Laboratory experiments to estimate interception of infrared radiation by tree canopies


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Introduction

Fire is a key earth-system and Anthropocene process (Bowman et al. 2009; Smith et al. 2016a). Fire impacts on the global carbon (C) cycle from both anthropogenic and natural sources, with 1350–3400 Tg C emitted from land-use changes, agricultural practices and residential uses, and 2750–4600 Tg C emitted in wildfire events, which exhibit high interannual variability (Westerling et al. 2006; van der Werf et al. 2010; Wotton et al. 2010; Balch et al. 2013; Lannom et al. 2014; Smith et al. 2016a).

Biomass burning emissions can be determined from top–down assessments such as the Global Fire Emissions Database (Kaiser et al. 2012) and bottom–up approaches via fuel and combustion properties, emission factors and area burned (Seiler and Crutzen 1980). Recently, an alternative bottom–up route that overcomes limitations associated with pre-fire fuel and combustion completeness data is to directly measure the radiant heat released (Hardy et al. 2001; Wooster et al. 2005).

Research to quantify fire radiative power (FRP, watts) and fire radiative energy (FRE, joules) has been conducted at satellite, field and laboratory scales (Wooster et al. 2005; Kremens et al. 2012; Smith et al. 2013, 2016a; Dickinson et al. 2016; Hudak et al. 2016). Specifically, instantaneous measurements of FRP have been demonstrated to be linearly related to the rate of biomass consumed (Wooster et al. 2005).

FRP is a dynamic measurement that changes continuously with regards to fuel and fire characteristics (Zhukov et al. 2006; Freeborn et al. 2008; Kremens et al. 2012). To estimate the total amount of biomass consumed across an affected landscape, FRP is integrated with time to calculate FRE, which is linearly related to total biomass consumed (Wooster et al. 2005; Kremens et al. 2012; Smith et al. 2013). Recently, FRE density (FRD, J m−2) has been widely applied to infer seedling mortality and post-fire growth, and consumption, as well as stand structural changes (Kremens et al. 2012; Hudak et al. 2016; Smith et al. 2016b).

As outlined in Smith et al. (2013), three principal methods have been developed to estimate FRP that can be generally described as dual-band infrared thermometry, 4-μm radiance and brightness temperature methods (Dozier 1981; Kaufman et al. 1998a, 1998b). The strengths and weaknesses of these methods for satellite imagery are detailed in the literature (Wooster et al. 2003; Kremens et al. 2010).

Although biomass consumption estimates are commonly derived from FRP and FRE, several studies have highlighted sources of uncertainty (Freeborn et al. 2008; Boschetti and Roy 2009; Kumar et al. 2011; Kremens et al. 2012; Smith et al. 2013). Notably, errors can be introduced owing to the nature of satellite systems with spatial and temporal undersampling that does not account for the natural variability of FRP (Boschetti and Roy 2009; Kumar et al. 2011). Variations in fuel moisture content have also been demonstrated to contribute to FRP and FRE uncertainty (Smith et al. 2013). However, a recognised but less researched source of uncertainty in FRP is the impacts of canopy closure (Freeborn et al. 2008; Hudak et al. 2016). Although many studies have sought to quantify canopy closure using geospatial datasets (Strand et al. 2006, 2008; Smith et al. 2008, 2009; Hudak et al. 2012), there has been limited attention on using these datasets to provide correction factors in the resultant FRP and FRE observations (Hudak et al. 2016).

Therefore, the present study seeks to characterise the degree to which a thermal signal received at the sensor is attenuated by tree canopy. Specific questions we seek to address are:

1. What is the magnitude of FRP attenuation as a function of tree canopy cover?
2. Does living but non-transpiring vs desiccated canopy affect the relationship between emitted and observed power?
Methods
Experimental setup
Experiments were conducted at the Idaho Fire Initiative for Research and Education (IFIRE) laboratory located in Moscow, Idaho, to explore the influence of canopy cover on FRP. The laboratory comprises an indoor climate-controlled burn chamber that allows the reduction of environmental effects (Smith et al. 2013). The experimental set-up is shown in Fig. 1. To minimise potential microclimate variations in temperature and humidity within the chamber, controls (i.e. non-canopy treatments) were replicated before each experimental measurement. To overcome a source of potential variation, we used a constant-power radiant heat source consisting of three propane-burning ceramic heaters (McMaster-Carr Model 1719K8) with an area totalling 0.21 m² or ~20% of the radiometer ground instantaneous field of view. The FRP from these three heaters was 9 kW (FRP density 4.3 kW m⁻²). Given that the experiment is evaluating relative magnitudes of FRP and is comparing the ratio of obstructed to unobstructed radiative power, the heat source did not need to encompass the total field of view of the sensor.

Radiation experiments were repeated a total of 26 times, conducted with two types of canopy: desiccated (n = 14) and living and non-transpiring (n = 12). We selected both live and desiccated branches to evaluate whether moisture content impacted on the observed FRP and FRE signal (i.e. Smith et al. 2013). We posit that heating from below the canopy without actual combustion in the live fuels will not produce enough water vapour to impact on the observed FRP signal. Approximately 30 ponderosa pine (Pinus ponderosa) branches were cut on the day of the experiment and were stored with the cut ends exposed. Ponderosa pine was selected owing to its preponderance in fire-prone systems within the western United States. Desiccated ponderosa pine branches, with held-fast needles turning from green to brown, were also collected from pre-cut slash piles and were allowed to fully cure to ambient conditions before the experiment. During the experiment, the branches were clamped to a stand to position them in a natural orientation as though from a tree trunk between the heat source and the radiometer (Fig. 1). Ambient temperatures averaged 20°C and relative humidity averaged 40.5%. The experiments were performed over a continuous range of canopy cover percentages from 0 to 90%.

FRP was determined using a dual-band radiometer purpose built using ST60 DX-1001 sensors with band-passes of 0.15–6.5 µm (spectral response function DC-6216-U1) and 8–14 µm (spectral response function DC-6073-W1). The full width at 1/2 of maximum response field of view of the sensors was 54°. The radiometer was installed 2.44 m above the heat source at nadir (Kremens and Dickinson 2015). Measurements were recorded every 0.5 s and calibrated to watts using infrared thermometry (Dozier 1981; Kremens et al. 2010). Canopy and needle temperatures were measured using type K thermocouple probes, with interior leaf temperature measured by threading a thermocouple inside the leaf and exterior temperatures by pressing a probe to the leaf surface. Given pine needles have very fast thermal response times, it is essential to use thermocouples that
have very fast response times (Bova and Dickinson 2008; Smith et al. 2016c). Consequently, we used 0.00254-mm-diameter wire, which has a time constant of 0.003 s. A white background was laid on the ground for contrast enhancement and hemispherical images were taken before each burn at nadir and later used to quantify the percentage of canopy cover obscuring the radiometer field of view.

Data analysis

Hemispherical images were analysed using the Hemiview software package and canopy cover calculated based on the radiometer field of view (Fig. 1). Given the time required for the heat source to achieve steady-state power output (Fig. 2), only values within the asymptote were used in the calculation of the ratio between obscured and unobscured datasets. To determine whether individual data points were within the asymptote region, a non-linear least-squares model was fitted to the raw data:

\[ Y = a - be^{-cx} \]  

where \( Y \) is the value of FRP, \( a \) is the approximate asymptote value, \( b \) and \( c \) are constants, and \( x \) is time. Least-squares models were fitted to the obscured and unobscured FRP data and a linear regression model was fit to the ratio of the asymptote values and canopy cover. The full linear model was:

\[ Y_{ijk} = \mu + p_i + a_j + b_k + e_{ijk} \]

where \( Y_{ijk} \) is the ratio of sensor-observed obscured to unobscured radiant power, \( \mu \) is the overall mean, \( p_i \) is the fixed effect for being in the \( i \)th group (canopy cover type), \( a_j \) is the random effect of temperature, \( b_k \) is the random effect of relative humidity, and \( e_{ijk} \) is the experimental error. A \( t \)-test with an \( x \) level of 0.05 was performed on the normalised means (the ratio over the percentage canopy cover) of the two canopy types to determine if there was a difference between the two groups. Under a no-canopy scenario, the power observed by the sensor was assumed to be 100% and therefore the data were normalised accordingly.

