P1.18 ASSESSMENT OF FUEL DRYNESS INDEX ON MEDITERRANEAN VEGETATION

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1. INTRODUCTION

Various approaches and models have been developed to determine moisture content for all fuel levels since the amount of moisture in fuel determines how much of the fuel will burn. All well-known integrated rating systems such as the Canadian Forest Fire Weather Index (*FWI*), the McArthur Fire Danger Index (*FDI*), the remote sensing based Fire Potential Index (*FPI*), and the U.S. National Fire Danger Rating System (*NFDRS*) include sub-models for estimating fine fuel availability and fine fuel moisture. The most commonly used sub-models are the Keetch-Byram Drought Index (*KBDI*) from Keetch and Byram (1968) and the time lag fuel moisture classes of the *NFDRS*, the fine fuel moisture, duff and drought codes of the Canadian *FWI*, and the drought factor and the fuel moisture sub-model of the *FDI*.

Live fuel above ground (aerial) 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 and remotely sensed observations provide data useful for parameterizing the quantity of moisture content in live vegetation to prepare greenness maps (Burgan, 1988; Burgan et al., 1998).

Different methods can be used to predict moisture content of the surface dead fuel. In the *NFDRS*, dead fuel moisture response is separated into four time lag classes (Deeming et al., 1977). 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 (Deeming et al., 1977). In *FWI* (Van Wagner, 1987), three separate indices for three distinct dead fuel classes are included. The moisture content of litter and other fine fuels, with a time lag less than one day, is estimated using the Fine Fuel Moisture Code (*FFMC*).

A numerical rating of average moisture content of ground fuel level is often used as 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. For example, the *FWI* System includes specific Duff Moisture (*DMC*) and Drought Codes (*DC*) as described by Van Wagner (1987).

A relatively low cost method to monitor grasslands and obtain a fuel dryness index (*Fd*) was recently presented (Snyder et al., 2003; Snyder et al., 2005). Fd gives information on both the daily variation and the seasonal trend of fuel moisture content. The comparison of the *Fd* values and trends with three well-known slow response fire danger indices showed that *Fd* can provide accurate information on fuel dryness condition of a live vegetation grassland being more responsive to daily changes than most of the other indices. An advantage from using this method is that the dryness index integrates contributions of all combustion materials, so calibration for different surfaces seems unnecessary. In addition, the method is based on biophysical principles associated with energy exchange rather than empirical functions of weather variables.

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In this paper the *Fd* index was used to investigate the potential for characterization of fuel dryness in Mediterranean shrublands where the canopy volume is larger than in grassland and the fuel includes living vegetation and dead material.

2. MATERIALS AND METHODS

An experiment was conducted over Mediterranean vegetation near Alghero, Italy (latitude: 38º N; longitude: 8º E; elevation: 50 m) from April 2004 through July 2005. 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.

The amount of fuel moisture was estimated using the fuel dryness index. *Fd* is based on the surface energy balance, where available energy (*Rn* - *G*) is partitioned into sensible and latent heat exchanges (*H* + *LE*). When soil water is not limiting, then *H* is typically small relative to *LE* and (*Rn* - *G*) is a measure of the potential or maximum possible *LE*. When the surface is dry and soil water is limited, evaporation from the surface is reduced, *LE* decreases relative to (*Rn* - *G*) and *H* increases. Therefore, the fuel dryness index can be calculated as:

$$F_d = 1 - \frac{LE}{R_n - G} = \frac{H}{R_n - G} \quad (1)$$

Fd approaches 0 when fire potential is low, because of high values of ecosystem moisture, and it approaches 1 as the moisture is low and the chances of wildfire increase. When both the surface litter and the plants show little evapotranspiration, this implies local drought conditions are severe and the fire danger is high.

Micrometeorological methods for estimating *H* and *LE* in conjunction with *Rn* and *G* measurements were used to provide accurate values of *Fd*.

A three-dimensional sonic anemometer (Model CSAT3 sonic anemometer, Campbell Scientific, Logan, Utah) was installed at a height of 3.5 m over Mediterranean vegetation. Sonic temperature and three wind components were recorded at 10 Hz. An infrared gas analyzers (Li-7500, Licor Inc, Lincoln, Nebraska, USA) was 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 (*Rn*) and soil heat flux density (*G*) were measured with net radiometers (Model MR40, Eko Instruments, Tokyo, Japan) 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 and volumetric soil water content was measured at 0.2 depth using time-domain reflectometry probes (Model CS616-L, Campbell Scientific, Logan, Utah).

