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# Relationships between Firing Pattern, Fuel Consumption, and Turbulence and Energy Exchange during Prescribed Fires

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## Introduction

Fuel loading and consumption during prescribed fires are well-characterized for many pine-dominated forests, but relationships between firing practices, consumption of specific fuel components, and above-canopy turbulence and energy exchange have received less attention (Ottmar et al. 2016, Clements et al. 2016). However, quantitative information on how firing patterns and the resultant fire behavior control the consumption of surface, understory and canopy fuels is important for "fine tuning" the effectiveness of fuel reduction treatments while simultaneously minimizing the adverse impacts of ember transport and smoke dispersion on local air quality. To better understand these relationships, we estimated fuel consumption using pre- and post-burn destructive sampling to quantify surface and understory fuels and LiDAR data to quantify canopy fuels, and measured turbulence and energy exchange from a network of above-canopy towers using sonic anemometers and meteorological sensors during eight prescribed fires ranging in intensity from low-intensity backing fires to high-intensity head fires in the New Jersey Pinelands. In two stands with relatively low surface and understory fuel loading, a backing and an attempted head fire were ignited, respectively. In the remaining six stands with relatively high surface and understory fuel loading, three backing and three head fires were ignited. We then explored the relationships between firing practice and the resultant fire behavior, consumption of surface, understory and canopy fuels, and above-canopy heating and turbulence.

## Materials and methods

Fuel loading and consumption in each stand were estimated from pre- and post-burn sampling in 1 $m^2$ plots (n = 10 to 32 per stand). Forest floor samples (L horizon only) were dried at 70 ºC, separated into 1-hr fine, 1-hr wood and 10-hr wood, and weighed. Shrubs, seedlings and saplings < 2 m tall were separated into foliage, 1-hr stems and 10-hr stems, and dried and weighed. Canopy fuel loading and consumption were estimated from pre- and post-burn LiDAR acquisitions, calibrated for pitch pine canopies (Skowronski et al. 2011, Clark et al. 2013). One to three above-canopy flux towers were located in each stand to be burned, and one to three control towers were located in the adjacent burn block and/or in similar forests in the Pinelands. All towers were instrumented with one to three sonic anemometers (RM Young model 81000V, Traverse City, MI, USA) and fine wire thermocouples (Omega Engineering, Inc., Stamford, CT, USA). Turbulent kinetic energy was calculated for 1-minute intervals, and values were not corrected for the effects of the fire (i.e., we did not use a pre-fire or control values as 1-minute means to calculate horizontal and vertical wind velocity deviations). Delta values between maximum sonic temperatures and TKE values were calculated for control towers versus the towers in burn blocks. In addition to sonic anemometers and thermocouples, control towers were instrumented with standard meteorological sensors (air temperature, relative humidity, wind speed and direction) 4 meters above canopy and at 2 meters within the canopy, and 10-hr fuel moisture and temperature, soil temperature and soil heat flux sensors (Clark et al. 2012, Heilman et al. 2015). All prescribed burns were conducted within a fairly narrow range of conditions, with ambient air temperature between 0.9 ± 0.9 and 16.7 ± 1.7 °C, relative humidity between 20.2 ± 1.1 and 38.6 ± 3.6 %, and wind speeds between 1.5 ± 0.3 and 4.3 ± 0.6 m $s^{-1}$ (mean ± 1 SD; Table 1).

Table 1. Forest type, surface and understory fuel loading, and consumption estimated from pre- and post-burn sampling, meteorological conditions during the burn, and predominant fire behavior for eight prescribed burns in the New Jersey Pinelands.

| Forest type | Fuels[a] (tons $ha^{-1}$) | | Meteorological conditions | | | Fire behavior |
|---|---|---|---|---|---|---|
| | Pre-burn | Consumed | Air (ºC) | RH (%) | Wind (m $sec^{-1}$) | |
| Low fuel loading | | | | | | |
| 1. Pine oak | 11.0 ± 2.5 | 5.1 | 5.8 ± 1.4 | 21.6 ± 2.2 | 2.2 ± 0.3 | Backing fire |
| 2. Pine scrub oak | 9.7 ± 2.4 | 4.7 | 3.7 ± 0.9 | 20.2 ± 1.1 | 2.7 ± 0.4 | Attempted head fire |
| Low intensity burns | | | | | | |
| 3. Pine oak | 16.1 ± 5.2 | 8.0 | 0.9 ± 0.9 | 31.1 ± 3.0 | 3.0 ± 3.0 | Backing fire |
| 4. Pine scrub oak | 21.4 ± 3.5 | 10.2 | 9.0 ± 1.3 | 34.9 ± 7.1 | 2.2 ± 0.4 | Backing fire |
| 5. Pine scrub oak | 15.7 ± 5.8 | 9.9 | 7.2 ± 1.2 | 34.3 ± 2.0 | 4.3 ± 0.6 | Backing fire |
| High intensity burns | | | | | | |
| 6. Pine oak | 14.8 ± 3.9 | 6.9 | 8.6 ± 1.9 | 37.1 ± 8.4 | 2.1 ± 0.6 | Flanking fire, torching |
| 7. Pine scrub oak | 15.5 ± 3.8 | 10.4 | 7.6 ± 1.0 | 38.6 ± 3.6 | 1.5 ± 0.3 | Head fire, torching |
| 8. Pine scrub oak | 17.0 ± 3.1 | 11.6 | 16.7 ± 1.1 | 33.1 ± 4.5 | 2.9 ± 0.4 | Head fire, torching |

