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Quantification of fuel moisture effects on biomass consumed derived from fire radiative energy retrievals

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[1] Satellite based fire radiant energy retrievals are widely applied to assess biomass consumed and emissions at regional to global scales. A known potential source of uncertainty in biomass burning estimates arises from fuel moisture but this impact has not been quantified in previous studies. Controlled fire laboratory experiments are used in this study to examine the biomass consumed and the radiant energy release (Fire Radiative Energy, FRE, (MJ)) for western white pine needle fuels burned with water content (W_C, unitless) from 0.01 to 0.14. Results indicate a significant relationship: FRE per kilogram of fuel consumed = −5.32 W_C + 3.025 (r^2 = 0.83, n = 24, P < 0.001) and imply that not taking into account fuel moisture variations in the assumed relationship between FRE and fuel consumed can lead to systematic biases. A methodological framework to derive a revised formula that enables the estimation of biomass consumed from FRE, which explicitly takes into account fuel water content, is presented. **Citation:** Smith, A. M. S., W. T. Tinkham, D. P. Roy, L. Boschetti, R. L. Kremens, S. S. Kumar, A. M. Sparks, and M. J. Falkowski (2013), Quantification of fuel moisture effects on biomass consumed derived from fire radiative energy retrievals, *Geophys. Res. Lett.*, *40*, 6298–6302, doi:10.1002/2013GL058232.

1. Introduction

[2] Biomass burning is a significant source of atmospheric trace gas and aerosol emissions, accounting globally for ~40% of annual carbon dioxide and carbon monoxide emissions [*van der Werf et al.*, 2010], although the exact quantities vary with interannual variability of climate processes [*Slegert et al.*, 2001; *Littell et al.*, 2009]. Quantifying biomass consumed and subsequent emissions is fundamental in understanding terrestrial-atmospheric Earth system processes and climate change [*Bowman et al.*, 2009]. Regional to global scale emission estimates are obtained conventionally via remotely sensed estimates of the area burned, model estimates of the quantity of fuel consumed, and the emission factors of the associated emitted greenhouse and trace gases [*Crutzen and Andreae*, 1990]. Recently, fire radiant energy remote sensing products from polar-orbiting and geostationary coarse resolution fire products have been applied to infer fire behavior and biomass consumed at regional to global scales [*Kaufman et al.*, 1998; *Wooster*, 2002; *Roberts et al.*, 2005; *Smith and Wooster*, 2005; *Wooster et al.*, 2005; *Roberts and Wooster*, 2008; *Kumar et al.*, 2011; *Kaiser et al.*, 2012; *Zhang et al.*, 2012; *Heward et al.*, 2013]. The fire radiant power (FRP; units: W) retrieved at the time of satellite overpass is related to the instantaneous rate of biomass consumed; temporal integration of sampled FRP over the fire duration provides the Fire Radiative Energy (FRE; units: J) which has been shown, with both laboratory and field measurements, to be linearly related to the amount of biomass burned [*Wooster*, 2002; *Wooster et al.*, 2005; *Freeborn et al.*, 2008; *Kremens et al.*, 2012].