Sonic anemometer data were also used to compute *H* using the Surface Renewal (*SR*) method (Paw U and Brunet, 1991). The *SR* method is based on the concept of coherent structures, which are characterized by air sweeps and ejections to and from the surface (Gao et al., 1989). When in or near the canopy, air parcels heat or cool as sensible heat exchanges with canopy elements. The rate of temperature change over time is related to sensible heat flux density (Paw U et al., 1995). When plotted, temperature traces show ramp like characteristics, and the mean amplitude (*a*) and duration of ramp event (*d* + *s*), where *d* is the duration of the ramp period and *s* is the duration of the quiescent period between ramps, can be quantified using structure function analysis (Van Atta, 1977).

Paw U et al. (1995) showed that an expression for *H* can be derived from the conservation of energy:

$$H = \alpha H_{SR} = \alpha\left(\rho C_p \frac{a}{d+s} z\right) \qquad (2)$$

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 and other factors (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., 1997; Spano et al., 2000)

In *SR* analysis high frequency temperature data were used to compute half-hour means of the 2nd, 3rd, and 5th order moments of the time lag (r = 0.5, 1.0, 1.5 s) temperature differences, which constitute structure functions (Van Atta, 1977; Snyder et al., 1996). Then H_{SR} values were calculated using half-hour statistical structure function moments following the procedure in Snyder et al. (1996). After calculating H_{SR}, the sensible heat flux density αH_{SR} was computed using Eq. (2) and the α factor calibrated for the Mediterranean vegetation.

The *Fd* index was compared with three slow response fire danger indices including the *KBDI* (Keetch and Byram, 1968) drought index and two modified versions (Noble el al., 1980 and Griffiths, 1999) of the drought factor (*D*) in the McArthur (1966, 1967) forest fire danger meter, and the fast response *FFMC* of the Canadian *FWI*. The McArthur forest fire danger meter (*Mk5*), derived by Noble et al. (1980), was also compared with the *Fd* index.

In addition, a modified version of the *KBDI*, with the evapotranspiration estimate (*ET*) from the Hargreaves and Samani (1982) equation was computed and compared with the *Fd* calculations.

5. RESULTS AND DISCUSSION

In Figure 1 the energy balance closure from half-hour eddy covariance data is shown. Regression statistics of *H* + *LE* versus *Rn* – *G* were acceptable for energy balance closure (Baldocchi, 2003).

Table 1 shows the results of the regression of H_{SR} calculated from sonic anemometer temperature versus *H* from eddy covariance by time lag. The α factor values ranged from 0.50 (r = 0.5 s) to 0.56 (r = 1.5 s) with R^2 values greater than 0.91 for the three time lags. The linear regression through the origin of *H* versus αH_{SR} gave a slope b = 1 and root mean square errors equal to 44 W m^{-2} for r = 0.5 s, 47 W m^{-2} for r = 1.0 and 48 W m^{-2} for r = 1.5 s. This demonstrates that *SR* analysis can provide accurate *H* estimates.

Fd depends on the ratio of *H* to *Rn* – *G*, so accuracy of the *H* measurements is important to attain accurate *Fd* values. Daily values of *H* from the sonic anemometer (H_{EC}) and αH_{SR} using *SR* analysis match well as shown in Figure 2 for the 2004 period.

The time trace of *Fd* index shows a strong response to precipitation and volumetric soil water content (Figure 3). *Fd* generally ranges between 0.2 and 0.6 in spring, linked to frequent precipitation and a wet surface. As precipitation amounts and frequencies decrease from late June to mid-September, *Fd* increased from about 0.6 to 1.0. Rainfall caused a drop of *Fd* from the end of September. Similar trend was observed during the 2005 (Figure 3).

