instrumented prescribed burns in the Pinelands National Reserve. Units are g m⁻² $\pm$ 1 SD.

Site/Fuel Type	Pre-Burn	Post-Burn	Consumed	Percent
Low-intensity fires				
Pitch pine–scrub oak, Cedar Bridge 2008, n = 10				
Understory	445 $\pm$ 102	301 $\pm$ 133	144	32.4
1 + 10 h wood	207 $\pm$ 97	129 $\pm$ 44	78	37.7
Fine litter	1492 $\pm$ 359	712 $\pm$ 178	780	52.3
Total	2144 $\pm$ 350	1142 $\pm$ 225	1002	46.7

Table A3. Cont.

Site/Fuel Type	Pre-Burn	Post-Burn	Consumed	Percent
Pitch pine–scrub oak, Cedar Bridge 2013, n = 10				
Understory	411 ± 334	176 ± 93	235	57.2
1 h wood	182 ± 134	59 ± 25	123	67.6
10 h wood	187 ± 142	138 ± 122	49	26.2
Fine litter	785 ± 259	204 ± 68	581	74.0
Total	1565 ± 583	577 ± 114	988	63.1
Pitch pine–scrub oak, Warren Grove 2015, n = 36				
Understory	230 ± 122	95 ± 51	134	58.3
1 h wood	100 ± 67	88 ± 32	12	12.0
10 h wood	77 ± 49	89 ± 55	−11	−14.3
Fine litter	558 ± 152	224 ± 71	334	59.9
Total	965 ± 235	495 ± 161	469	48.6
Pitch pine–scrub oak, Cedar Bridge 2020, n = 10				
Understory	686 ± 196	563 ± 204	123	17.9
1 h wood	101 ± 79	89 ± 36	12	11.9
10 h wood	83 ± 76	21 ± 32	61	73.5
Fine litter	1231 ± 282	748 ± 144	483	39.2
Total	2101 ± 514	1421 ± 282	680	32.4
Pine–oak, Joint Base MDL 2006, n = 15				
Understory	486 ± 360	199 ± 155	287	59.1
1 + 10 h wood	191 ± 125	185 ± 98	6	3.1
Fine litter	933 ± 360	423 ± 164	510	54.7
Total	1610 ± 520	807 ± 293	803	49.9
Oak–pine, Silas Little EF 2012, n = 24				
Understory	170 ± 132	127 ± 56	43	25.3
1 h wood	113 ± 67	95 ± 42	18	15.9
10 h wood	74 ± 73	64 ± 65	10	13.5
Fine litter	747 ± 116	311 ± 78	436	58.4
Total	1104 ± 246	597 ± 134	507	45.9
Oak–pine, Silas Little EF 2019, n = 12				
Understory	287 ± 96	261 ± 125	26	9.1
1 h wood	85 ± 38	85 ± 26	0	0.0
10 h wood	29 ± 17	33 ± 22	−3	−10.3
Fine litter	929 ± 293	605 ± 116	325	35.0
Total	1330 ± 338	983 ± 119	347	26.1
High-intensity fires				
Pitch pine–scrub oak, Warren Grove 2013, n = 36				
Understory	380 ± 219	114 ± 86	266	70.0
1 h wood	294 ± 174	107 ± 25	186	63.3
10 h wood	133 ± 122	66 ± 26	67	50.4
Fine litter	741 ± 80	217 ± 56	524	70.7
Total	1547 ± 327	504 ± 136	1042	67.4
Pitch pine–scrub oak, Warren Grove 2014, n = 36				
Understory	473 ± 134	123 ± 79	350	74.0
1 h wood	163 ± 88	83 ± 27	80	49.1
10 h wood	103 ± 80	66 ± 60	37	35.9
Fine litter	963 ± 232	272 ± 69	691	71.8
Total	1702 ± 307	543 ± 131	1158	68.0

Table A3. *Cont.*

Site/Fuel Type	Pre-Burn	Post-Burn	Consumed	Percent
Pine-oak, Brendan Byrne SF 2011, n = 27				
Understory	632 ± 289	268 ± 175	364	57.6
1 h wood	73 ± 56	34 ± 36	39	53.4
10 h wood	41 ± 63	41 ± 66	0	0.0
Fine litter	732 ± 232	446 ± 150	287	39.2
Total	1478 ± 388	789 ± 269	689	46.6

Table A4. Maximum air temperature and turbulence statistics for all towers during the 11 instrumented prescribed fires conducted in the Pinelands. Towers designated with the letter “C” are control towers outside of the burn areas. Averaged differences are designated as “Δ values”. Re- and post-burn fuel loading and estimated consumption during the 11 instrumented prescribed burns in the Pinelands National Reserve. Units are g m^{−2} ± 1 SD.

