FIREFLUX EXPERIMENTS IN THE NEW JERSEY PINE BARRENS

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1. ABSTRACT

We measured fuel consumption, turbulent exchanges of energy, water vapor and carbon dioxide, and PM 2.5 concentrations during an operational prescribed fire conducted by the New Jersey Forest Fire Service in the Pine Barren of New Jersey in March 2008. Fuel consumption was quantified using pre- and postburn sampling of the forest floor and understory, and LIDAR data to estimate canopy and understory fuel consumption during the fire. Eddy covariance and standard meteorological measurements were used to estimate turbulence and net fluxes of sensible heat, latent heat, and CO₂. PM 2.5 (particulate matter with diameters < 2.5 µm) was quantified using E-BAM Beta particle attenuators at two sites, one located within the burn block and the second located in an adjacent clearing that was not burned.

Fuel consumption was 8.3 ± 1.9 , 0.8 ± 0.8 and 0.7 ± 1.1 metric T ha⁻¹ for 1-hour, 10-hour and understory vegetation, representing 54, 38 and 15 % of pre-burn loadings, respectively. Turbulent transfer, as estimated using halfhourly averaged friction velocity (u*; m s⁻¹) four meters above the canopy during the prescribed fire increased ca. 32% over typical values for ambient conditions. Energy flux, calculated as the sum of latent and sensible heat fluxes above the canopy, was five times greater than available energy during the fire; half-hourly sensible heat flux peaked at 1675 W m⁻², and water vapor flux at 483 W m⁻². Net CO₂ release during the fire was 204 g C m^{-2} , representing 160% of the annual C uptake averaged over the previous three years (2005-2007). However, fuel combustion estimated from pre- and post sampling was 410 g C m⁻², indicating that flux measurement may have underestimated actual fuel consumption.

PM 2.5 concentrations at 2 meter height peaked at 4155 ug m⁻³ in the fire, but dropped to below 35 ug m⁻³ within 8 hours. PM 2.5

concentrations in the clearing peaked at 873 ug m⁻³ during the fire, and also decreased rapidly when the combustion plume dissipated. Simultaneous quantification of fluxes and fuel consumption during fires are essential for evaluating predictive plume dispersion models.

Keywords: Energy and water vapor fluxes, eddy covariance, prescribed fire, Pitch Pine, Pine Barrens, New Jersey

2. INTRODUCTION

Prescribed fires are essential for the protection of homes and property from wildfires. Turbulent transfer of gasses and particulates from prescribed fires contributes to atmospheric pollutant loads, and where prescribed fires are conducted near urban centers or in nonattainment areas, the potential exists for exceeding federal, state or local air quality standards. In addition, impairment of visibility by smoke on roads and highways is a safety hazard.

A number of predictive plume dispersion models, including the Weather Research and Forecasting (WRF) – FLEXPART model and the Regional Atmospheric Modeling System -Forest Large Eddy Simulation (RAFLES) model. and fuel combustion models such as CONSUME3 are available to predict emissions from prescribed fires. These are based on the amount of fuel consumed, information on canopy characteristics, and relevant meteorological variables to calculate smoke emissions and dispersion. All models require a number of assumptions about turbulent transfer of gasses and particles within and above the canopy to the atmosphere, and ground-truthing of model predictions is essential to ensure their accuracy. A number of these assumptions and model predictions can be evaluated using micrometeorological measurements, but it is equally important that eddy covariance data quantify surface fluxes during fires correctly. An ideal situation is to have a number of

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independent estimates available to evaluate model predictions.

We measured turbulence, energy, water vapor and carbon dioxide fluxes using eddy covariance during operational prescribed fires conducted by the New Jersey Forest Fire Service in the Pine Barrens of New Jersey in March 2008. Measurements made at the Cedar Bridge fire tower in the Greenwood Wildlife Management, NJ, and were coupled with field biometric sampling and LIDAR measurements to estimate fuel consumption, and with surface measurements of PM 2.5 particulates.

3. METHODS

3.1. Site Description: The site was located in Ocean Co. in the Pine Barrens of New Jersey. The Pine Barrens is the largest continuous forested landscape on the Northeastern coastal plain. The climate is cool temperate, with mean monthly temperatures of 0.3 and 23.8 °C in January and June, respectively (1930-2004; State Climatologist of NJ). Mean annual precipitation is 1123 ± 182 mm. Soils are derived from the Cohansey and Kirkwood Formations, and are sandy, coarse-grained, and have low nutrient status. This landscape is also characterized by a high frequency and intensity of wildfires relative to other forest ecosystems in the Northeastern US (Little & Moore 1948, Little 1979).