Figure 4 shows the trend in *Fd*, *KBDI* (Keetch and Byram, 1968), *KBDI* using the Hargreaves and Samani (1982) *ET* equation (*HS KBDI*) during 2004. As expected, daily weather conditions and rainfall events had little impact on the *KBDI* index. In addition, the highest *KBDI* values (about 150) were reached at the end of September maintaining the index below the maximum potential value (203.5). The *KBDI* equation includes an exponential function of the mean annual rainfall in the denominator to adjust *ET* estimates for rainfall effects: higher annual rainfall total leads to higher *ET* rates. Since mean annual rainfall is low in this area compared with the annual values typical of the regions where the *KBDI* was calibrated, *ET* from the *KBDI* seems to be underestimated during most of the year. When the Hargreaves and Samani (1982) equation for evapotranspiration estimate (*ET*) was used in the Keetch and Byram (1968) *KBDI* calculations, the seasonal trend changed dramatically and values greater than 150 were observed from early July (Figure 4). Since *KBDI* was proposed as an estimate of long term drought effect on fuel availability, the seasonal trend obtained using *ET* from the Hargreaves-Samani equation seems consistent with the actual seasonal changes in fuel availability and fire danger.

The *Fd* trends were also compared with the drought factor (*D*) of the McArthur fire-danger meters (*FDI*) as reported by Noble et al. (1980) and Griffiths (1999). These two models showed a faster response to rainfall events than the *KBDI* (Figure 5). Both indices had values above 5 during the winter rainy period, when fire danger was essentially non-existent and both were at the maximum value of 10 during most of the summer. While the two models indices dipped in response to rainfall, the magnitude and duration of the drops were unrelated to the surface conditions that were quantified by the *Fd* calculations. Except for reduced fire danger during rainy periods, neither of the equations provided information on daily variations in fuel dryness.

The *FFMC* seasonal trend was computed and plotted (Figure 6). The *FFMC* did not seem to give a reasonable estimate of fire danger for Mediterranean shrublands. The *FFMC* indicated a high fire danger during most of the year with short-term drops only occurring during rainy periods. While the *FFMC* performs well in Canadian forests, it clearly is not designed for the conditions of a Mediterranean shrubland.

The final comparison was made between the *Fd* index and the forest *Mk5* fire danger index (Figure 7). The *Mk5* index showed more fluctuations in general than the *Fd* index, partly due to the inclusion of wind speed in the model as an indicator of fire spread. Wind speed is not included in the *Fd* model, which is meant to index fuel dryness rather than fire spread.

6. CONCLUSIONS

Based on the results, the *SR* method in combination with *Rn* and *G* data, provides an accurate method to calculate *Fd* (Eq. 1) as an indicator of fuel dryness.

The *Fd* index was more responsive to daily meteorological and biological changes than the *KBDI*, McArthur's fire danger meters, and the Canadian *FFMC* index. It was also noted that the potential *ET* estimation method in the *KBDI* calculation could be improved by using a newer *ET* equation. This could improve the indices of Noble et al. (1980) and Griffiths (1999) as well because they use the *KBDI* in their equations.

The *Fd* index was shown to provide useful information on fuel dryness conditions of a Mediterranean shrubland.

The *Fd* index quantifies fuel dryness and it could be used with remotely sensed data on fuel availability to improve fire danger models. The *Fd* index could be modified to be incorporated into the *NFDRS* supported *KBDI* which is used partially to assess soil and ecosystem dryness.

In addition, H_{SR} estimates can be used to assist in boundary layer stability assessments, which are used in fire weather analysis as outlined in Brotak and Reifsnyder (1977), Haines (1988), Reifsnyder and Albers (1994), and Potter (1996), when local atmospheric soundings are unavailable.

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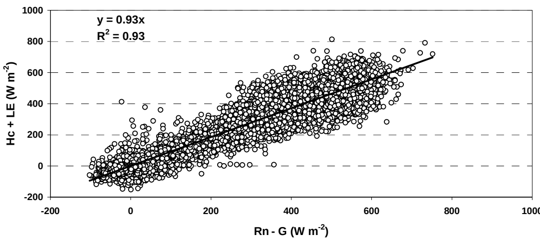

Figure 1. Energy balance closure measured over Mediterranean vegetation in Alghero, Italy during the 2004-2005 experiment.

Table 1. Weighting factor α, coefficient of determination R^2 and number of half-hour samples (N) for *H* from eddy covariance versus *H* from surface renewal over Mediterranean vegetation. Regressions were forced through the origin. H_{SR} was calculated using three different time lags (*r*).

	r = 0.5 s	r = 1.0 s	r = 1.5 s
α	0.50	0.53	0.56
R^2	0.92	0.92	0.91
N	15827	15482	14497

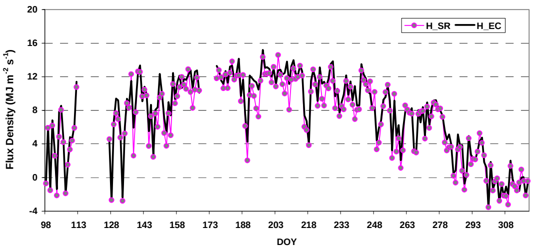

Figure 2. Sensible heat from the sonic anemometer (*H_EC*) and from surface renewal (*H_SR*) method plotted versus day of the year (DOY) using data from 2004.