[a]Sum of forest floor and understory fuels loading and consumption estimated from 1 $m^2$ plots.

**Results and Discussion**

Surface and understory fuel loading and consumption followed the order fine fuels on the forest floor > understory vegetation > 1 + 10-hr wood on the forest floor in all stands. Consumption of fine, 1 + 10-hr wood, and understory fuels were all strong functions of initial loading, with a trend towards greater proportional consumption of understory vegetation with increasing fire intensity (Fig. 1). Torching and significant canopy fuel consumption occurred only during the three head fires. The strong relationship between loading of specific fuels and consumption is similar to results obtained from a landscape-scale census of 35 prescribed burns across upland forest types in the Pinelands which represented a wider range of initial fuel loading and consumption estimates (Clark et al. 2015).

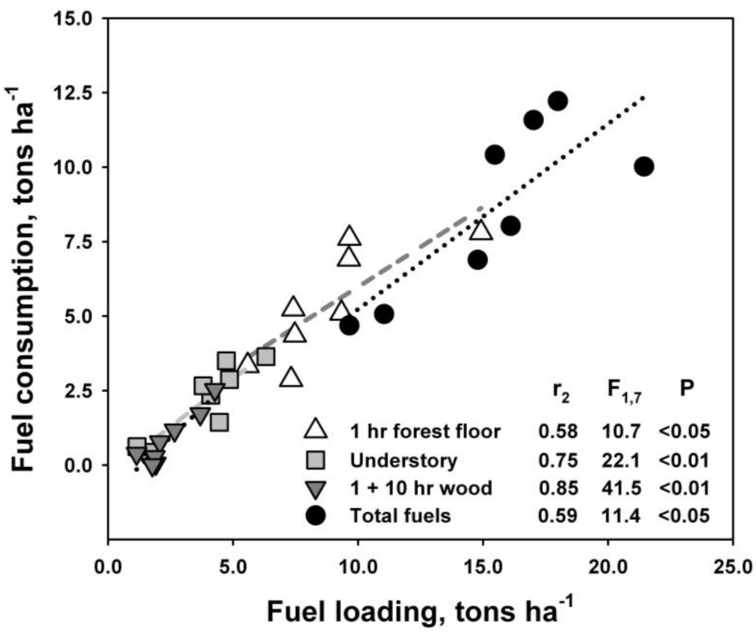


**Figure 1. Surface and understory fuel loading and consumption estimated from 1.0 m$^2$ plots (n=10 to 32 in each burn) during eight prescribed burns in the New Jersey Pinelands.**

10 Hz vertical wind speed, 10 Hz air temperature, and turbulent kinetic energy (TKE; $m^{-2}$ $s^{-2}$) measured above-canopy from towers during low-intensity backing fires were enhanced up to 1.1, 4.8 and 1.1 times over values at control towers. During high-intensity fires, values were enhanced up to 4.3, 13.8, and 5.6 times over those at control towers, respectively (Fig. 2, Table 2). Maximum values for above-canopy 10 Hz vertical wind speed, 10 Hz air temperature, and TKE in head fires were 9.4 m $s^{-1}$, > 142 °C, and 9.7 $m^2$ $s^{-2}$. There was a significant relationship between peak Δ air temperature and peak Δ TKE during fires (Figure 3; $r^2 = 0.56$, $F_{1,7} = 10.0$, $P < 0.05$). Surprisingly, other relationships were much weaker; total fuel (surface + understory + canopy) consumption was only weakly related to maximum Δ temperature above the canopy during fires ($r^2 = 0.25$, $F_{1,7} = 3.4$, P = NS), and the relationship between total fuel consumption and Δ TKE during fires was especially weak ($r^2 = 0.10$, $F_{1,7} = 1.8$, P = NS).

