11.7 MICROMETEOROLOGICAL MEASUREMENTS TO ASSESS FIRE FUEL DRYNESS

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1. INTRODUCTION

The amount of moisture in fuel is the major element that determines how much of the fuel components (i.e., aerial, surface and ground) will burn (available fuel). Therefore, estimates of fuel moisture content are a key component of most fire danger research programs. Various approaches and models were developed and applied to determine moisture content for each fuel level. The “aerial” (i.e., above-ground, living vegetation) fuel is commonly determined using numerous parameters that define live fuel loads by size class, surface area to volume ratios of the various size classes, heat content, etc (Rothermel, 1972). Recently, geographic information systems (GIS) and space-borne observations provide data useful for “green maps”, which parameterize the quantity of moisture content in live vegetation (Burgan, 1988; Burgan et al., 1998). Methods to predict “dead” fuel moisture content (i.e., from dead vegetation) are included in most fire danger systems and are mainly based on separating dead fuel moisture response into time lag classes of 1, 10, 100, and 1000 hours (Deeming et al., 1977). A fuel time lag is proportional to fuel diameter and is defined as the time it takes a fuel particle to change its moisture content about 2/3 of the difference between initial and final conditions in one time lag period. The 1- to 10-h time lag response category was shown to be the most critical dead fuel class involved in determining fire spread rate and it is commonly used to represent the moisture content of all dead vegetation. The 10-h fuel class can be computed from measurements of temperature, humidity, and cloudiness or observed from a standard set of 10-h fuel sticks. A numerical rating of average moisture content of deep, compact, organic soil layer is a useful indicator of fuel consumption in moderate “duff” layers and medium-size woody material and of seasonal drought and amount of smoldering in deep duff layers. Several drought indexes were designed specifically for fire potential assessment, for example Keetch and Byram (1968) proposed a drought index (KBDI) based on the net effect of evapotranspiration and precipitation in producing cumulative moisture deficit in deep duff and upper soil layers.

The assessment of moisture content for each fuel level on a large spatial scale requires several observations and estimates and is often time consuming and costly due to labor and transportation expenses. Consequently, there is a need for a simpler, less costly method to remotely assess the F_d index.

In this paper, we will present a simple, relatively low cost method to remotely obtain a fuel dryness index that can greatly improve our ability to evaluate the influence of fuel dryness and hence fire risk index (F_d). The method can be adapted to assess not only fine fuel moisture or 1-hour lag fuel moisture, but also the 10-hour, 100-hour, and 1000-hour lag fuel moistures. In addition, it could be modified to be incorporated into the U.S. National Fire Danger Rating Sistem supported KBDI which is used partially to assess soil and ecosystem dryness.

2. FUEL DRYNESS INDEX THEORY

We base our method on the surface energy balance, where available energy (R_n - G) is partitioned into sensible and latent heat exchanges ($H + LE$). Conventionally, net radiation (R_n) is positive downwards, both sensible heat flux density (H) and latent heat flux density (LE) are positive upwards and soil heat flux density (G) is positive downwards. When soil water is not limiting, then H is typically small relative to LE and $R_n - G$ is a measure of the potential or maximum possible LE. In advective conditions, LE can be greater than $R_n - G$, but only if the surface is moist. When the surface is dry and soil water is limited, evaporation from the surface is reduced and LE decreases relative to $R_n - G$, so:

$$R = \frac{LE}{R_n - G} \tag{1}$$

is an integrated measure of dryness conditions (surface dryness). When $R > 1.0$, the surface fuel is clearly moist, so an upper limit of $R = 1.0$ is employed in practice. As a surface changes from wet to dry, R changes from $R \approx 1.0$ to $R \approx 0.0$. Therefore, the fuel dryness index (F_d) can be calculated as:

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$$F_i = 1 - \frac{LE}{R_n - G} \tag{2}$$

F_d approaches 0.0 when fire potential is low, because of high values of surface fuel and ecosystem moisture, and it rises to 1.0 as the moisture is low and the chances of wildfire increase. One advantage of the F_d index is that it provides a weighted measure of dryness of all fuel on the surface and the integrated plant ecosystem, as opposed to only material used in a “fire stick test” or used in a measure of relative water content. When both the surface and the plants show little evapotranspiration, this implies local drought conditions are commencing, and both the surface litter moisture and the soil depths where the plant roots reside are dry. Therefore F_d represents a form of a weighted average of the 1-hour, 10-hour, 100-hour, and 1000-hour time lag fuel moistures, with decreasing weights for the longer time lags. Integration (averaging) of F_d over time could be performed to more formally arrive at indexes roughly equivalent to the longer time lag moisture components, and to the KBDI. Similar equivalences could be made for the Drought Code and Duff Moisture Code of the Canadian Forest Fire Weather Index (FWI).