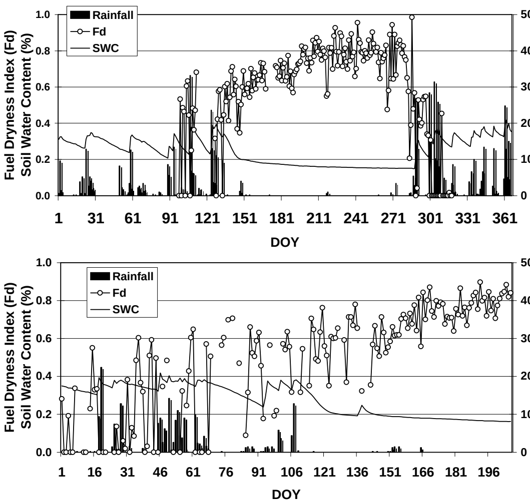

Figure 3. Plots of daily fuel dryness index (*Fd*) from *SR* analysis, rainfall and volumetric soil water content (SWC) during 2004 (above) and 2005 (below).

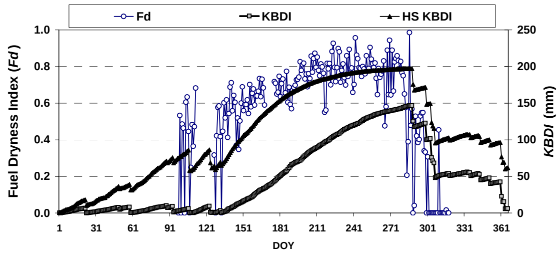

Figure 4. Plots of daily fuel dryness index (F_d) from *SR* analysis, *KBDI* index (*KBDI*) from Keetch and Byram (1968), *KBDI* index computed using the Hargreaves-Samani (1982) *ET* equation (*HS KBDI*) during 2004.

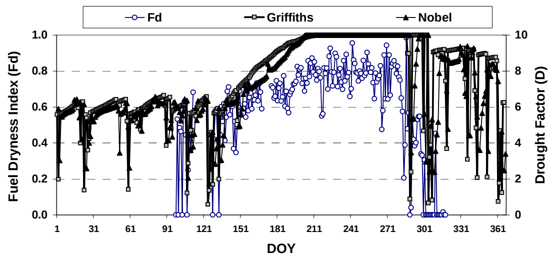

Figure 5. Plots of the fuel dryness index (*Fd*) and the drought factor of the McArthur's fire-danger meters as reported by Noble et al. (1980) and Griffiths (1999) (*DN* and *DG*, respectively) from data collected during 2004.

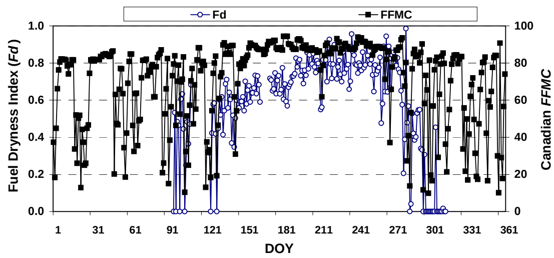

Figure 6. Plots of the fuel dryness index (*Fd*) and the fine fuel moisture code (*FFMC*) of the Canadian Forest Fire Weather Index from data collected during 2004.

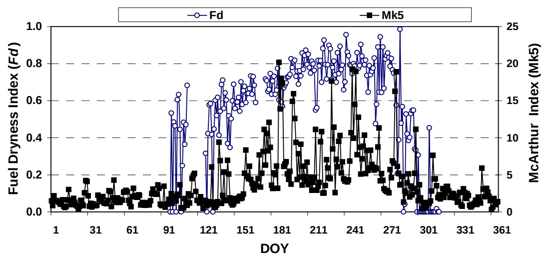

Figure 7. The fuel dryness index (*Fd*) and McArthur's forest Mk5 fire-danger index plotted versus time from data collected during 2004.