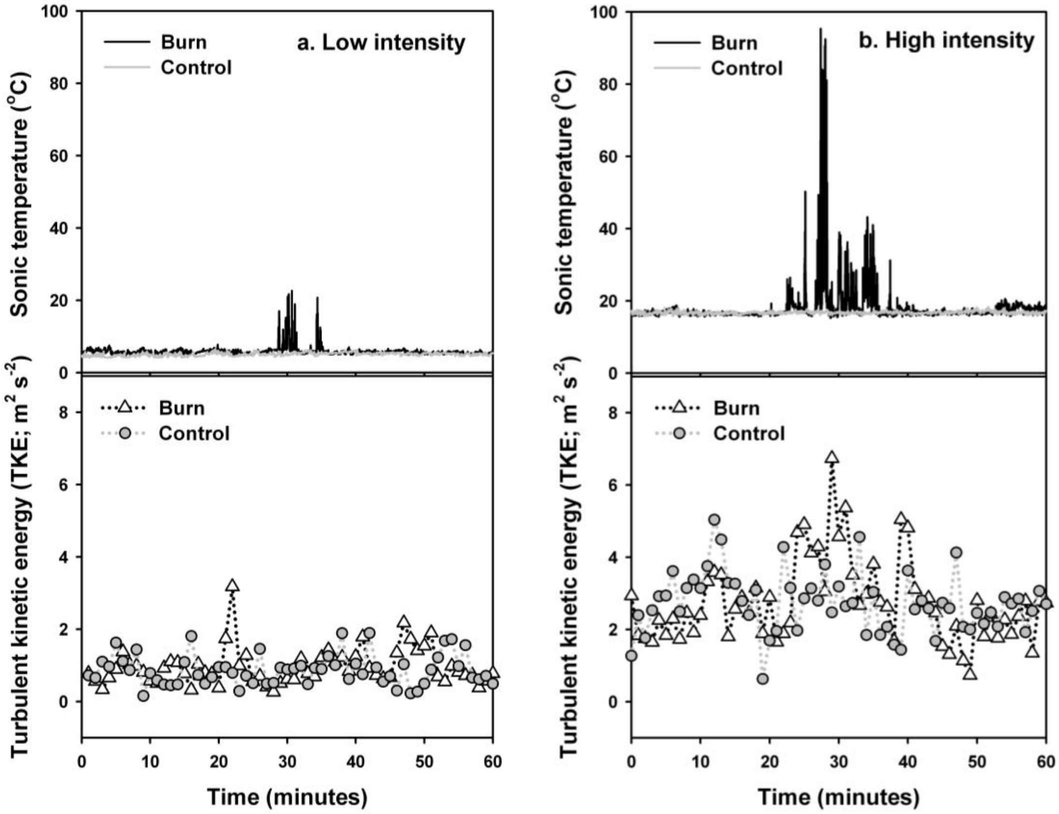


**Figure 2. Above-canopy air temperature (°C) and turbulent kinetic energy (TKE; $m^2 s^{-2}$) measured using sonic anemometers in burned and control stands during prescribed burns in (a) a pine – oak stand with low fuel loading burned in 2012 (stand #1 in Tables 1 and 2), and (b) a pitch pine-scrub oak stand burned in a head fire in 2014 (stand #8 in Tables 1 and 2). Sonic temperature and 3-D wind speed data were measured at 10 Hz. Sonic temperature data were then integrated to 1-second averages, and TKE values are 1-minute averages.**

Table 2. Forest type, maximum 1-second vertical wind speed (w; m $s^{-1}$), maximum above-canopy 1-second sonic air temperature (°C), and turbulent kinetic energy above the canopy in burned and control stands for eight prescribed burns in the New Jersey Pinelands. Values are means ± 1 SD. Maximum 10 Hz values are shown in parentheses.