Clearly, any method to measure or accurately estimate R_n, G and LE can be used to calculate F_d. The problem is to find a method that is low cost, robust and that lends itself to simplified networking or remote monitoring. Such a method could be used in conjunction with remotely-sensed methods and indexes such as the Fire Potential Index (Burgan et al., 1998), to assist in ground-truthing remotely-sensed data and analysis.

3. SURFACE RENEWAL METHOD

The surface renewal (SR) method for estimating H from surfaces in conjunction with R_n and G estimates provides a simple, robust and low-cost method to estimate latent heat flux density (*LE*) from grasslands and forests (Paw U et al., 1995). The method lends itself to distributed, automated networks and it can potentially provide the data needed to obtain spatial estimates of F_d.

The SR method is based on the idea that traces of high frequency temperature data above and within plant canopies exhibit ramp-like shapes that are related to coherent structures (Paw U and Brunet, 1991). The mean amplitude (a) and inverse ramp frequency ($d+s$) can be quantified using a structure function (Van Atta, 1977; Snyder et al., 1996). Using conservation of energy, Paw U et al. (1995) showed that an expression for H can be derived from the conservation of energy:

$$H = \alpha H_{SR} = \alpha\left(\rho C_p \frac{a}{d+s} z\right) \tag{3}$$

where z is the measurement height (m), ρ is the air density (kg m^{-3}) and C_p is the specific heat of the air (J kg^{-1} K^{-1}). The factor H_{SR} is the SR sensible heat flux density assuming uniform heating from the ground up to the measurement height (z) and α accounts for unequal heating of the air volume under the temperature sensor (Paw U et al., 1995). The α factor is determined by calculating the slope of the linear regression (through the origin) of H from an accurate independent method such as eddy-covariance using a sonic anemometer versus H_{SR}. Once determined, α seems to be relatively conservative for a given surface regardless of weather conditions (Snyder et al., 1996; Snyder et al., 1997; Spano et al., 1997a; Spano et al., 2000)

A CR10X data-logged program was written to collect high frequency temperature data to compute half-hour means of the 2nd, 3rd, and 5th order moments of the time lag temperature differences, which constitute structure functions (Van Atta, 1977; Snyder et al., 1996). The half-hour statistical structure function moments are stored in the logger memory until transferred to a computer where H_{SR} is calculated following the procedure in Snyder et al. (1996).

After calculating H_{SR}, the sensible heat flux density αH_{SR} is computed using Eq. (3) and the α factor calibrated for that vegetation or crop type. For practical purposes, α changes little with stability, wind speed, or other weather factors. *LE* is determined using measured or estimated R_n and G and αH_{SR} in the energy balance equation:

$$LE = R_n - G - \alpha H_{SR} \tag{4}$$

The *LE* calculations are done on a half-hourly basis, and the daily energy fluxes due to R_n, G and *LE* are computed. The daily F_d is computed (Eq. 2) as an index for fuel dryness.

4. METHODS

Two experiments were conducted to test the use of the SR method to measure the fuel dryness index (F_d) on grassland and Mediterranean maquis. The first experiment was conducted over rainfed grasslands near Ione, California (latitude: 38° N; longitude: 120° W; elevation: 129 m) from February 9 – October 2, 2002. During the experiment, the canopy averaged 0.25 m in height. The grassland is actively growing between November and May and it is dry and warm from mid-spring through early-fall. For other detail site information, readers are referred to Xu and Baldocchi (2004) and Baldocchi et al. (2004).

A second experiment was conducted over Mediterranean vegetation near Alghero, Italy (latitude: 38° N; longitude: 8° E; elevation: 50 m) from July 30 – October 17, 2003 and from April 6 – June 9, 2004. The experimental site is mainly covered with vegetation of a maximum height of 2.0 m including sclerophyll species and some scattered shrubs. The climate is semi-arid with a remarkable water deficit from May through September. Even winter season can be dry and temperature not so low to determine vegetation dormancy.

