CSIRO PUBLISHING

International Journal of Wildland Fire **2016**, *25*, 1009–1014
http://dx.doi.org/10.1071/WF16007

Research Note

Laboratory experiments to estimate interception of infrared radiation by tree canopies

Bill J. Mathews[A], *Eva K. Strand*[A,E], *Alistair M. S. Smith*[A], *Andrew T. Hudak*[B], *Matthew B. Dickinson*[C] and *Robert L. Kremens*[D]

[A]Forest, Rangeland and Fire Sciences, College of Natural Resources, 875 Perimeter Drive MS 1135, University of Idaho, Moscow, ID 83844, USA.
[B]Rocky Mountain Research Station, USDA Forest Service, 1221 South Main Street, Moscow, ID 83843, USA.
[C]US Forest Service Northern Research Station, 359 Main Road, Delaware, OH 43015, USA.
[D]Rochester Institute of Technology, Center for Imaging Science, 54 Lomb Memorial Drive, Rochester, NY 14623, USA.
[E]Corresponding author. Email: evas@uidaho.edu

Additional keywords: biomass combustion, fire intensity, FRE, FRP, fuel consumption, remote sensing.

Received 14 January 2016, accepted 27 June 2016, published online 1 August 2016

Introduction

Fire is a key earth-system and Anthropocene process (Bowman *et al.* 2009; Smith *et al.* 2016*a*). 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.* 2016*a*). 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, 2016*b*; 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 (FRED, 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.* 2016*b*). 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.* 1998*a*, 1998*b*). 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 m^2 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

Fig. 1. Schematic drawing of the experimental setup in the laboratory and hemispherical photos of different canopy cover levels explored in the laboratory burn experiments. The hemispherical camera was centred over the heat source at the time the photo was taken and the simulated canopy was centred over the heat source during the experiment.

have very fast response times (Bova and Dickinson 2008; Smith *et al.* 2016*c*). 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:

$$Y = a - be^{-cx} \quad (1)$$

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:

$$Y_{ijk} = \mu + \rho_i + a_j + b_k + e_{ijk} \quad (2)$$

where Y_{ijk} is the ratio of sensor-observed obscured to unobscured radiant power, μ is the overall mean, ρ_i is the fixed effect for being in the *ith* 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 α 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

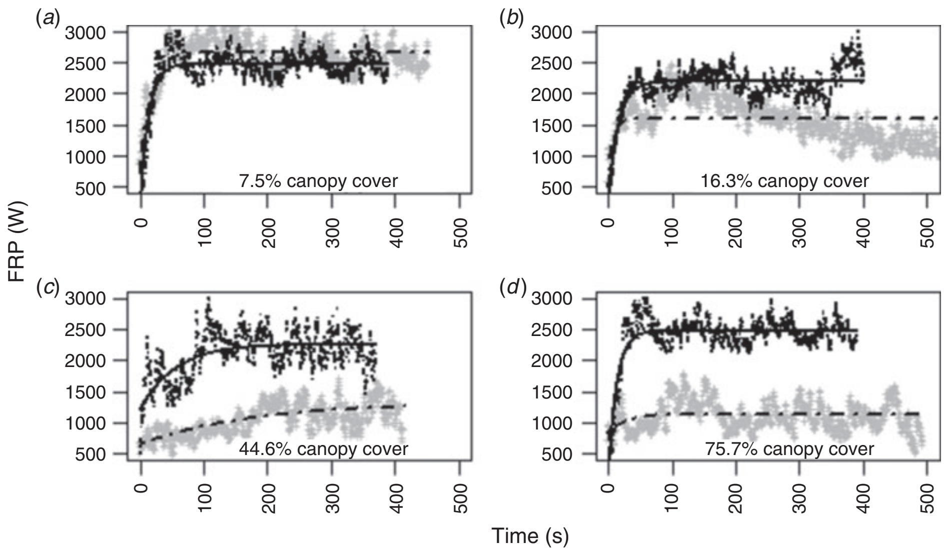

Fig. 2. Calibrated fire radiative power (FRP) data with temporal sampling every 0.5 s at four different canopy cover levels: (*a*) 7.5% canopy cover, (*b*) 16.3%, (*c*) 44.6% and (*d*) 75.7%. Grey points represent the obscured data, while black represents the control. The fitted non-linear least-squares model is shown as the solid line for the control and dashed for the obscured data.