[3] A known potential source of uncertainty arises from water contained within the fuel but this impact has yet to be quantified by remote sensing FRE studies [*Brown and Davis*, 1973; *Freeborn et al.*, 2008; *Kremens et al.*, 2012; *Roy et al.*, 2013; *Wooster et al.*, 2013]. The fuel may not be completely dry when it is burned, depending on the precipitation and temperature regimes, the amount of drying due to the antecedent and current incoming solar radiation, the relative humidity of the atmosphere, condensation of dew onto the fuel surface, the state of decay of the fuels, and the proportion of live vegetation in the fuel. In terms of FRP measurement, the latent energy required to change the phase of liquid water in the fuel to water vapor (i.e., the enthalpy of vaporization) is not measured when sensing the combusting fuel within an actively burning fire. Moreover, the energy required to raise the liquid water in the fuel from ambient to boiling temperature and the energy required to drive the moisture out of the fuel (i.e., the heat of desorption) will reduce the emitted energy that is remotely sensed [*Brown and Davis*, 1973]. The emitted radiant energy may also be absorbed by water vapor and smoke in the atmospheric column between the fuel and the sensor and may be reemitted in a direction away from the sensor. The combined impact of these loss mechanisms on fire radiant energy retrievals has yet to be quantified, which limits the confidence in using satellite derived radiant energy products for the assessment of regional to continental biomass consumed and emission estimates. Arguably these uncertainties, in addition to FRP sampling issues [*Boschetti and Roy*, 2009; *Kumar et al.* 2011], may have prevented a wider uptake of FRP-based emission estimations. However, recent continental and global emission estimation systems that use FRP also rely on other data, for example, using empirical coefficients based on aerosol optical thickness retrievals [*Sofiev et al.* 2009] or, as in *Kaiser et al.*, [2012] normalizing the FRP-based emission

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retrievals against the Global Fire Emissions Database which is produced using a conventional bottom-up emission estimation approach [*van der Werf et al.*, 2010]. For the first time, we present results from a laboratory experiment to quantify how increasing moisture content impacts remotely sensed fire radiant energy retrievals.

2. Methodology

2.1. Experimental Setup

[4] Fire experiments were conducted at the Idaho Fire Institute of Research and Education located in an indoor climatically controlled environment that is shielded from weather effects. Multiple approaches exist to estimate FRP, including single-band midwave-infrared thermal imagers, dual-band thermometry, and Planck function curve fitting of 0.3–2.5 μm spectroradiometer data; the relative merits and the variation of FRP retrieved from these different methods are discussed in past studies [*Dozier*, 1981; *Wooster et al.*, 2005; *Kremens et al.*, 2010]. In this study, we used a dual-band infrared radiometer (0.15–11 μm and 6.5–20 μm) developed by the Rochester Institute of Technology to estimate FRP per unit area ($W\,m^{-2}$) at 0.5 s intervals using dual-band thermometry, where in contrast to single wavelength devices, measurements are acquired independently of emissivity [*Kremens et al.*, 2010, 2012]. As detailed in the literature [*Dozier*, 1981; *Daniels*, 2007; *Kremens et al.*, 2010, 2012], dual-band thermometry uses the principal that for a black- or grey-body radiation source the ratio of two infrared bands enables the kinetic temperature of the source to be estimated via a two point fit to the Planck function. The radiometer employs a ST60 dual-detector infrared thermopile (Dexter Research Center, Michigan) as an active element with custom noise filtering and amplifying electronics mounted on a printed circuit board in a ventilated fire resistant housing [*Kremens et al.*, 2012]. The system was radiometrically calibrated using standard blackbody radiation sources (Omega Engineering part # BB-4A and #BB-704) between 373 K and 1250 K [*Wolfe and Zissis*, 1993]. During operation, dry air was streamed across the dual-band infrared radiometer to reduce fouling due to soot and other smoke particulates. The ambient temperature of the dual-detector infrared thermopile was measured using a digital thermometer. The dual-band infrared radiometer has a 52° instrument field of view and was positioned at a fixed height of 1.16 m directly above the center of a 1 m^2 circular fuel bed, so that the extent of the fuel bed was equal to the sensor field of view. To minimize the effects of conductive heat transfer, the fuel bed was placed on a low conductivity fiberglass mesh reinforced ceramic board. The board was placed on a Sartorius EB Series scale (65 kg capacity, accurate to 1 g), synchronized with the dual-band radiometer to record fuel mass loss throughout the burn period. Fuels were collected from a single species western white pine (*Pinus monticola*) stand located adjacent to the University of Idaho, USA and were manually sorted to remove impurities such as bark flakes, lichens, etc.

