Turbulence and Energy Fluxes During Prescribed Fires in the New Jersey Pinelands

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Introduction

Smoke emission models require a number of assumptions regarding turbulent transfer of gasses and particulates within and above the forest canopy. Some of these assumptions as well as model predictions can be evaluated using micrometeorological measurements during fires. However, it is important that eddy covariance data quantify heat and momentum transfer processes correctly, because instruments are likely operating beyond their performance thresholds within the fire environment.

One solution is to evaluate forest energy balance terms during fires, as is often employed to ensure the accuracy of longer-term carbon and water flux measurements above forests. Stand energy balance can be approximated as:

$$R_{net} – G – \Delta S_{air} - \Delta S_{bio} = H + \lambda E$$

Where, R_{net} = net radiation, G = soil heat flux, ΔS_{air} = heat storage in the canopy air space, ΔS_{bio} = heat storage in aboveground biomass, H = sensible heat flux, and λE = latent heat flux. Fuel combustion adds a second source of heat, but has rarely have these terms been evaluated together during fires.

We first evaluated long-term energy balance closure in each stand. We then compared energy exchange estimated from eddy covariance and standard meteorological measurements to energy release calculated from measurements of fuel consumption during four operational prescribed fires conducted in the Pine Barrens of New Jersey from 2006-2012.

Figure 1. Eddy flux towers in the New Jersey Pinelands used during "Fireflux" experiments. Mixed pine – oak stands were located at Fort Dix (2006) and Brendan Byrne State Forest (2011).

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In our experiments, at least one above-canopy flux tower was operating within the burn block during the prescribed fire, and two other "control" towers were operating simultaneously in unburned stands. Fuel consumption was quantified using pre- and post-burn sampling of the understory and forest floor in 1 m^2 plots located throughout each burn block. Fuel moisture was sampled throughout the day during each prescribed burn.

Results and Discussion

Pre- and post-burn energy balance closure was high in all stands (Table 1; Clark et al. 2012).

Table 1. Pre- and post-burn energy balance closure at three stands. Data were fit to H + λLE = α (R_{net} - G - ΔS_{air} - ΔS_{bio}) + β. P < 0.001 for all models.

Stand	Year	n	α	β	r^2
Mixed	2006	7747	0.99	8.5	0.93
Pine	2008	10918	0.93	9.9	0.89
Oak	2012	8426	0.98	5.4	0.86

During prescribed fires, instantaneous vertical windspeed and air temperature measured at 10 Hz four meters above the canopy were enhanced up to 2.4 and 11.6 times ambient conditions in control stands (Figure 2, Table 2).