Upland forests comprise ca. 62% of the forested areas in the Pine Barrens, and are dominated by three major forest communities; Oak - Pine, Pine - Oak, and Pine - Scrub oak (McCormick & Jones 1973, Lathrop & Kaplan 2004). Among mature upland stands of approximately the same age, understory fuel loading and "ladder fuels" are typically denser in Pine - Scrub oak and Pine - Oak stands than in Oak-dominated stands (Skowronski *et al.* 2007, Clark et al. 2009b). Pine – Scrub oak stands have the highest incidence of wildfire of the three major upland forest types, thus are a major focus of fuel reduction treatments by fire managers in the Pine Barrens.

The research stand was a Pine - Scrub oak stand east of the Cedar Bridge fire tower, dominated by Pitch pine with scrub oaks (*Q. ilicifolia*, *Q. marlandica*) in the understory. Ericaceous shrubs in the understory included huckleberry (*Gaylussacia bacata*, *G. frondosa*) and blueberry (*Vaccinium* spp.). The stand had last burned in a wildfire in 1995. Plow lines were installed for fire control in December, 2007, and the stand was burned on March 22, 2008 by the NJ Forest Fire Service in an operational prescribed fire.

3.2. Fuel Consumption measurements: Fuel consumption was quantified by sampling the forest floor and understory pre- and post-burn. One-hour. 10-hour and 100-hour fuels were collected from ten 1.0 m² plots located randomly within 100 m of the flux tower (described below) before and after the prescribed fire. Samples were separated, dried at 70 °C and then weighed. Shrubs, seedlings and saplings were harvested from the same 1.0 m² plots, separated into stems and foliage, and dried and weighed. Sub-samples of Pitch pine needles, shrub stems, and 1-hour and 10-hour fuels were placed in plastic bags and then weighed before and after drying to estimate fuel moisture content during the prescribed fire. Additional plot measurements consisted of five 201 m² forest census plots located randomly within 100 m of the flux tower, and a grid of 48 plots distributed over 1 km² centered on the flux tower (Skowronski et al. 2007).

3.3. LIDAR measurements: LIDAR data were used to estimate canopy and understory fuel consumption during the fire. A multiple return scanning LiDAR system (Optech ALTM 2025/2050, Optech Inc., Vaughn, Ontario) mounted on a fixed-wing aircraft was flown over the site on June 9, 2006, by Airborne 1 Corp. (El Segundo, CA). A second flyover occurred on October 11, 2008, using a Leica ALS-50 (Leica Geosystems AG, St. Gallen, Switzerland) on a fixed-wing aircraft by IIC Technologies (Columbia, MD). LIDAR data were analyzed to calculate canopy structure and fuel loading in 1-meter height bins, following Skowronski et al. (2007).

3.4. Eddy flux measurements: Net exchanges of energy, water vapor and CO₂ were estimated using a closed-path eddy covariance system mounted on a 16 m antenna tower at the site. Near-continuous flux measurements were initiated in June 2005 (Clark *et al.* 2009a). The eddy covariance system was composed of a 3-dimensional sonic anemometer (RM 80001V, R. M. Young, Inc., Traverse City, MI), a closed-path infrared gas analyzer (LI-7000, Li-Cor Inc., Lincoln, NE), a 5 m long, 0.4 cm ID teflon coated

tube and an air pump, and a lap-top PC (Clark et al. 2009a). The inlet of the air sampling tube was placed between the upper and lower sensors of the sonic anemometer, and air drawn through the LI-7000 at 8.0 L min⁻¹. N₂ was used as a blank, and the LI-7000 was calibrated for CO₂ and H₂O every 2-7 days. Data were collected at 10 hz, and coordinate rotation of the raw sonic anemometer signals was used to obtain turbulence statistics perpendicular to the local streamline. The maximum values for the covariance between turbulence and scalar concentrations were compared to half-hourly block averages to calculate fluxes. Fluxes were then corrected for frequency attenuation of scalar concentrations down the sampling tube and non-ideal frequency response of the LI-7000 using transfer functions. Barometric pressure data was then used to calculate half-hourly fluxes at ambient atmospheric pressure.

3.5. Meteorological measurements:

Continuous meteorological data were collected from the flux tower and from a 3 m tall understory tower. Incoming shortwave radiation (LI-200, Li-Cor, Inc., Lincoln, NE), photosynthetically active radiation (PPFD; LI-190, Li-Cor, Inc.), net radiation (NRLite, Kipp and Zonen, Inc., Delft, the Netherlands), air temperature and relative humidity (#HMP45, Vaisala, Inc., Woburn, MA), windspeed and direction (05013-5, R. M. Young, Inc.), and precipitation (TE525, Texas Electronics, Inc., Dallas, TX) were measured above the canopy at 15 meter height, and at 2 meter height on an understory tower. Soil heat flux was measured using heat flux transducers (#HFT-3.1, Radiation and Energy Balance Systems, Inc., Seattle, WA) buried at 10 cm depth within 10 m of the tower. and soil temperature was measured at 5 cm depth (107-L, Campbell Scientific, Inc., Logan, UT) near the understory tower. Barometric pressure (PTB 100A, Vaisala, Inc.) was measured at a nearby tower. Meteorological data were recorded with automated data loggers (CR23x and CR10x, Campbell Scientific, Inc.).