A CR10X data-logger was set up to measure high-frequency temperature with fine-wire thermocouples for estimating H using the SR method. Two 76.2 μm diameter thermocouples were mounted at 1.0 m height in the California experiment and at 3.0 m in Italy. The sampling frequency was f=4 Hz and time lags r=0.25 and r=0.50 s were used with the structure function to estimate ramp characteristics. The current reading and two previous temperature readings (e.g., 0.25 and 0.50 s earlier) were stored in the data logger. For the time lags, temperature differences were calculated and the 2nd, 3rd and 5th moments of each temperature difference were computed. At the end of a half hour, the means of the three moments were stored in the output table for each of two time lags for both thermocouples. The average H_{SR} value for the two thermocouples and two time lags was used in the analysis. Three-dimensional sonic anemometers (Model 1352, Gill Instruments Ltd, Lymington, UK in California and Model CSAT3 sonic anemometer, Campbell Scientific, Logan, Utah in Italy) were installed at a height of 2 m over grass and at 3.5 m over Mediterranen bushes. Virtual temperature and three wind components were recorded at 10 Hz. In both experiments, infrared gas analyzers (Li-7500, Licor Inc, Lincoln, Nebraska, USA) were used to collect high frequency humidity data. H and LE flux density was calculated using the eddy covariance method accounting for the WPL correction (Webb et al., 1980). In addition, net radiation (R_n) and soil heat flux density (G) were measured with net radiometers (model NR Lite, Kipp and Zonen, Delft, The Netherlands in California and Model MR40, Eko Instruments, Tokyo, Japan in Italy) and soil heat flux plates (model HFP-01, Hukseflux Thermal Sensors, Delft, The Netherlands). Soil temperature was measured with thermocouples above the heat flux plates to correct G for heat storage above the plates. Rainfall was recorded with a tipping bucket rain gauge in both sites.

5. RESULTS AND DISCUSSION

Using all of the half-hour data, regressions of H+LE versus R_n–G from the eddy covariance system are reported in Figure 1 and 2. Statistically acceptable values for energy balance closure were observed (Baldocchi, 2003).

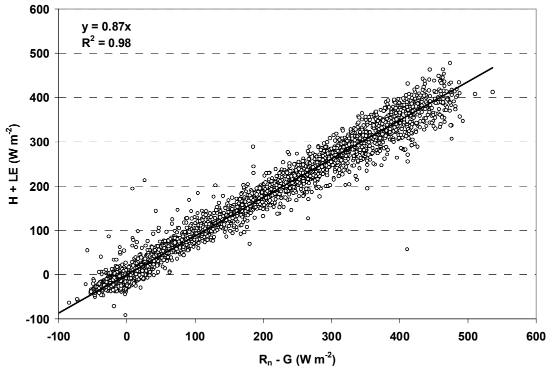

Figure 1. Energy balance closure measured over grassland in Iona, California during the 2002 experiment

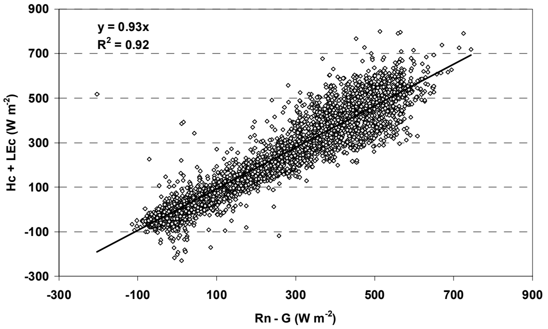

Figure 2. Energy balance closure measured over Mediterranean maquis in Alghero, Italy during the 2003-2004 experiment.

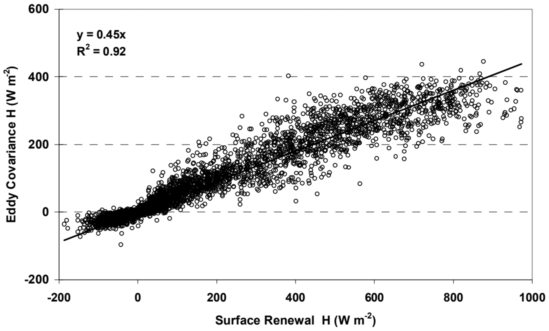

Figure 3. Regression of H from the Eddy Covariance system versus H from Surface Renewal measured over grassland in Iona, California during the 2002 experiment.

