Inferring energy incident on sensors in low-intensity surface fires from remotely sensed radiation and using it to predict tree stem injury


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Abstract. Remotely sensed radiation, attractive for its spatial and temporal coverage, offers a means of inferring energy deposition in fires (e.g. on soils, fuels and tree stems) but coordinated remote and in situ (in-flame) measurements are lacking. We relate remotely sensed measurements of fire radiative energy density (FRED) from nadir (overhead) radiometers on towers and the Wildfire Airborne Sensor Program (WASP) infrared camera on a piloted, fixed-wing aircraft to energy incident on in situ, horizontally oriented, wide-angle total flux sensors positioned ~0.5 m above ground level. Measurements were obtained in non-forested herbaceous and shrub-dominated sites and in (forested) longleaf pine (Pinus palustris Miller) savanna. Using log–log scaling to reveal downward bias, incident energy was positively related to FRED from nadir radiometers ($R^2 = 0.47$) and WASP ($R^2 = 0.50$). As a demonstration of how this result could be used to describe ecological effects, we predict stem injury for turkey oak (Quercus laevis Walter), a common tree species at our study site, using incident energy inferred from remotely sensed FRED. On average, larger-diameter stems were expected to be killed in the forested than in the non-forested sites. Though the approach appears promising, challenges remain for remote and in situ measurement.

Additional keywords: Eglin Air Force Base, fire behaviour, fire effects, fire radiated energy, longleaf pine, Pinus palustris, Quercus laevis, RxCADRE project, tree mortality, turkey oak, Wildfire Airborne Sensor Program (WASP).

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Introduction

Airborne, space-borne and near-ground sensors with nadir (overhead) perspective have shown promise for spatially quantifying fireline progression (Paugam et al. 2013), fire intensity (Kremens et al. 2012; Johnston et al. 2017), area burned (Giglio et al. 2006), biomass consumption (Wooster et al. 2003, 2005), emissions production (Ichoku and Kaufman 2005) and post-fire effects (Lentile et al. 2006; Kremens et al. 2010). Energy production, transfer and deposition on fuels drive wildland fire ignition, rate of spread (ROS) and intensity (Anderson 1969; Yedinak et al. 2006; Anderson et al. 2010), while first-order fire effects are determined by heat deposition on plants and soils (Butler and Dickinson 2010). However, even basic understanding of energy transfer in wildland flames is limited (Sacadura 2005; Viskanta 2008; Finney et al. 2010; Finney et al. 2015), likely owing to complex logistics associated with sensor deployment, measurement uncertainty, the high-temperature environment and high-frequency temporal variability (Freeborn et al. 2008; Hiers et al. 2009; Frankman et al. 2013). At the same time, the accuracy of remotely sensed data remains uncertain (Schroeder et al. 2014; Kremens and Dickinson 2015; Dickinson et al. 2016).

Advancing understanding of energy transfer and deposition in wildland fires, based generally on in situ (in-flame) measurements and modelling, in concert with the continued development of active-fire remote sensing, promises a stronger foundation for describing wildland fire behaviour and predicting effects (Butler and Dickinson 2010; Kremens et al. 2010).
Table 1. Averaged characteristics of fires in non-forested and forested burn blocks from the RxCADRE 2012 fires