[5] For each ignition, a small amount of lighter fluid was added to the edge of the fuel bed and ignited to provide a uniformly spreading flaming front. Each burn trial was considered complete once no mass loss was observed for at least 20 s. The radiometer recorded zero FRP values after the fire had extinguished, indicating the radiant energy emitted from the heated board was below the radiometer's detection limit. Prior to each ignition, all fuel beds were compressed to a constant bulk density of 85.7 $kg\,m^{-3}$ to minimize variation in fire behavior and combustion completeness across the burn trials.

[6] The FRE was derived as the discrete integral of the FRP over the duration of each burn:

$$\mathrm{FRE} = \sum_{t1}^{t2} \mathrm{FRP}_t \Delta \mathrm{t}, \tag{1}$$

where t_1 (s) and t_2 (s) denote, respectively, the start and end of combustion, as defined above; FRP_t (W) is the power measured by the radiometer at time t; and $\Delta t = 0.5$ s is the measurement sampling interval.

2.2. Fuel Water Content

[7] Fuel moisture was quantified in terms of water content, defined as the percentage of water over the total mass of the (wet) sample:

$$W_C = \frac{W_M}{S_M} = \frac{W_M}{D_M + W_M}, \tag{2}$$

where W_C (dimensionless) is the fuel water content, S_M (kg) is the total mass of the wet fuel sample, W_M (kg) is the water mass, and D_M (kg) is the dry mass of the fuel sample. The water content W_C is univocally related to the fuel moisture content (FMC), commonly used in the fire ecology community, which is defined as the water content (W_C) divided by the dry mass (D_M). The fuel moisture was controlled by reducing all materials to $W_C < 0.01$ in an oven, weighing the fuel beds to derive the dry mass, and then allowing the fuel to equilibrate outside the oven to the mass associated with the desired water content.

2.3. Theoretical Heat Budget

[8] The radiant energy release fraction (f_r), defined as the fraction of total energy released during combustion in the form of radiation [*Freeborn et al.*, 2008], was calculated as

$$f_r = \frac{\mathrm{FRE}}{H_C * \mathrm{BC}}, \tag{3}$$

where H_C (MJ kg^{-1}) is the heat of combustion, FRE (MJ) is defined via (1), and BC (kg) is the total biomass consumed as measured by the scale.

[9] A theoretical radiant heat budget per unit mass consumed was derived to independently quantify the deficit of retrieved fire radiant energy due to fuel moisture. The theoretical FRE released by a burnt sample is defined [*Brown and Davis*, 1973; *Kremens et al.*, 2012] as

$$\mathrm{FRE} = f_r * \left[H_C D_M - W_M \left(H_{\mathrm{vap}} + C_W (373 - T_a) + H_{\mathrm{Des}} \right) \right] \tag{4}$$

where f_r is defined as (3), H_C is the heat of combustion of pine needles (20.138 MJ kg^{-1}) [*Font et al.*, 2009], D_M is the dry mass of the sample, W_M is the water content of the sample, H_{vap} is the enthalpy of water vaporization at atmospheric pressure (2.257 MJ kg^{-1}), C_W is the heat capacity of water (0.0042 MJ kg^{-1}), T_a = ambient temperature (300 K), and H_{Des} is the heat of desorption = 0.1 MJ kg^{-1} [*Brown and Davis*, 1973; *Shottafer and Shuller*, 1974].