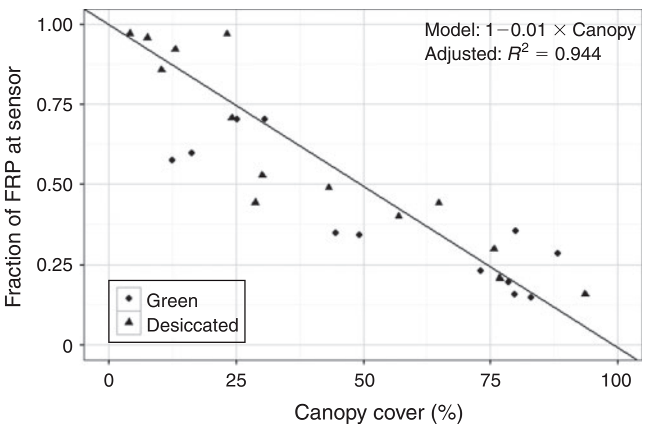

Fig. 3. Effect of canopy interception on the sensor-observed FRP (fire radiative power). Data points of green and desiccated material were combined because no significant difference was observed between the canopy types. The regression equation includes the assumption that the radiometer receives radiation at a maximum (fraction of 1) when no canopy intervenes.

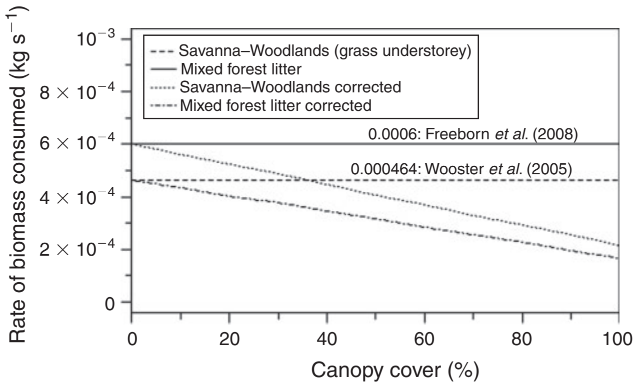

Fig. 4. Modelled impacts of forest canopy on the observed biomass combustion rate developed by Wooster *et al.* (2005) for grasses and by Freeborn *et al.* (2008) for mixed forest litter. These modelled estimates have not been experimentally validated and are presented to merely illustrate the potential impact of the results.

constants in different ecosystems as a function of canopy cover (Fig. 4). For example, for grass-dominated fuel beds, the biomass conversion rate constants presented by Wooster *et al.* (2005) of 0.464×10^{-3} kg MJ^{-1} lead to the reduction shown in the hashed line, whereas surface fires occurring in mixed-forest litter of 0.60×10^{-3} kg MJ^{-1} as presented by Freeborn *et al.* (2008) are shown by the solid line (Fig. 4). These results suggest that in cases of complete or near-complete canopy closure and high leaf area index values, surface fires may be below the detection threshold of above-canopy FRP sensors, although detection via observations of torching and crown fires may not be similarly affected.

With the increased availability of high-spatial-resolution satellite imagery and lidar-derived canopy cover measures, FRP density corrections for canopy cover can be made with high precision at landscape scales. Hudak *et al.* (2016) used canopy cover measures derived from airborne lidar data to account for canopy interception of observed FRED from prescribed fires; their approach effectively doubled estimated FRED in cases where canopy cover was 100%. Further research is needed to account for the interacting effects of variable sensor view angles and the three-dimensional geometry of the tree crowns that compose canopy structure. In areas without spatially explicit canopy measurements, landcover datasets such as those available from LANDFIRE (www.landfire.gov, accessed 29 April 2016) or similar programs could be used for more generalised corrections of FRP density. Under fire conditions that result in removal of canopy through torching or crowning, the use of pre-fire canopy data products could be misleading. In these cases, post-fire geospatial products such as aerial photography or burn severity maps that measure crown consumption could be consulted to preclude an FRP density correction from being erroneously applied.

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-simulated canopy cover increases, and in terms of (2), no significant difference was observed between the live and desiccated branches.

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 synoptic scales (Hudak *et al.* 2016). 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, multistorey, 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 (Smith *et al.* 2013). 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 multistorey forest canopies and humid south-eastern longleaf pine forests).

Acknowledgements

Experiments were conducted within the IFIRE combustion laboratory in Moscow, ID; we thank staff and students who contributed to the laboratory experiments. A. Smith was partially supported via the National Science Foundation through awards 1520873 and 1301792. Funding was provided by US Forest Service Joint Venture Agreements 12-JV-11221637–136 (Wildland Fire Science Partnership) and Joint Fire Science Program award 13-JV-11221633–112 (Joint Fire Science Program Project no. 11–2–1–11).