| Forest type | Vertical wind speed (m $s^{-1}$) Control | Vertical wind speed (m $s^{-1}$) Burn | Air temperature (°C) Control | Air temperature (°C) Burn | TKE ($m^2 s^{-2}$) Control | TKE ($m^2 s^{-2}$) Burn |
|---|---|---|---|---|---|---|
| Low fuel loading | | | | | | |
| 1. Pine oak | 1.9 ± 0.3 | 2.2 ± 0.3 (3.3) | 6.5 ± 0.1 | 24.6 ± 7.4 (31.8) | 3.27 | 3.17 |
| 2. Pine scrub oak | 2.6 ± 0.9 | 3.6 ± 0.7 (5.9) | 8.0 ± 0.1 | 57.3 ± 4.9 (67.6) | 3.64 | 3.69 |
| Low intensity burns | | | | | | |
| 3. Pine oak | 2.7 ± 0.3 | 3.1 ± 0.3 (3.7) | 2 .6 ± 0.1 | 31.2 ± 1.3 (32.3) | 3.64 | 4.63 |
| 4. Pine scrub oak | 2.9 ± 0.3 | 2.7 ± 0.6 (3.8) | 10.8 ± 0.3 | 41.7 ± 2.5 (44.2) | 3.06 | 2.77 |
| 5. Pine scrub oak | 3.2 ± 0.5 | 4.1 ± 1.4 (5.8) | 10.8 ± 0.2 | 31.7 ± 4.6 (51.5) | 8.80 | 8.70 |
| High intensity burns | | | | | | |
| 6. Pine oak | 3.3 ± 0.3 | 5.3 ± 1.5 (8.3) | 11.0 ± 0.1 | 99.7 ± 9.8 (121.0) | 3.28 | 7.70 |
| 7. Pine scrub oak | 1.5 ± 0.1 | 6.5 ± 2.3 (9.4) | 9.9 ± 0.2 | 109.6 ± 54.7 (142.1) | 1.74 | 9.72 |
| 8. Pine scrub oak | 3.2 ± 0.5 | 5.4 ± 3.2 (9.0) | 20.7 ± 0.1 | 122.3 ± 5.3 (127.3) | 5.03 | 6.95 |

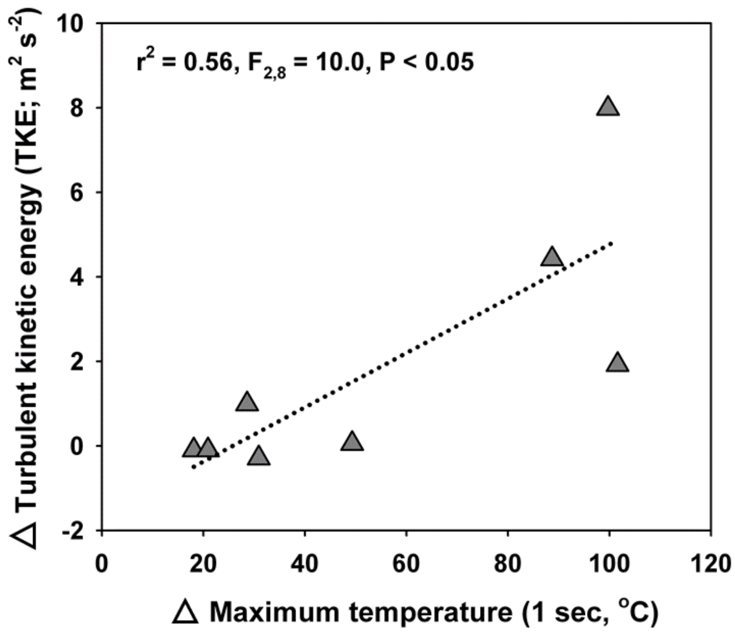


**Figure 3. The relationship between maximum above-canopy Δ temperature and maximum Δ turbulent kinetic energy for the eight prescribed burns.**

Our results indicate that low-intensity fires in the Pinelands can be highly effective at reducing fine and woody fuels on the forest floor, but are less effective at reducing understory vegetation and ladder fuels in the lower canopy. Residence time of low-intensity flame fronts on the forest floor was a key factor in their effectiveness in consuming surface fuels. Head fires resulted in much greater consumption of canopy fuels, but not necessarily greater consumption of surface fuels, and enhanced turbulent transfer of smoke and embers above the canopy. In some cases, high intensity fires are preferable for their ecological benefits, but are usually not feasible in WUI areas where ember management and fire-line control during hazardous fuel reduction treatments are also major objectives. These results can assist wildland fire managers assess tradeoffs between reducing hazardous fuels and mitigating emissions when planning and conducting prescribed fires. Our research also provides valuable information for the development and evaluation of next-generation fire behavior and smoke emission models.

## Conclusions

Consumption of forest floor and understory fuels was strongly correlated with initial loading, and was less affected by firing practice (backing vs. head fires). Longer residence times of flame fronts during low-intensity backing fires contributed to their effectiveness in reducing surface and understory story fuels. Consumption of ladder and canopy fuels only occurred during high intensity fires, but these are also associated with higher turbulence and greater potential for smoke dispersion and ember production. Our results can assist wildland fire managers optimize hazardous fuel reduction goals while minimizing adverse local air-quality impacts and ember production when planning and conducting prescribed fires.

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