<table>
<thead>
<tr>
<th>Fire</th>
<th>Fuel</th>
<th>Date</th>
<th>Nadir radiometers</th>
<th>Hudak et al. (2016b)</th>
<th>$W$ (Mg ha$^{-1}$)</th>
<th>Flame height (m)</th>
<th>Flame depth (m)</th>
<th>Spread rate (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2F</td>
<td>Forested</td>
<td>11-Nov-2012</td>
<td>907 (9, 670)</td>
<td>5.0 (9, 2.6)</td>
<td>6.36</td>
<td>0.9 (5, 0.5)</td>
<td>1.3 (5, 0.7)</td>
<td>0.04 (2, 0.05)</td>
</tr>
<tr>
<td>L1G</td>
<td>Non-forested</td>
<td>4-Nov-2012</td>
<td>529 (9, 316)</td>
<td>1.3 (9, 0.5)</td>
<td>1.54</td>
<td>0.7 (6, 0.5)</td>
<td>1.1 (5, 0.8)</td>
<td>0.24 (4, 0.30)</td>
</tr>
<tr>
<td>L2G</td>
<td>Non-forested</td>
<td>10-Nov-2012</td>
<td>739 (12, 358)</td>
<td>1.5 (12, 0.6)</td>
<td>3.09</td>
<td>0.5 (9, 0.2)</td>
<td>0.8 (9, 0.4)</td>
<td>0.89 (3, 0.38)</td>
</tr>
<tr>
<td>S3</td>
<td>Non-forested</td>
<td>1-Nov-2012</td>
<td>479 (5, 79)</td>
<td>1.7 (5, 0.2)</td>
<td>2.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>Non-forested</td>
<td>1-Nov-2012</td>
<td>234 (4, 172)</td>
<td>1.6 (4, 0.7)</td>
<td>2.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>Non-forested</td>
<td>1-Nov-2012</td>
<td>564 (5, 269)</td>
<td>2.2 (5, 0.6)</td>
<td>2.19</td>
<td>0.4 (4, 0)</td>
<td>0.8 (4, 0.3)</td>
<td>0.36 (2, 0.28)</td>
</tr>
<tr>
<td>S7</td>
<td>Non-forested</td>
<td>7-Nov-2012</td>
<td>1179 (4, 641)</td>
<td>3.3 (4, 1.8)</td>
<td>1.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>Non-forested</td>
<td>7-Nov-2012</td>
<td>512 (4, 318)</td>
<td>1.9 (4, 0.7)</td>
<td>2.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>Non-forested</td>
<td>7-Nov-2012</td>
<td>861 (5, 115)</td>
<td>1.8 (5, 0.9)</td>
<td>1.40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Efforts continue to develop more physically based fire effects models that promise to be more generally applicable than statistical models (Dickinson and Ryan 2010; Chatziiefstratiou et al. 2013; Massman 2015). These models generally require measured or modelled heat deposition from fires but options are limited by which heat deposition can be inferred from measured or modelled fire characteristics (Butler and Dickinson 2010). We explore how well energy incident on in situ (in-flame) sensors can be inferred from ground-leading fire radiated energy density (kJ m$^{-2}$, FRED) measured from nadir (overhead) tower-based radiometers and an airborne longwave infrared sensor during spreading experimental fires in south-eastern US fuels. In turn, we demonstrate how inferred energy deposition can be used to predict tree stem injury, an important ecological effect, for a common south-eastern tree species.

Methods

Data were collected in early November 2012 within an 8 × 4-km area of Eglin Air Force Base in north-western Florida during the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE), a coordinated measurements campaign described in Ottmar et al. (2016a) and associated papers. Nadir radiometer (Dickinson and Kremens 2015) and airborne (Hudak et al. 2016a) data used here are available on the USDA Forest Service Research Data Archive (https://doi.org/10.2737/RDS-2016-0007, accessed 29 January 2019). Burn blocks were characterised by either a herbaceous and shrub fuel mix maintained as open range through mowing, fire and herbicide application (hereafter termed non-forested), or fire-maintained pine savanna with fuel beds including needle cast, turkey oak litter, herbaceous and shrub vegetation, and woody material (hereafter termed forested). Non-forested blocks included large (L1G and L2G) and small (S3, S4, S5, S7, S8, and S9) burn blocks while there was a single large forested block (L2F). Burn blocks, fuels and fire behaviour are described in Hudak et al. (2016b), Ottmar et al. (2016b) and Butler et al. (2016) and are summarised in Table 1.