References

Balch JK, Bradley BA, D'Antonio C, Gomez-Dans J (2013) Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology* **19**, 173–183. doi:10.1111/GCB.12046

Boschetti L, Roy DP (2009) Strategies for the fusion of satellite fire radiative power with burned area data for fire radiative energy derivation. *Journal Geophysical Research* **114**, D20302. doi:10.1029/2008JD011645

Bova AS, Dickinson MB (2008) Beyond 'fire temperatures': calibrating thermocouple probes and modeling their response to surface fires in hardwood fuels. *Canadian Journal of Forest Research* **38**, 1008–1020. doi:10.1139/X07-204

Bowman DM, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, Defries RS, Doyle JC, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf GR, Pyne SJ (2009) Fire in the Earth system. *Science* **324**, 481–484. doi:10.1126/SCIENCE.1163886

Dickinson MB, Hudak AT, Zajkowski T, Loudermilk EL, Schroeder W, Ellison L, Kremens RL, Holley W, Martinez O, Paxton A, Bright BC, O'Brien JJ, Hornsby BS, Ichoku C, Faulring J, Gerace A, Peterson D, Mauceri J (2016) Measuring radiant emissions from entire prescribed fires with ground, airborne and satellite sensors – RxCADRE 2012. *International Journal of Wildland Fire* **25**, 48–61. doi:10.1071/WF15090

Dozier J (1981) A method for satellite identification of surface temperature fields of subpixel resolution. *Remote Sensing of Environment* **11**, 221–229. doi:10.1016/0034-4257(81)90021-3

Freeborn PH, Wooster MJ, Hao WM, Ryan CA, Nordgren BL, Baker SP, Ichoku C (2008) Relationships between energy release, fuel mass loss, and trace gas and aerosol emissions during laboratory biomass fires. *Journal of Geophysical Research Atmospheres* **113**, D01301. doi:10.1029/2007JD008679

Hardy CC, Ottmar RD, Peterson JL, Core JE, Seamon P (Eds) (2001) 'Smoke management guide for prescribed and wildland fire: 2001 edition.' Publication Management System (PMS) 420–2. National Fire Equipment System NFES Publication 1279. (National Wildfire Coordination Group: Boise, ID)

Hudak AT, Strand EK, Veirling LA, Bryne JC, Eitel JU, Martinuzzi S, Falkowski MJ (2012) Quantifying aboveground forest carbon pools and fluxes from repeat LiDAR surveys. *Remote Sensing of Environment* **123**, 25–40. doi:10.1016/J.RSE.2012.02.023

Hudak AT, Dickinson MB, Bright BC, Kremens RL, Loudermilk E, O'Brien JJ, Hornsby BS, Ottmar RD (2016) Measurements relating fire radiative energy density and surface fuel consumption – RxCADRE 2011 and 2012. *International Journal of Wildland Fire* **25**, 25–37. doi:10.1071/WF14159

Kaiser JW, Heil A, Andreae MO, Benedetti A, Chubarova N, Jones L, Morcrette JJ, Razinger M, Schultz MG, Suttie M, van der Werf GR (2012) Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiant power. *Biogeosciences* **9**, 527–554. doi:10.5194/BG-9-527-2012

Kaufman YJ, Justice CO, Flynn LP, Kendall JD, Prins EM, Giglio L, Ward DE, Menzel WP (1998*a*) Potential global fire monitoring from EOS-MODIS. *Journal of Geophysical Research* **103**(D24), 32215–32238. doi:10.1029/98JD01644

Kaufman YJ, Kleidman RG, King MD (1998*b*) SCAR-B fires in the tropics: properties and remote sensing from EOS-MODIS. *Journal of Geophysical Research* **103**(D24), 31955–31968. doi:10.1029/98JD02460

Kremens RL, Dickinson MB (2015) Estimating radiated flux density from wildland fires using the raw output of limited bandpass detectors. *International Journal of Wildland Fire* **24**, 461–469. doi:10.1071/WF14036

Kremens RL, Smith AMS, Dickinson MB (2010) Fire metrology: current and future directions in physics-based methods. *Fire Ecology* **6**(1), 13–35. doi:10.4996/FIREECOLOGY.0601013

Kremens RL, Dickinson MB, Bova AS (2012) Radiant flux density, energy density and fuel consumption in mixed-oak forest surface fires. *International Journal of Wildland Fire* **21**, 722–730. doi:10.1071/WF10143