Using the high frequency temperature data from thermocouples the α factors were 0.46 in California and 0.63 in Italy with R^2 values of 0.82 and 0.83, respectively (Figures 3 and 4). Regression of H from the sonic anemometer versus αH_{SR} from the thermocouple data and SR analysis with α = 0.46, yields a slope b = 1 and an R^2 = 0.92 (Figure 5) for the experiment in California. A plot of H versus αH_{SR} from the Alghero experiment gave a slope b = 1 and an R^2 = 0.83 (Figure 6). This demonstrates that using a low-cost thermocouple and SR analysis can provide accurate H estimates. The results here confirm earlier analyses, with the α differing greatly from unity when compared to the sonic temperature-based analysis, and match previous reports on the sensitivity of surface renewal to temperature sensor size (Duce et al., 1998) and to measurement height (Spano et al., 1997b). Root mean square errors between H and αH_{SR} were 41.8 W m^{-2} for 2002 and 66.6 W m^{-2} for 2003-2004.

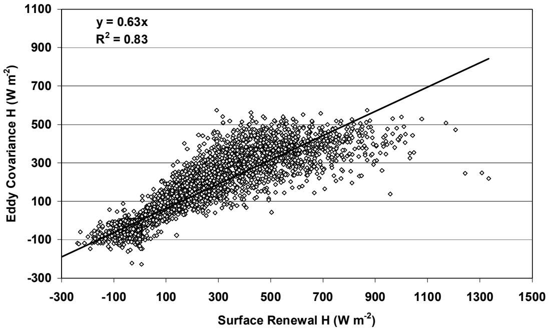

Figure 4. Regression of H from the Eddy Covariance system versus H from Surface Renewal measured over Mediterranean maquis near Alghero, Italy during the 2003-2004 experiment.

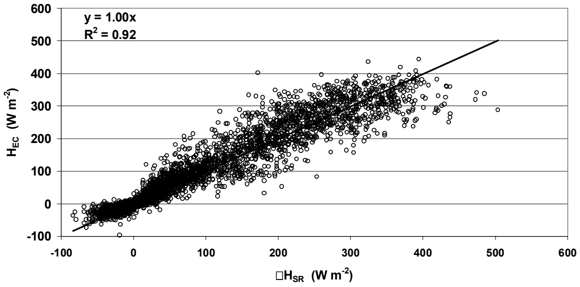

Figure 5. Sonic anemometer H versus αH_{SR} from thermocouple data measured at 1.0 m above the ground and SR analysis with α = 0.46 during the 2002 experiment in California.

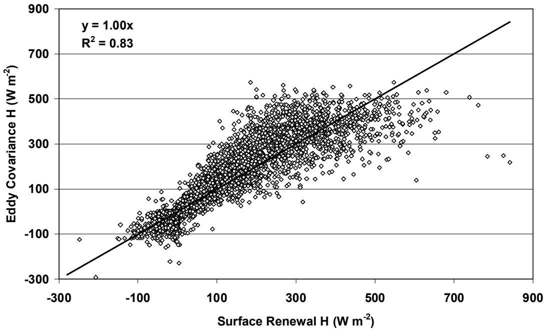

Figure 6. Sonic anemometer H versus αH_{SR} from thermocouple data measured at 3.0 m above the ground and SR analysis with α = 0.63 during the 2003-2004 experiment in Italy.

Figure 7 shows the daily energy flux density values from February 9–October 2, 2002, where H was estimated using the SR method and LE was calculated as the residual of the energy balance equation. Most of $R_n - G$ was contributing to LE from February until early May. Then there was a sharp increase in H and decrease in LE as the soil dried and grass became water deficient. From mid-June the LE rates were low with less than 2.0 MJ m^{-2}d^{-1} most of the time.

In Alghero site from the end of July through August 2003, the LE rates varied from less than 2.0 MJ m^{-2}d^{-1} to 6.0 MJ m^{-2}d^{-1} in relation to weather conditions. Similar results were obtained for the 2004 measurements.

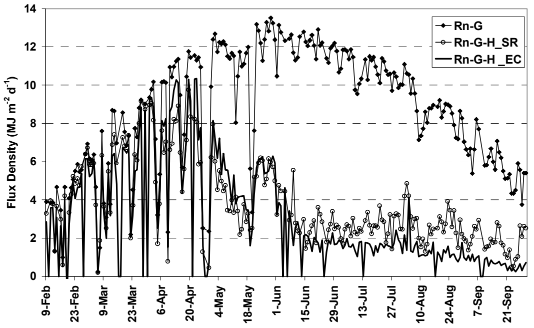

Figure 7. Available energy (R_n - G) and $LE = R - G - H$ using the EC and SR methods during the experiment in California.