Measurements from two in situ instruments (incident flux sensors and cameras) and two remote radiation sensors (tower-mounted and airborne) are considered in the present study. In situ measurements were made with a horizontally viewing, wide-angle, incident total flux sensor housed with electronics in a fire-hardened container placed on a tripod 0.5 m above ground level (agl) and typically viewed from a perpendicular perspective by a visible video camera housed in a separate container (Butler et al. 2010; Butler et al. 2016). The incident total flux sensor is one of two sensors in MedTherm Corporation’s uncooled dual-sensor. The other is a radiant flux sensor, the data from which are not used in the present study. The incident total flux sensor (hereafter the incident flux sensor) has near-hemispherical sensitivity to fire radiation incident on a black high-emissivity surface over a thermopile detector contained within a copper plug. The sensor surface is also heated by convection. Raw voltages were recorded at 10 Hz and calibrated to incident flux (kW m$^{-2}$; see Butler and Jimenez 2009; Frankman et al. 2013), which was then time-integrated to provide incident energy (kJ m$^{-2}$) used in the present study. For the 26 datasets for which video analysis is available, 87% showed fire approaching the face of the incident flux sensor from within ±60°, formerly shown to be the acceptance angle within which fire approach angle has no effect on measurements.

Single-pixel dual-band radiometers were placed on towers with a downward (nadir) perspective (Dickinson et al. 2016). The nadir radiometers include a mid- (3–5 μm, Dexter Research LWPSiL2) and long-wave (6.5–20 μm, Dexter Research MW) sensors. See further details in Dickinson et al. (2016) along with information on data analysis and application provided in Kremens et al. (2010, 2012), Cannon et al. (2014) and Hudak et al. (2016b). The nadir radiometers were mounted 5.5 m agl and, at that height, detect radiation from an area of regard of ~23 m$^2$ (~2.7-m radius) based on their 52° field of view (FOV).

Fire Radiated Flux Density (FRFD, kW m$^{-2}$) is the instantaneous, spatial average aerial emission from the fraction of the nadir radiometer area of regard (pixel) that is
radiating above background (also known as the fire fractional area, $A_f$, which varies from 0 to 1; see supplementary material available online):

$$ \text{FRFD} = \varepsilon A_f \sigma T^4 $$

(1)

where $\varepsilon$ is emissivity (0 to 1), $\sigma$ is the Stefan–Boltzmann constant and $T$ is effective temperature of the scene determined by blackbody calibration from the ratio of mid- and long-wave infrared (LWIR) signals. The calculation of FRFD from a dual-band nadir radiometer is described in Kremens et al. (2010). Peak FRFD was used to estimate fireline intensity (see supplementary material). FRFD was integrated through time (from first rise above background to first fall to background during cooling) to provide FRED (kJ m$^{-2}$).

The distribution of in situ sensors across large and small burn blocks is mapped in Butler et al. (2016). A nadir radiometer was co-located with each in situ package so that the incident flux sensor faced inward from the margin of the nadir radiometer’s area of regard. Given occasional instrument failures, we report sensor faced inward from the margin of the nadir radiometer’s area of regard. Given occasional instrument failures, we report data from $n = 7$ co-located measurements in the large forested block and $n = 42$ co-located measurements in non-forested blocks. All ground sensors were geolocated with sub-metre accuracy with a survey-grade global positioning system (GPS).

The Wildfire Airborne Sensor Program (WASP) LWIR camera was flown 1550–3160 m agl on a piloted, fixed-wing aircraft that made repeated passes over the three large burn blocks (see Hudak et al. 2016a, 2016b for data and more detail respectively). The WASP passband is 8–9.2 $\mu$m with the spectral response function on file with the Rochester Institute of Technology, Carlson Center for Imaging Science. The WASP camera collected image frames at a 3-s interval as it passed over burn units and there was a 3–4-min gap between the last image frame on a pass and the first frame on the next pass made after turning. Image frames were georectified with GDAL based on inertial measurement unit data. Measured voltages, blackbody calibration and a model of radiation from pixels containing a mix of combusting fuels and background were used to calculate FRFD as described in Kremens and Dickinson (2015) and Dickinson et al. (2016). Time series for each pixel of radiated flux greater than the background of 1070 W m$^{-2}$ (FRFD) were time integrated as follows:

$$ \text{FRFD}_{\text{obs}} = \sum_{i=\text{initial}}^{n} 0.5(\text{FRED}_{i+1} + \text{FRED}_i)(t_{i+1} - t_i) $$

(2)

where $i$ is image frame number, $t$ is time (s), and the integration is performed from the initial to final ($n$) frame containing above-background values. A burn-block average correction of resulting FRED$_{\text{obs}}$ maps was applied to account for temporal undersampling and the occasional lack of full coverage of burn blocks by image frames on every pass. Finally, kriging of the resulting FRED estimates where only the pixels with the greatest FRED values (primarily those along flame fronts) were interpolated providing a spatially continuous map of FRED more accurate at the burn block level (see details in Klauberg et al. 2018). Average FRED was then calculated for each nadir radiometer (circular) area of regard by re-sampling FRED maps from Klauberg et al. (2018).