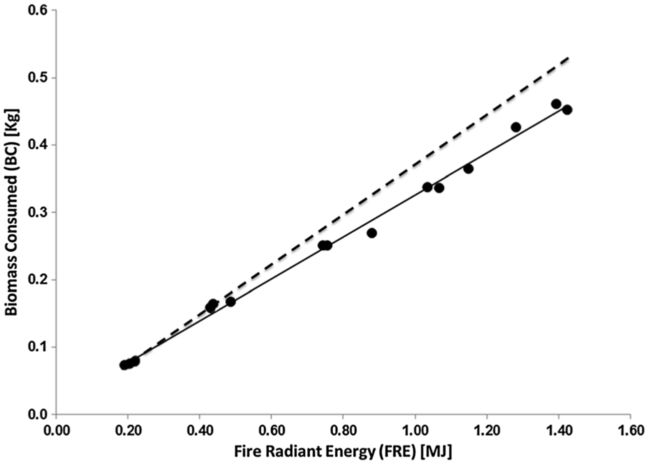

Figure 1. Relationship between fire radiant energy (FRE) and biomass consumed (BC) for 15 dry (<0.01 W_C) pine needle experimental burns (closed circles). The best fit linear regression passing through the origin (BC = (0.325 ± 0.008) *FRE, $r^2 = 0.998$, $n = 15$, $P < 0.01$) is shown as a continuous line. The dashed line shows the BC predicted from the retrieved FRE using the conventional relationship described by (7).

[10] Rearranging the terms of (4), substituting (2), and normalizing for mass, provides

$$\frac{\mathrm{FRE}}{\mathrm{BC}} = f_r\left[H_C - W_C\left(H_C + H_{\mathrm{vap}} + C_W(373 - T_a) + H_{\mathrm{Des}}\right)\right], \quad (5)$$

which can be simplified into a general equation that expresses the relationship between FRE, BC, and W_C as

$$\mathrm{BC} = (b - m^* W_C)^{-1} {}^*\mathrm{FRE}, \quad (6)$$

where b (MJ kg^{-1}) is the FRE emitted per unit of biomass consumed by a dry fuel (0 W_C), and m is any bias in the FRE per unit of biomass due to change in W_C.

2.4. Experimental Burns

[11] An initial set of 15 dry (< 0.01 W_C) needle fuel beds were created, with a range of fuel loads from 100 to 500 g m^{-2} to test the conventional biomass consumed FRE relationship described by *Wooster et al.* [2005] as

$$\mathrm{BC}_{\mathrm{Wooster}} = 0.368(\pm 0.015)^*\mathrm{FRE}, \quad (7)$$

where $\mathrm{BC}_{\mathrm{wooster}}$ is the biomass consumed (kg) and FRE (MJ) is derived from (1). *Wooster et al.* [2005] derived this relationship from the combustion of *Miscanthus* grasses with ~0.12 moisture content sensed with a Medium-Wave Infrared (MWIR) imager. Using the experimental FRE and BC data from the combustion of the 15 dry fuel beds, the slope coefficient of (7), together with its 95% confidence interval, was estimated by linear regression. The radiant energy release fraction (f_r) was also determined for each of the 15 dry fuel burns using (3) and an average calculated.

[12] Subsequently, 24 pine needle fuel beds were burned with W_C ranging from 0.01 to 0.14. A dry fuel load of 300 g m^{-2} was used for each of these 24 burns to reflect typical conifer *Pinus* spp. forest needle fuel loading [*Nelson and Heirs*, 2008]. The measured W_C, BC, and retrieved FRE were used to estimate the terms m and b in (6) by linear regression.

3. Results and Discussion

[13] Figure 1 compares the biomass consumed of dry pine needles with the retrieved fire radiant energy (closed circles) and demonstrates a strong ($r^2 = 0.998$, $n = 15$, $P < 0.001$) linear relationship, with a 0.325 ± 0.008 slope. The observed variability in the plotted data is attributed to differences in the fuel bed bulk density and homogeneity of the fuel load among the 15 experimental dry burns. The pine needle radiant energy release fraction (f_r) was 14.7 ± 1% and is comparable to values observed by other researchers for *Miscanthus* grass ($f_r = 13 \pm 3\%$) [*Wooster et al.*, 2005], mixed fuel beds of needles and wood ($f_r = 11.7 \pm 2.4\%$) [*Freeborn et al.*, 2008], and oak savannah litter ($f_r = 17 \pm 3\%$) [*Kremens et al.*, 2012]. The dashed line shows the biomass consumed predicted from the retrieved FRE using the conventional relationship described by (7). Differences in the slope functions can be attributed to the fuel type, the moisture content of the fuel, and the experimental approach (i.e., dual-band thermometry versus MWIR imager). Specifically, *Wooster et al.* [2005] used *Miscanthus* grass that has a lower heat of combustion (H_C = 17.100–19.400 MJ kg^{-1}) compared to the pine needles (20.138 MJ kg^{-1}), and the grass had $W_C \sim 0.12$.