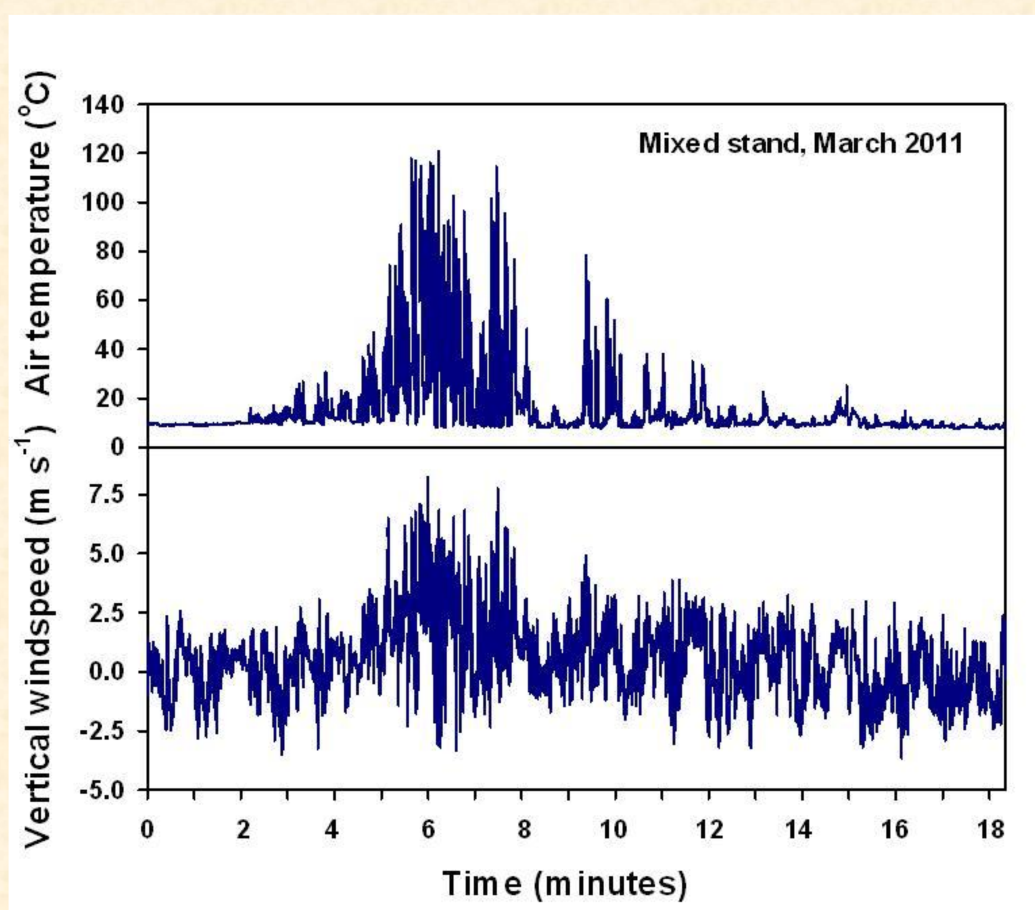

Figure 2. 10 hz sonic air temperature (°C) and vertical windspeed (m s^{-1}) measured at 20 m height during the prescribed burn in a mixed pine-oak stand in Brendan Byrne State Forest in 2011.

Table 2. Maximum vertical windspeed (w) and air temperature (T) measured at 10 Hz above burned and control stands during three prescribed fires.

Stand / Date	w (m s^{-1}) burn	w (m s^{-1}) control	T (°C) burn	T (°C) control
Mixed 2006	4.0	3.6	23.2	2.0
Pine 2008	3.8	3.6	44.2	12.8
Mixed 2011	8.3	3.4	121.0	11.3
Oak 2012	3.3	3.0	31.8	6.6

10 Hz upward vertical windspeed velocity and air temperature were positively correlated during each fire, with correlations highest at the hottest burn at the mixed stand in 2011 (r^2 = 0.48, p <0.0001).

During the burns at the mixed and pine stands , the sum of latent and sensible heat fluxes above the canopy was 4.8 and 5 times greater than available energy, R_{net} – G. Half-hourly sensible heat flux peaked at 3128 and 1675 W m^{-2}, and water vapor flux at 443 and 483 W m^{-2}, respectively (Figure 3). Energy release during these fires calculated from the "excess" H and LE flux after correction for available energy was 7,827 and 8,346 kJ m^{-2}.