Results and discussion

Fig. 1 is a first examination of how to infer in situ energy deposition from spatially extensive remotely sensed active-fire measurements. The highest incident energies were in the forested block where surface-leaving radiative energy was greatest. We can also conclude that the highest incident energies were where fuel consumption was greatest as confirmed by both measurements (Hudak et al. 2016b) and the well-established correlations between FRED measured from nadir or near-nadir sensors and fuel consumption (Wooster et al. 2005; Freeborn et al. 2008; Kremens et al. 2012). Higher fire intensities also lead to greater incident energy (Bova and Dickinson 2005) and intensities estimated for the forested block included some of the highest in our dataset (Table 1).
Relationships between incident energy and fire characteristics, however, are not likely to be universal across fuel types and fire environments (Kremens et al. 2012; Frankman et al. 2013; Smith et al. 2013) and, as such, the relationships in Fig. 1 are not likely to be universal.

Uncertainty in incident energy inferred from remote measurements is particularly evident for the non-forested blocks where incident energy is plotted against FRED measurements, both log scaled to reveal bias (Fig. 1). For the five incident energy estimates with the greatest deviation from the trend lines in Fig. 1, the three for which we analysed coincident video all had flame heights below the sensor face. In future work, in situ sensor heights should better match expected flame heights. As well, a more physical approach to linking flame characteristics with incident energy is needed where radiative and convective heat fluxes to surfaces and objects of interest are modelled explicitly (e.g. Bova and Dickinson 2008). Apart from other benefits, a physical model could help rescale measurements to a common basis, for instance, maximum incident energy or incident energy at mid-flame height. A physical model will have to account for the often substantial variation in the partition of incident energy between convection and radiation (Frankman et al. 2013).

Despite interpolating FRED using primarily flame front values (Klauberg et al. 2018), we suspect that there remains a downward bias in WASP FRED related to temporal undersampling that would particularly affect measurements of low-energy flame fronts. The apparent bias is evident in lower estimates of FRED for WASP (Fig. 1b) than nadir radiometers (Fig. 1a). FRED measurements with high temporal frequency that include peak FRFD (such as collected by nadir radiometers) are required because the time period around the peak accounts for a large fraction of the radiation. High-spatial-resolution airborne data in Riggan et al. (2004) show this clearly. In relatively low-frequency airborne imagery collected from a piloted, fixed-wing aircraft that makes repeated passes over a fire, peak FRFD is only captured where image pixels coincide spatially with a flame front. If the return time is short enough relative to the residence time of the fire and the cool-down period, one can expect a reasonable estimate of time-integrated FRED for those flame-front pixels. Return intervals of 3–4 min were achieved here (Dickinson et al. 2016; Hudak et al. 2016b) and were ~10 min in other studies (e.g. Peterson et al. 2013; Schroeder et al. 2014). Even a 3–4-min sampling interval resulted in large parts of fire area in our non-forested burn blocks where FRED could not be estimated because of a lack of above-background FRFD measurements in time series (Klauberg et al. 2018). Although spatial interpolation allows continuous maps to be produced, and was used to provide data in Fig. 1, it will always be an averaged representation of fire that is dynamic in time and space (Hiers et al. 2009; Hoffman et al. 2012) and will underestimate FRED to the extent that the interpolation process includes pixels where flame-fronts were not captured. Spatial interpolation of FRED could likely be improved in future work by data-driven fire spread simulation (e.g. Rochoux et al. 2014, 2015).