[14] Figure 2 compares the ratio of the FRE to the biomass consumed with the water content (closed circles). The retrieved FRE decreases with increasing moisture content. A significant relationship is observed: FRE per kilogram of fuel consumed = −5.32 W_C + 3.025 ($r^2 = 0.83$, $n = 24$, $SE = 0.104$, $P < 0.001$). The regression coefficient standard errors were one and two orders of magnitude smaller than the regression coefficient values (standard errors of 0.5 and 0.038 for the gradient and intercept coefficients, respectively). The observed variability in the plotted data around the regression line is most likely due to experimental measurement error (radiometer, mass scale, and W_C). The theoretical radiant heat budget per unit mass consumed (5) is shown in Figure 2 (dashed line) and indicates general agreement, within the range of the variability of the observed data. The absolute

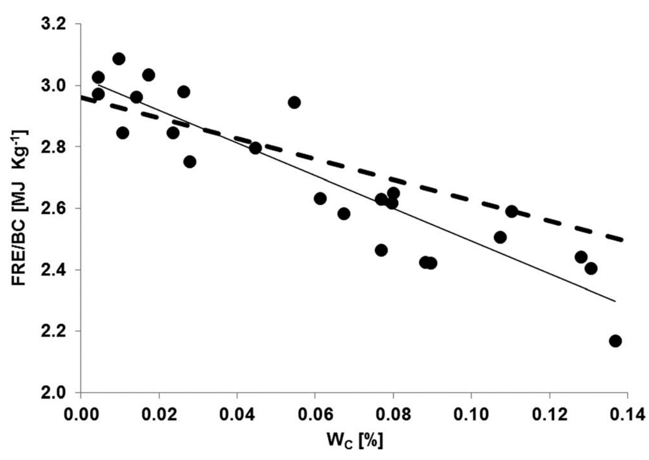

Figure 2. The impact of water content, W_C, on the FRE per unit of biomass consumed (FRE/BC) for 24 experimental burns (closed circles). The regression of these data (solid line) is: FRE/BC (MJ kg^{-1}) = −5.32W_C + 3.025 ($r^2 = 0.832$, $n = 24$, $P < 0.001$). The 95% confidence intervals for the gradient and intercept are ±1.05 and ±0.079, respectively. The theoretical radiant heat budget per unit mass consumed (5) is shown as a dashed line.

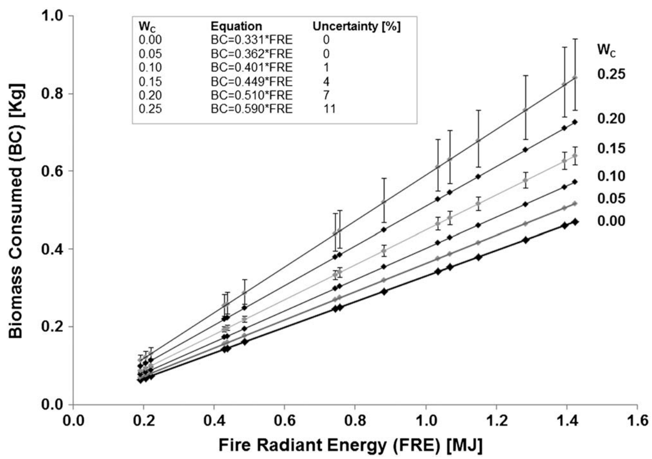

Figure 3. Impact of fuel water content, W_C (dimensionless), on the relationship between retrieved FRE and biomass consumed (BC). Equation (8) is theoretically demonstrated for W_C values from 0 to 0.25 for the 15 dry pine fuel FRE retrievals illustrated in Figure 1, and the resulting linear equations are plotted as diagonal lines. The % uncertainty is calculated for each W_C line by applying the 95% confidence intervals from the gradient and intercept coefficients in (8). Only the error bars associated with 0.15 and 0.25 are shown for illustrative purposes. Pine needles do not burn if the water content is higher than ~0.26. The reported equations values are derived from the current experimental data and are in close correspondence to the theoretical values that can be derived from (5).