Site	Air Temperature (°C)			Vertical Wind (m s ^{−1})			Horizontal Wind (m s ^{−1})		
	10 Hz	1 s	1 min	10 Hz	1 s	1 min	10 Hz	1 s	1 min
Low-intensity fires									
Pitch pine–scrub oak, Cedar Bridge 2008									
CB 1	49.3	39.4	11.8	3.79	2.84	0.73	8.50	8.29	5.65
CB C1	11.2	11.0	9.7	3.63	2.84	0.71	8.99	8.02	4.67
CB C2	11.2	10.9	9.4	3.43	2.78	0.75	9.72	9.04	5.18
Δ Values	38.2	26.9	2.3	0.26	0.03	0.00	−0.86	−0.24	0.72
Pitch pine–scrub oak, Cedar Bridge 2013									
CB 2	51.5	34.1	13.9	5.78	3.94	0.70	13.94	12.78	7.22
CB C1	11.2	10.8	10.2	5.16	3.22	0.72	14.90	13.85	9.83
CB C2	11.3	11.2	10.0	5.42	3.01	0.48	14.83	13.09	5.95
Δ Values	40.3	23.1	3.8	0.49	0.83	0.09	−0.93	−0.70	−0.67
Pitch pine–scrub oak, Warren Grove 2015									
WG 1	67.6	57.3	21.0	5.93	3.64	1.38	9.28	7.64	4.49
WG 2	49.3	36.7	17.4	3.86	3.00	0.98	11.15	8.44	5.09
WG 3	37.3	27.9	9.7	3.71	2.72	0.58	9.55	8.47	5.29
WG C1	8.2	8.0	6.6	3.20	2.60	0.53	9.28	8.10	5.23
Δ Values	43.2	32.6	9.5	1.30	0.52	0.45	0.71	0.08	−0.27
Pitch pine–scrub oak, Cedar Bridge 2020									
CB W	25.2	18.8	4.4	5.35	3.84	0.70	15.60	14.23	7.80
CB C1	3.6	2.6	1.9	5.21	3.09	0.58	14.10	12.05	6.31
Δ Values	21.6	16.2	2.5	0.14	0.75	0.12	1.5	2.18	1.49
Pitch pine–scrub oak, Cedar Bridge 2020									
CB E	74.0	55.4	10.7	5.31	3.63	0.65	15.15	13.20	6.71
CB C1	5.7	3.9	1.8	5.29	3.15	0.50	12.56	11.22	5.87
Δ Values	68.3	51.5	8.9	0.02	0.48	0.15	2.59	1.98	0.84
Pine-oak, Joint Base MDL 2006									
JB 1	24.4	21.4	8.4	4.03	3.09	1.38	11.04	10.32	6.52
JB C1	2.5	2.3	1.6	3.65	2.74	0.64	10.04	9.16	6.23
JB C2	2.9	2.6	1.5	4.08	3.10	0.55	10.53	8.08	5.2
Δ Values	21.7	18.9	6.9	0.17	0.17	0.79	0.75	1.70	0.81
Oak-pine, Silas Little EF 2012									
SL 1	31.8	24.6	12.1	3.28	2.27	0.69	8.16	7.39	5.33
SL C1	6.6	6.5	5.9	2.95	2.19	0.89	8.34	7.61	5.76
SL C2	9.4	9.2	8.2	3.76	2.45	0.77	9.24	8.08	5.33
Δ Values	23.8	16.7	5.1	−0.14	−0.05	−0.14	−0.63	−0.46	−0.22

Table A4. Cont.