3.5. PM 2.5 Concentrations: PM 2.5

(particulate matter with diameters < $2.5 \ \mu$ m) was quantified using E-BAM beta particle attenuators (Met One Instruments, Grants Pass, OR) at two sites, one located within the burn block near the flux tower, and the second located in an adjacent feed plot clearing that did not burn (see Figure 1).

4. RESULTS and DISCUSSION

In a 10-day period, over 3,500 acres were burned in the Cedar Bridge Area (Fig. 1). Figure 2 shows pre- and post LiDAR data for understory height 1 - 2 m. The image is color coded, with green indicating low values of understory fuel loading and red indicating high values (Skowronski *et al.* submitted). The combustion of understory shrubs and ladder fuels is apparent when pre- and post-burn images are compared.

The southeastern margin of the stand was first fired at ca. 10:00 on March 22, 2008. At ca. 12:00, the burn block near the main flux tower was fired. At ca. 15:00, the large block to the north of the feed plot was ignited. By 18:00, a backing fire approached the flux tower from the east. Burning operations continued on the western edge of the block until after sunset.



Figure 1. Digital orthophoto of the Cedar Bridge area following prescribed fires conducted in March 2009. The tower and feed plot are indicated with arrows. Unburned crowns are green and areas of crown scorch appear dark grey and black.



LIDAR 1-2 m, pre-burn



LIDAR 1-2 m, post-burn

Figure 2. Pre- and post prescribed fire images of understory fuel loading generated from LiDAR canopy height measurements at 1 - 2 meter height aboveground. Green indicates low fuel loading amounts, and red indicates high values (from Skowronski et al., submitted)

4.1. Fuel combustion: Loading was moderate for stands in the Pine Barrens, with ca.15.4 T ha as 1 hour fuels, and 2.1 T ha⁻¹ as 10 hour fuels (Table 1; Clark et al. 2009b). Live and dead stem mass in the understory (understory oaks and shrubs were leafless in March) totaled 4.4 T ha⁻¹. Consumption of 1-hr and 10-hr fuels on the forest floor was 9.1 T ha⁻¹ (52% of pre-burn loading), and of standing live and dead stems only 0.7 T ha⁻¹ (15% of pre-burn loading). Total consumption was 9.8 T ha⁻¹, representing ca. 44 % of pre-burn fuel loading (Table 1).

Table 1. Pre- and post-prescribed burn loading of 1-hour and 10-hour fuels on the forest floor. and shrubs, saplings and seedlings in 1 m^2 plots within 100 m of the Cedar Bridge flux tower. Values are mean T ha⁻¹ ± 1 SD.

1-hour	10-hour	Shrubs	Total
	Tons ha ⁻¹ ± 1 SD		
Pre-burn 15.4 ± 3.6 Post-burn 7.1 ± 1.8 Consumed 8.3 ± 1.9	2.1 ± 1.0 1.3 ± 0.4 0.8 ± 0.8	4.4 ± 1.0 3.8 ± 2.0 0.7 ± 1.1	22.0 12.2 9.8

4.2. Eddy covariance measurements:

Turbulent transfer, as estimated using halfhourly friction velocity (u*; m s⁻¹) measured 4 m above the canopy, averaged 0.63 m s throughout the prescribed fire. Half-hourly values were 0.15 m s⁻¹ (ca. 32%) above mean values measured at similar windspeeds at 4 m above the canopy during the month before the burn ($u^* = 0.211^*$ mean windspeed, $r^2 = 0.648$ for Feb. 15th to March 15th, 2008).

Maximum air temperature four meters above the canopy estimated from 10 hz sonic anemometer "speed of sound" measurements was 44.2 °C. Maximum half-hourly sensible + latent heat flux (H + LE, W m^{-2}) was 2158 W m^{-2} , corresponding with the flame front at the flux tower (Fig. 3). Values exceed available energy $(R_{net} - G, W m^2)$ five-fold during this half-hour period; the relationship between sensible + latent heat flux and available energy characterizing typical conditions was H + LE = $0.866 (R_{net} - G) + 16.209, r^2 = 0.889.$ Total energy release during the fire calculated from the "excess" H and LE flux was 7,256 kJ m⁻². Heat of combustion, calculated assuming complete combustion of consumed fuels in Table 1, was estimated at 11,700 to 17,600 kJ m^{-2} for the prescribed burn.



March 22, 2008 Prescribed fire at Cedar Bridge

Figure 3. Time series of half-hourly available energy (net radiation – soil heat flux, $R_{net} - G$) and the sum of sensible and latent heat flux (H + λE) on March 22, 2008 at the Cedar Bridge flux tower.