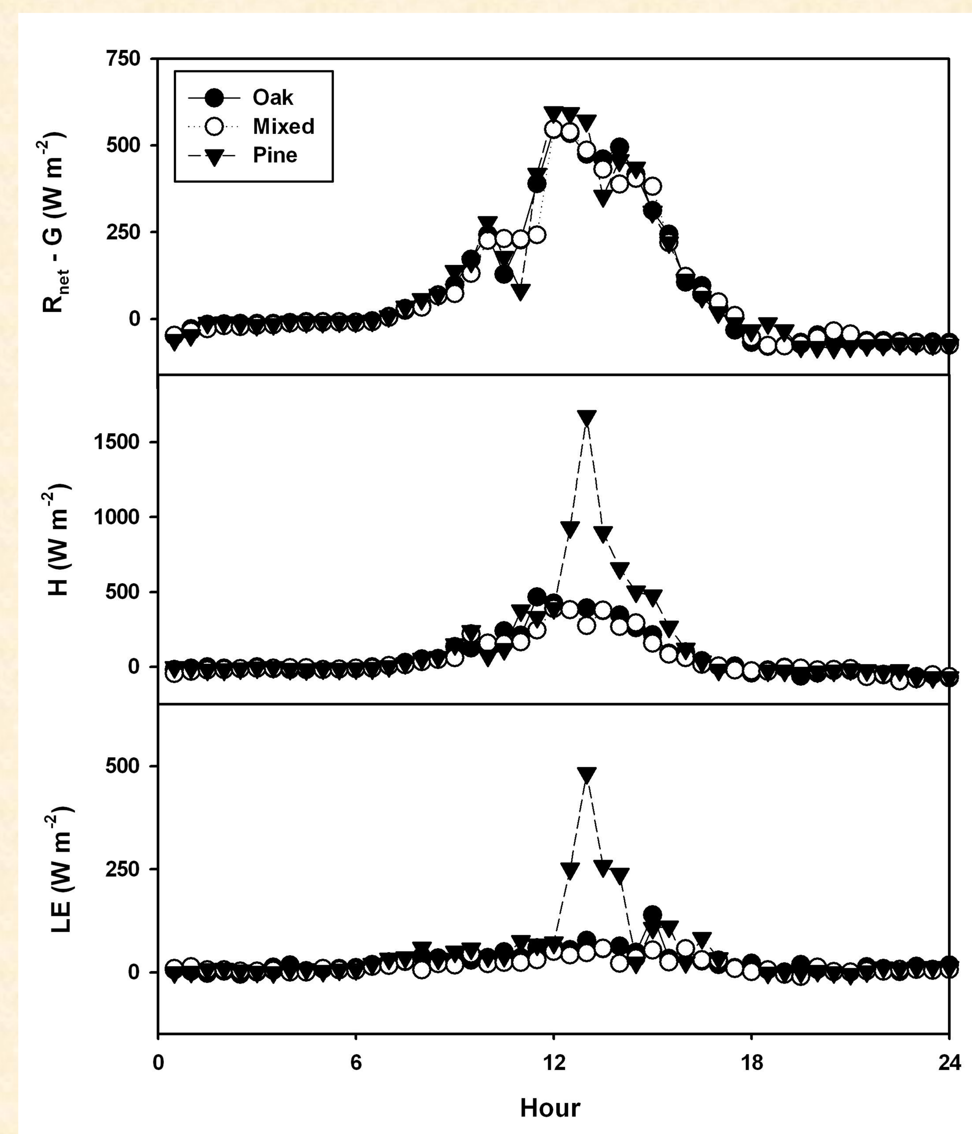

Figure 3. Half-hourly values of available energy, sensible heat flux, and latent heat flux at the three sites on March 22, 2008. All units are W m^{-2}.

At the mixed stand in 2011, crowing near the 20-m tower resulted in H > 15,500 W m^{-2} over the half-hour period during the passage of the fire front shown in Figure 2. Instantaneous heat storage in the canopy air space peaked at 198 W m^{-2} , but integrated over longer time scales ΔS_{air} was much lower due to rapid cooling and occasional influx of cooler air behind the flame front.

Table 3. Mass of understory and forest consumed, % consumption, and estimated heat release at measured moisture contents during prescribed burns.

Stand / Date	Consumed (kg m^{-2})	%	Energy release (kJ m^{-2})
Mixed 2006	0.82	52.6	10,078
Pine 2008	0.98	44.0	9,860
Mixed 2011	0.69	46.7	7,233
Oak 2012	0.50	44.6	4,155

Flux measurements totaled ca. 78% and 85% of the estimated energy release calculated from fuel consumption measurements at the mixed and pine stands (Table 3). Although values compare well, a number of potential errors can occur during "fireflux" experiments. For example, it is possible that the flux measurements only sample a limited portion of the plume (or oversample, in the case of the mixed stand in 2011), 10 Hz data may underestimate instantaneous fluxes during enhanced turbulent transfer occurring in fires, smoke occasionally interfered with the sonic sensors, and the LiCor LI-7000 used to sample water vapor may not accurately sample such large fluctuations in H_20 concentrations. Quantifying consumption using pre- and post-burn field plots also is not without error. For example, the SD for consumption of 1-hour fuels represents 23-32% of the mean value. 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.

Conclusions

Landscape-scale tower networks are valuable for evaluating energy fluxes during prescribed burns. A large proportion of energy released from complex fuel beds was measured as "excess" H + LE above the canopy. Despite sampling limitations, simultaneous quantification of fluxes and fuel consumption during fires are essential for evaluating predictive plume dispersion and fire behavior models (see posters by Heilman et al., Kiefer et al., and Skowronski et al. also).