Site	Air Temperature (°C)			Vertical Wind (m s ^{−1})			Horizontal Wind (m s ^{−1})		
	10 Hz	1 s	1 min	10 Hz	1 s	1 min	10 Hz	1 s	1 min
Oak–pine, Silas Little EF 2019									
SL N	36.4	29.6	17.9	3.05	2.69	0.67	8.78	7.92	4.64
SL W	44.6	35.0	17.3	4.23	2.74	1.02	8.52	7.39	4.57
SL Flux	54.4	40.8	19.9	4.65	3.42	1.04	8.43	7.80	6.10
SL E	37.4	32.6	17.2	4.57	3.34	1.19	8.81	8.19	5.51
SL C1	14.2	14.0	12.6	3.63	2.26	0.66	9.45	8.26	5.16
Δ Values	29.0	20.0	5.5	0.50	0.79	0.32	−0.82	−0.44	0.04
High-intensity fires									
Pitch pine–scrub oak, Warren Grove 2013									
WG 1	122.8	109.6	41.9	9.37	6.73	1.78	12.84	9.72	4.76
WG 2	332.1	228.1	78.4	10.32	7.22	2.08	16.01	8.27	3.95
WG 3	159.3	129.1	42.0	6.22	4.47	2.52	10.02	6.31	4.12
WG C1	10.3	9.9	8.8	2.2	1.5	0.40	6.43	5.9	3.84
Δ Values	194.5	145.7	45.3	6.44	5.52	1.73	6.53	3.41	0.44
Pitch pine–scrub oak, Warren Grove 2014									
WG 1	233.0	198.8	76.8	9.04	5.82	2.55	13.42	11.17	6.54
WG 2	154.0	100.8	38.8	9.35	5.56	1.16	14.6	10.63	6.46
WG 3	113.4	63.4	27.8	5.78	4.09	1.08	14.71	10.05	6.26
WG C1	20.9	20.4	19.0	4.34	3.19	0.43	11.4	10.31	5.9
Δ Value	145.9	100.6	28.8	3.72	1.97	1.17	2.84	0.31	0.52
Pine–oak, Brendan Byrne SF 2011									
BB 1	121	100.6	49	8.26	5.25	2.62	12.73	9.64	6.18
BB C1	11.3	10.8	8.5	3.35	2.64	0.67	8.64	7.9	5.32
BB C2	11.4	11	9.9	4.03	3.25	0.99	9.12	8.59	5.98
Δ Values	109.6	89.7	39.9	4.57	2.31	1.79	3.86	1.39	0.53

Table A5. Mean and maximum values of sensible heat flux and turbulent kinetic energy measured at 1 min intervals for burn area and control towers during the 11 instrumented prescribed fires conducted in the Pinelands. Towers designated with the letter “C” are control towers outside of the burn areas, and sensible heat flux and TKE values are averaged for the time periods that prescribed fires were burning in the vicinity of and under burn area towers during flame front passage. Averaged differences between control and burn area towers are designated as “Δ values”.

Fire Behavior and Stand	Time (Minutes)	Sensible Heat Flux (kW min ^{−1})		TKE (m ² s ^{−2} min ^{−1})	
		Mean ± 1 SD	Maximum	Mean ± 1 SD	Maximum
Low-intensity prescribed burns					
Pitch pine–scrub oak, Cedar Bridge 2008					
CB 1	30	1.738 ± 0.966	4.030	2.627 ± 1.194	5.438
CB C1		0.256 ± 0.144	0.767	0.829 ± 0.467	3.807
CB C2		0.276 ± 0.208	0.948	0.504 ± 0.289	3.047
Δ Values		1.472	3.173	1.965	2.011
Pitch pine–scrub oak, Cedar Bridge 2013					
CB 2	40	1.900 ± 1.864	6.890	4.930 ± 1.512	8.194
CB C1		0.087 ± 0.049	0.635	3.267 ± 1.464	8.837
CB C2		0.192 ± 0.096	0.541	2.300 ± 0.998	8.163
Δ Values		1.761	6.302	1.980	

Table A5. Cont.