Maximum 10 hz water vapor content four meters above the canopy was 14.1 mmol H_20 mol⁻¹ when the flame front was near the tower, ca. 76% greater than ambient levels. Half-hourly latent heat flux peaked at 483 W m⁻² at this time (Fig. 4).



Figure 4. Time series of half-hourly sensible heat (H), Latent heat (λ E) and net CO₂ exchange (ug CO₂ m⁻² s⁻¹ on right axis) on March 22, 2008 at the Cedar Bridge flux tower.

"Excess" latent energy flux associated with the prescribed fire was 1848 kJ m⁻². Percent fuel moisture contents were 42 \pm 14 for 1-hour fuels and 16 \pm 5 for 10-hour fuel immediately prior to the burn. Using data in Table 1, we calculated that the latent heat flux released from combusted fuels was 818 kJ m⁻² during the prescribed fire. The latter value underestimates the total flux during the fire, because it does not include evaporation from the remaining forest floor, or from foliage that was scorched but not combusted during the fire.

Maximum half-hourly net CO₂ exchange was 3932 μ mol m⁻² s⁻¹, which also occurred when the flame front was near the tower (Fig. 4). Net CO₂ release during the fire was estimated at +204 g C m⁻², representing 160% of the annual net CO₂ uptake averaged over the previous three years (-127 g C m⁻² for 2005-2007; Clark et al. 2009a). Fuel combustion estimated from pre- and post sampling was equivalent to +410 g $C m^{-2}$ (Table 1), suggesting that flux measurements underestimated actual fuel consumption. It is possible that the flux measurements only sampled a small portion of the plume, because we may not have burned as intensely directly under the tower compared to other areas in the burn block. In contrast, preand post measurements in the field were distributed in a 100 m radius around the tower. In addition, 10 hz data may underestimate instantaneous fluxes during enhanced turbulent transfer occurring in fires, because the LI-7000 may not accurately sample such large fluctuations in CO₂ concentrations, and smoke could interfere with the sonic sensors, dampening higher speed turbulence signals.

Quantifying consumption using pre- and post-burn field plots also is not without error, and the calculated SD for consumption of 1-hour fuels represents 23% of the total. In addition, char particles < 2 mm diameter that were produced from litter during the prescribed fire were not sampled, because we sifted samples through 2 mm mesh size screens to remove sand and fine grained organic matter.

4.3. PM 2.5 concentrations: At ca. 12:00 when the stand near the main flux tower was fired, hourly PM 2.5 concentrations peaked at 4155 μ g m⁻³ when the flame front and smoldering fire were burning within 1 m of the instrument, and then decreased exponentially (Fig. 5). At ca. 15:00, when the large block to the north of the feed plot was ignited, hourly PM 2.5 concentrations at the feed plot instrument peaked at 873 μ g m⁻³ (Fig. 5). By 18:00, a backing fire approached the flux tower from the

east. Burning operations continued on the western edge of the block until after sunset. Overall, hourly concentrations peaked when flame fronts and smoldering fire were burning close to the instruments, and then decreased exponentially to below ambient air standards within 11 hours (Figs. 5 and 6).



Figure 5. Hourly PM 2.5 concentrations at the Cedar Bridge flux tower (\bullet) and the adjacent feed plot (\circ) from March 15th to 26th, 2008.



Figure 6. Inset of hourly PM 2.5 concentrations at the Cedar Bridge flux tower (•) and the adjacent feed plot (\circ) from March 15th to 26th, 2008. Scale is -10 to 100 µg PM 2.5 m⁻³.

We calculated particulate emissions from the prescribed fire at 12.5 ± 2.1 g PM 2.5 per m², assuming an emission factor of 12.8 g PM 2.5 kg⁻¹ fuel consumed and data in Table 1. Values were at the high end of consumption, and PM 2.5 emissions were greater than the average calculated PM 2.5 emissions from 20 operational burns conducted by the New Jersey Forest Fire Service (8.2 ± 3.8 g m⁻²; Clark et al. 2009c).

5. SUMMARY

Eddy covariance was used to measure turbulent exchanges of energy, water vapor and CO₂, and field biometric and LIDAR measurements were used to estimate fuel consumption during an operational burn conducted by the New Jersey Forest Fire Service in the NJ Pine Barrens. Energy release calculated from fuel consumption data and heat of combustion measurements was higher than the sum of sensible and latent heat flux during the fire. Carbon release calculated from fuel consumption measurements was also greater than CO₂ flux measured using eddy covariance during the fire. However, uncertainties exist with the similarity of the "footprints" of the eddy covariance and biometric data, and with the response of the LI-7000 and sonic anemometer sensors in smoke to rapidly fluctuating conditions during fires.

6. REFERENCES

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