Results and discussion

Fig. 2 illustrates the reduction in observed radiant power with increases in canopy obstruction, where the overlain black line represents 0% canopy cover and the displayed grey points represent the observed radiant power at these four canopy cover percentages. In each case, the modelled asymptotes of both the unobstructed (separate run for each experimental treatment) and the obstructed case are shown. The results demonstrate a clear reduction in FRP associated with canopy obstruction.

Fig. 3 demonstrates that a robust and expected linear relationship is apparent with increases in canopy cover and sensed FRP \((r^2 = 0.944, n = 26, s.e. = 0.00048, P < 0.001)\). A \( t \)-test performed on the normalised means (the proportion sensed FRP over the percentage canopy cover) for non-transpiring green tree branches and desiccated tree branches showed that there was no significant difference between the two classes \((n = 26, P = 0.084)\). The robustness of this relationship that spans both living and desiccated branches demonstrates that potential exists to build on these laboratory experiments to develop sophisticated FRP correction factors applicable to a wide range of forest canopies, ranging from young and live to old canopies or canopies with dead branches. Clearly, further research is warranted to investigate whether such relationships scale to aerial and satellite-based assessments of FRP.

To illustrate the wider applicability of these results, we further modelled the percentage reduction that would be observed in the literature-based biomass conversion rate

![Fig. 2](image-url)  

**Fig. 2.** Calibrated fire radiative power (FRP) data with temporal sampling every 0.5 s at four different canopy cover levels: (a) 7.5% canopy cover, (b) 16.3%, (c) 44.6% and (d) 75.7%. Grey points represent the obscured data, while black represents the control. The fitted non-linear least-squares model is shown as the solid line for the control and dashed for the obscured data.
The magnitude of FRP attenuation due to increases in simulated canopy cover is an important consideration in fire behavior studies. Data points of green and desiccated material were combined because no significant difference was observed between the canopy types. The regression equation includes the assumption that the radiometer receives radiation at a maximum (fraction of 1) when no canopy intervenes.

Conclusions

The specific questions we sought to address were: (1) what is the magnitude of FRP attenuation due to increases in simulated tree canopy cover? And (2) does living but non-transpiring versus desiccated canopy affect the relationship between emitted and observed power? In terms of (1), we recorded clear linear decreases in observed FRP as a result of laboratory-emitted and observed power? In terms of (2), modelled estimates have not been experimentally validated and are presented to merely illustrate the potential impact of the results.

The present study improves our understanding of how to correct observed FRP values for increases in canopy cover and provides a scalable method to correct for the bias caused by canopy attenuation of FRP reaching the sensor, which will in turn aid in the estimation of FRE and biomass consumed. Physically based measures of canopy cover, which can be derived from airborne lidar data, can be used to correct for canopy interception at sympatric scales. Such remote-sensing studies have the potential to test our laboratory results on FRP impacts on canopy interception at landscape scales. At coarser spatial scales where lidar data are unavailable, application of leaf area index-based products may provide a route to correct FRP estimates. In addition to sensor view angle and its interaction with the 3D distribution of canopy elements, other factors will likely contribute to reductions in observed FRP. Specifically, (i) height to live canopy may play a role in whether or not needle waxes melt under certain fire conditions; (ii) the structural stage of the forest (stem exclusion, multi-storey, old growth, etc.) will likely significantly affect how FRP is attenuated; (iii) high leaf area index conditions (such as in tropical forests) may lead to very high FRP attenuation during surface fires; and (iv) moisture content in both surface and canopy fuels (live or dead) will likely lead to further reductions in observed FRP.

In summary, we suggest that further research is warranted to test the scalability of these laboratory results to landscape-scale fires and fire-prone ecosystems with very different vertical vegetation structures and fire behaviour properties (e.g. boreal forest ecosystems with belowground fires, tropical multi-storey forest canopies and humid southeastern longleaf pine forests).
Tree canopy effects on fire radiative power

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