mean difference between the theoretical and observed values across the range of W_C was 0.13 with a standard deviation of 0.09 MJ kg^{-1}. This difference is likely due to errors in the parameterization of (4), for example, the heat of desorption is not particularly well defined in the literature, or due to an additional unaccounted for processes such as the absorption of emitted energy by water vapor and smoke in the atmospheric column [*Brown and Davis*, 1973; *Freeborn et al.*, 2008].

[15] The 24 measured W_C, BC, and retrieved FRE values were used to estimate the terms b and m in (6) by linear regression to provide $b = 3.025$ (MJ kg^{-1}) and $m = 5.32$ with 95% confidence intervals ±0.079 and ±1.05, respectively. This provides

$$\mathrm{BC} = (3.025 - 5.32 * W_C)^{-1} * \mathrm{FRE}, \tag{8}$$

where BC (kg) is the total biomass consumed and FRE (MJ) is the fire radiative energy. Equation (8) enables the estimation of biomass consumed from FRE explicitly taking into account fuel water content and updates the conventional biomass consumed FRE relationship described by *Wooster et al.* [2005] and (7).

[16] Figure 3 shows the results of the application of (8) for water content ranging from 0 to 0.25 applied to the 15 dry fuel FRE values illustrated in Figure 1. Clearly, changes in fuel moisture will bias conventional biomass burning estimates from FRE (7). It should be noted that while pine needles do not combust at $W_C \sim 0.26$, peat and other fuels can combust at significantly higher moisture contents [*Benscoter et al.*, 2011], potentially making the impact of fuel water content on FRE biomass burned retrieval even more pronounced for these fuel types. Comparison of (8) and (7), which was parameterized at $W_C \sim 0.12$, yields a 14% difference in the gradient. This difference can be partly attributed to the variations in the heat of combustion, time from W_C calculation to combustion, and the different FRP retrieval methods [*Wooster et al.*, 2003, 2005].

4. Conclusions

[17] This research confirms past studies showing strong linear relationships between biomass consumed and integrated fire radiant energy. Measurements from two sets of experimental burns were used to quantify the impact of fuel water content on fire radiant energy, and to derive a new formula where the linear relationship between biomass consumed and fire radiant energy is parameterized for fuel water content. Comparison of these results to past studies demonstrates that dual-band thermometry produces data of comparable accuracy and precision to other FRP retrieval approaches. The results of this study have several implications for the future use of satellite based fire energy retrievals to estimate biomass consumed. Conventional biomass burning retrievals, using the equation proposed by *Wooster et al.* [2005], do not take into account fuel moisture and may systematically bias estimates of the biomass consumed. This is particularly relevant given that the fuel moisture may change through the fire season, and the seasonality of fire extent and intensity remains an area of active research [*Korontzi et al.*, 2004; *Roy et al.*, 2005; *Yates et al.*, 2008; *Archibald et al.*, 2010; *Meyer et al.*, 2012; *Randerson et al.*, 2012].

[18] This study suggests the need to test whether similar moisture content relationships are observed for diverse fuels such as in peat, woody debris, and leaf litter [*Hyde et al.*, 2011; *Kremens et al.*, 2012; *Brewer et al.*, 2013]. Moisture-corrected FRE biomass burned equations would improve the application of spaceborne fire radiant energy products in assessing biomass burning but this application will require spatially and temporally explicit estimation of fuel moisture. Future research to further validate the methodology is recommended. This should include cross-comparison of single band and dual-band FRP approaches to further evaluate moisture effects on FRP [*Wooster et al.*, 2005] and the application of the method to satellite FRP data and fuel stratification maps to determine fuel-type specific coefficients for (6); thus, enabling systematic moisture content corrections for FRE to be realized.

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