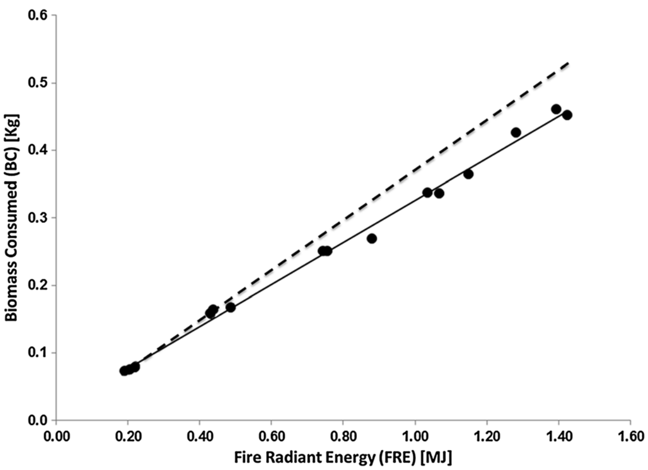

Figure 1. Relationship between fire radiant energy (FRE) and biomass consumed (BC) for 15 dry (<0.01 W_C) pine needle experimental burns (closed circles). The best fit linear regression passing through the origin (BC = (0.325 ± 0.008) *FRE, $r^2 = 0.998$, $n = 15$, $P < 0.01$) is shown as a continuous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

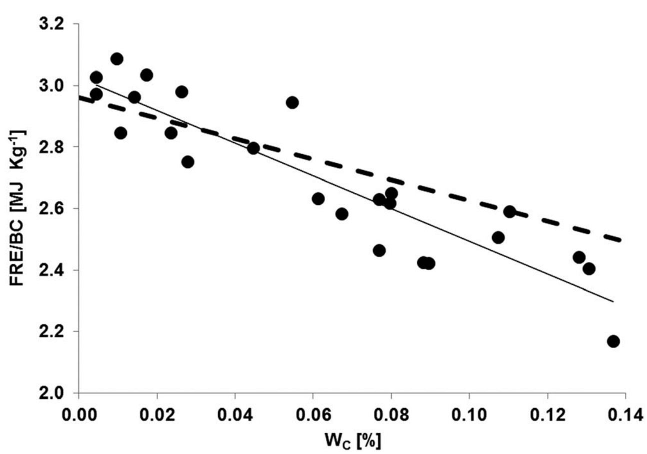

Figure 2. The impact of water content, W_C, on the FRE per unit of biomass consumed (FRE/BC) for 24 experimental burns (closed circles). The regression of these data (solid line) is: FRE/BC (MJ kg^{-1}) = −5.32W_C + 3.025 ($r^2 = 0.832$, $n = 24$, $P < 0.001$). The 95% confidence intervals for the gradient 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.