Fire Behavior and Stand	Time (Minutes)	Sensible Heat Flux (kW min ⁻¹)		TKE (m ² s ⁻² min ⁻¹)	
		Mean ± 1 SD	Maximum	Mean ± 1 SD	Maximum
Pitch pine–scrub oak, Warren Grove 2015					
WG 1 N	22	4.015 ± 6.013	30.022	2.234 ± 0.994	4.706
WG 2 W	28	2.899 ± 2.191	9.542	2.880 ± 1.345	7.230
WG 3 S	17	2.952 ± 3.691	14.623	4.524 ± 2.043	9.672
WG C1		0.134 ± 0.068	0.308	1.232 ± 0.648	3.636
Δ Values		3.155	17.754	1.981	3.567
Pitch pine–scrub oak, Cedar Bridge 2020					
CB W	30	1.052 ± 0.754	3.543	4.898 ± 1.849	8.903
CB C1		0.100 ± 0.063	0.291	3.537 ± 1.431	8.753
Δ Values		0.952	3.252	1.361	0.150
Pitch pine–scrub oak, Cedar Bridge 2020					
CB E	18	3.845 ± 5.109	20.431	6.237 ± 2.364	11.119
CB C1		0.146 ± 0.093	0.444	3.954 ± 1.179	7.308
Δ Values		3.699	19.987	2.283	3.811
Pine–oak, Joint Base MDL 2006					
JB 1	30	2.198 ± 1.730	7.563	5.128 ± 2.016	10.882
JB C1		0.163 ± 0.094	0.649	1.552 ± 0.627	4.039
JB C2		0.265 ± 0.152	0.802	1.695 ± 0.770	4.655
Δ Values		1.984	6.838	2.271	5.456
Oak–pine, Silas Little EF 2012					
SL 1	30	0.500 ± 1.060	4.975	2.659 ± 1.441	6.639
SL C1		0.114 ± 0.099	0.322	0.734 ± 0.381	3.266
SL C2		0.195 ± 0.122	0.508	1.071 ± 0.472	3.364
Δ Values		0.346	4.560	1.757	3.324
Oak–pine, Silas Little EF 2019					
SL N	20	2.333 ± 1.620	5.645	1.670 ± 0.570	2.678
SL W	20	2.500 ± 2.631	7.407	1.903 ± 0.870	3.337
SL Flux	15	1.771 ± 3.375	14.841	3.013 ± 1.087	5.248
SL E	15	2.584 ± 2.451	8.144	2.653 ± 1.030	4.232
SL C1		0.184 ± 0.170	0.646	1.138 ± 0.771	3.291
Δ Values		2.113	8.363	1.172	0.583
High-intensity prescribed burns					
Pitch pine–scrub oak, Warren Grove 2013					
WG 1 N	6	15.018 ± 23.290	54.030	6.377 ± 5.697	16.729
WG 2 W	12	7.342 ± 13.289	46.602	4.416 ± 2.007	7.448
WG 3 S	12	9.797 ± 34.512	26.173	4.661 ± 5.152	9.211
WG C1		0.193 ± 0.118	0.551	0.556 ± 0.331	1.746
Δ Value		10.987	49.765	4.595	9.383
Pitch pine–scrub oak, Warren Grove 2014					
WG N	10	6.928 ± 14.079	40.562	7.351 ± 4.212	15.800
WG W	12	7.730 ± 5.302	20.996	4.950 ± 1.757	9.234
WG S	10	8.878 ± 12.406	38.423	6.104 ± 2.451	9.873
WG C1		0.144 ± 0.069	0.308	2.634 ± 0.866	5.034
Δ Value		7.701	33.019	3.501	6.602

Table A5. Cont.

Fire Behavior and Stand	Time (Minutes)	Sensible Heat Flux (kW min ⁻¹)		TKE (m ² s ⁻² min ⁻¹)	
		Mean ± 1 SD	Maximum	Mean ± 1 SD	Maximum
Pine–oak, Brendan Byrne State Forest 2011					
BB 1	30	4.467 ± 8.718	42.322	8.719 ± 4.924	20.027
BB C1		0.308 ± 0.181	0.786	1.385 ± 0.591	3.276
BB C2		0.195 ± 0.147	0.532	1.457 ± 0.553	3.277
Δ Values		4.216	41.663	7.298	16.751

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