Kumar SS, Roy DP, Boschetti L, Kremens R (2011) Exploiting the power-law distribution properties of satellite fire radiative power retrievals: a method to estimate fire radiative energy and biomass burned from sparse satellite observations. *Journal of Geophysical Research* **116**, D19303. doi:10.1029/2011JD015676

Lannom KO, Tinkham WT, Smith AMS, Abatzoglou JT, Newingham BA, Hall TE, Morgan P, Strand EK, Paveglio TB, Anderson JW, Sparks AM (2014) Defining extreme wildland fires using geospatial data and ancillary metrics. *International Journal of Wildland Fire* **23**, 322–377. doi:10.1071/WF13065

Seiler W, Crutzen PJ (1980) Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* **2**, 207–247. doi:10.1007/BF00137988

Smith AMS, Strand EK, Steele CM, Hann DB, Garrity SR, Falkowski MJ, Evans JS (2008) Production of vegetation spatial-structure maps by per-object analysis of juniper encroachment in multitemporal aerial photographs. *Canadian Journal of Remote Sensing* **34**, S268–S285. doi:10.5589/M08-048

Smith AMS, Falkowski MJ, Hudak AT, Evans JS, Robinson AP, Steele CM (2009) A cross-comparison of field, spectral, and lidar estimates of forest canopy cover. *Canadian Journal of Remote Sensing* **35**, 447–459. doi:10.5589/M09-038

Smith AMS, Tinkham WT, Roy DP, Boschetti L, Kremens RL, Kumar SS, Sparks AM, Falkowski MJ (2013) Quantification of fuel moisture effects on biomass consumed derived from fire radiative energy retrievals. *Geophysical Research Letters* **40**(23), 6298–6302. doi:10.1002/2013GL058232

Smith AMS, Kolden CA, Paveglio T, Cochrane MA, Mortitz MA, Bowman DMJS, Hoffman CM, Lutz J, Queen LP, Hudak AT, Alessa L, Kliskey AD, Goetz S, Yedinak KM, Boschetti L, Higuera PE, Flannigan M, Strand EK, van Wagtendonk JW, Anderson JW, Stocks BJ, Abatzoglou JT (2016*a*) The science of firescapes: achieving fire resilient communities. *Bioscience* **66**(2), 130–146. doi:10.1093/BIOSCI/BIV182

Smith AMS, Sparks AM, Kolden CA, Abatzoglou JT, Talhelm AF, Johnson DM, Boschetti L, Lutz JA, Apostol KG, Yedinak KM, Tinkham WT, Kremens RJ (2016*b*) Towards a new paradigm in fire severity research using dose–response experiments. *International Journal of Wildland Fire* **25**, 158–166. doi:10.1071/WF15130

Smith AMS, Talhelm AF, Kolden CA, Newingham BA, Adams HD, Cohen JD, Yedinak KM, Kremens RL (2016*c*) The ability of winter grazing to reduce wildfire size and fire-induced plant mortality was not demonstrated: a comment on Davis *et al.* (2015). *International Journal of Wildland Fire* **25**, 484–488.

Strand E, Smith AMS, Bunting SC, Vierling LA, Hann DB, Gessler PE (2006) Wavelet estimation of plant spatial patterns in multitemporal aerial photography. *International Journal of Remote Sensing* **27**, 2049–2054. doi:10.1080/01431160500444764

Strand EK, Vierling LA, Smith AMS, Bunting SC (2008) Net changes in aboveground woody carbon stock in western juniper woodlands, 1946–1998. *Journal of Geophysical Research* **113**, G01013. doi:10.1029/2007JG000544

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Mu M, Kasibhatla PS, Morton DC, DeFries RS, Jin Y, van Leeuwen TT (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics* **10**. doi:10.5194/ACP-10-11707-2010

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

Wooster MJ, Zhukov B, Oertel D (2003) Fire radiative energy for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sensing of Environment* **86**(1), 83–107. doi:10.1016/S0034-4257(03)00070-1

Wooster MJ, Roberts G, Perry GLW, Kaufman YJ (2005) Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release *Journal of Geophysical Research* **110**(D24). doi:10.1029/2005JD006318

Wotton BM, Nock C, Flannigan MD (2010) Forest fire occurrence and climate change in Canada. *International Journal of Wildland Fire* **19**, 253–271. doi:10.1071/WF09002

Zhukov B, Lorenz E, Oertel D, Wooster MJ, Roberts G (2006) Space-borne detection and characterization of fires during the Bi-spectral Infrared Detection (BIRD) experimental small satellite mission 2001–2004. *Remote Sensing of Environment* **100**, 29–51. doi:10.1016/J.RSE.2005.09.019