The relationships in Fig. 1 are unlikely to be universal not only because of the likely effects of fuel and fire variability across ecosystems and temporal undersampling of fire radiation but also because of challenges for remotely sensed measurement and contrasts among remote sensors (Dickinson et al. 2016). We sometimes obtain non-physical estimates of the emissivity–area product ($eA_f$) (values $>1$) with the nadir radiometers that may be related to bias induced by non-ideal (i.e. non-greybody) radiation from hot gases (e.g. Dupuy et al. 2007; Boulet et al. 2009; Parent et al. 2010). Hot gas radiation (especially from CO$_2$ and CO; Boulet et al. 2009) is sensed because of the wide-band mid- and long-wave infrared sensors used in our nadir radiometers. A further potential source of error arises from the fact that tall flames are closer to the nadir radiometer than small flames, the effect of which could not be included in the current analysis for lack of co-located flame height measurements (see Kremens et al. 2010). In contrast, the WASP LWIR sensor has a narrow passband designed to avoid the influence of radiation absorption and emission by gases (Kremens and Dickinson 2015). Nadir radiometer FRED is greater than WASP FRED perhaps because it is a better estimate of total fire radiation, which includes both radiation from hot gases and greybody radiation from hot soot, fuels and substrate whereas WASP FRED may be a more accurate measurement of greybody radiation alone (Dickinson et al. 2016). Almost all airborne and satellite measurements in the literature likely provide better measurements of greybody than total radiation from fires (e.g. see measurements in Wooster et al. 2005). Differences among sensing systems in what they are measuring and measurement challenges generally (e.g. smoke absorption of radiation, Koseki and Mulholland 1991) show that we need to develop a more sophisticated understanding of wildland fire radiation and its measurement.

We now demonstrate how remotely sensed data could be used to assess woody stem mortality during surface fires. Incident energy inferred from FRED measured by nadir radiometers and WASP is used to predict depth of necrosis and, in turn, depth of necrosis is compared with bark thickness to determine threshold diameters at which turkey oak stems would survive a fire (Fig. 2). Bark thickness is whole-bark thickness, that is, depth from the bark surface to the vascular cambium, which, if killed by heating during fires around the stem’s circumference, kills the stem. Note that stem death does not necessarily mean death of the entire woody plant, as many species resprout from the roots or the base of the stem. FireStem2D was previously used to simulate tree stem heating and stem death over a wide range of incident energy, showing a close relationship between depth of necrosis and incident energy across a range of species (Chatzieszistratiou et al. 2013). We related modelled depth of necrosis to incident energy ($E_{IT}$) using a power-law fit to modelled data from fig. 7 in Chatzieszistratiou et al. (2013). The relationship is:

$$DN = 0.0021(E_{IT})^{0.99}$$

where necrosis depth ($DN$) is in units of millimetres and $E_{IT}$ in units of kilojoules per metre squared, and the relationship is limited to necrosis depths below 16 mm as appropriate for the fires in the present study. The relationship between bark thickness and turkey oak diameter is from Lutes (unpubl. data).

The median diameters of turkey oak stems that would have been expected to be killed were larger in the forested block than
in the non-forested blocks (Fig. 2), consistent with the greater fuel consumption and, often, fireline intensities in forested burn blocks. Two countervailing biases may affect our predictions. We would have expected tree vulnerability to be overestimated because convective energy, and thus incident energy, is likely to be higher for the copper-plug in situ incident flux sensors than for tree stems. Overestimation is likely because the copper plug rapidly conducts heat away from the sensor’s surface and maintains lower surface temperatures than adjacent, low-conductivity tree bark, and convection is proportional to the temperature difference between the hot flame gases and the surface to which heat is being transferred. In contrast, it appears that a handful of incident energy measurements in both forested and non-forested blocks were underestimated (see Fig. 1), probably related to small flames at some locations.

In future work, energy incident on tree stems needs to be evaluated directly in order to evaluate our stem mortality predictions. Incident energy will be affected by whether spread is backing, heading or flanking and by interactions between flames and tree stems (Gutsell and Johnson 1996). More physically realistic methods should also be explored to infer heat deposition from remotely sensed fire characteristics (Butler and Dickinson 2010). Remotely sensed flame spread, consumption and fireline intensity (e.g. Johnston et al. 2017) could serve as a basis for physical models of energy deposition (e.g. Bova and Dickinson 2008).

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