F_d depends on the ratio of LE to $R_n - G$ (Eq. 3), so accuracy of the LE measurements is important to attain accurate F_d values. Daily values of LE estimated from the energy balance (Eq. 4) using H from the sonic anemometer (EC) and αH_{SR} using the thermocouple data and SR analysis (SR) match well (Figures 7 and 8).

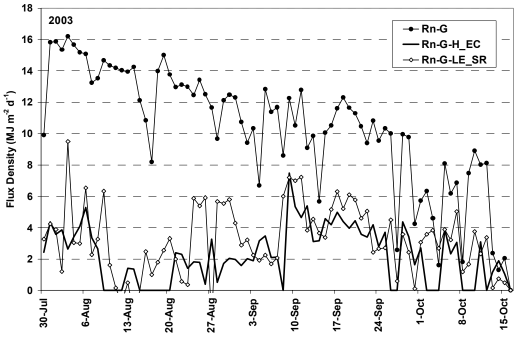

Figure 8. Available energy (R_n - G) and $LE = R - G - H$ using the EC and SR methods during the 2003 experiment in Italy.

The time trace of F_d index calculated with Eq. 2 shows a strong relationship to precipitation (Figures 9-11). In California, F_d generally ranges between 0 and 0.2

early in the year, linked to frequent precipitation and the wetness of surface. As the precipitation amounts and frequencies decrease in late March, F_d increases to between 0.3 and 0.7 (Fig. 9). After a decrease because of a rainy period and the resultant surface wetting in May, F_d increases to approximately 0.8 (by June) during the seasonal drought.

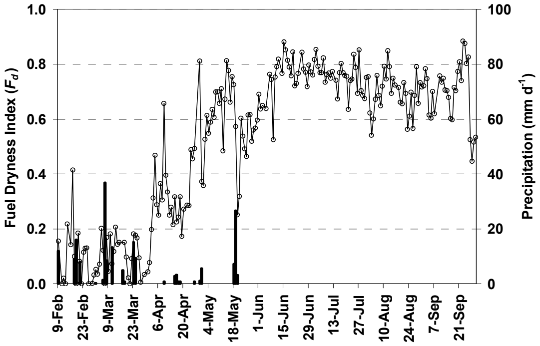

Figure 9. Plots of daily fire risk index (F_d) and precipitation from February 9 – October 2, 2002 over grassland near Ione, California.

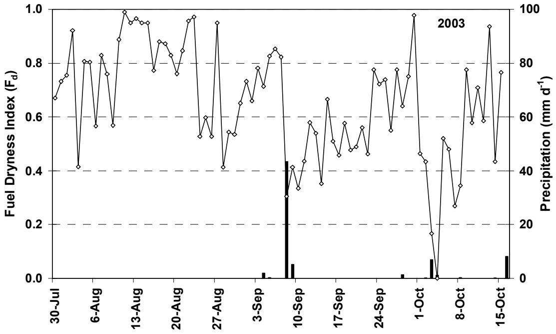

Figure 10. Plots of daily fire risk index (F_d) and precipitation from July 30 – October 17, 2003 over maquis near Alghero, Italy.

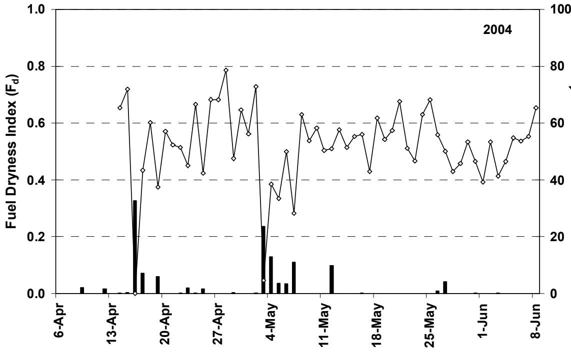

Figure 11. Plots of daily fire risk index (F_d) and precipitation from April 6 – June 9, 2004 over maquis near Alghero, Italy.

During the experiment in Italy, the fire risk index increased or decreased with rainfall events (Fig. 10). However, from mid-May 2004 the F_d seemed more stable ranging between 0.4 and 0.7 (Figure 11).

6. CONCLUSIONS

Based on the results, it is possible to conclude that estimating H, using thermocouples and the SR method in combination with R_n and G data, provides a low-cost method to calculate LE and F_d as an indicator of surface fuel and weighted plant and soil dryness. If telecommunication is used to transmit data from a remote site, in combination with the SR analysis, this method can potentially improve site specific information on fire fuel dryness without the need for travel and labor to visit remote sites for stick tests.

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