DEVELOPMENT AND APPLICATION OF A STAND LEVEL FUEL MOISTURE INDEX BASED ON MEASUREMENTS OF FOREST ENERGY BALANCE

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1. INTRODUCTION

Drought stress indices are a key component of most fire risk and fire danger rating systems, and have broader applications in the modeling of forest and agricultural productivity. Because direct measurements of fuel moisture contents are time consuming and costly to implement on a regular basis, there is a need to model the water status of forest ecosystems on an operational basis. The Keetch-Byram Drought Index (KBDI) is frequently used to estimate the moisture content of the litter layer and upper soil layers, and is based on a running balance of available moisture that can be used by vegetation for evapotranspiration. Daily precipitation and maximum temperature are used to estimate daily changes to the index value using "lookup tables", and high values of the KBDI (maximum of 800) indicate conditions that are favorable for the occurrence and spread of wildfires. The KBDI and other indices such as the Buildup Index generally work well in characterizing fuel moisture content in many forests under many conditions. Drawbacks of KBDI are that long runs of continuous meteorological data are necessary, dating back to the time when the litter, humus and soil were saturated (an "initial conditions" problem). Look up tables calculate daily (24-hour) changes in moisture content well, but fuel moisture can change dramatically during dry, windy conditions, even when the daily maximum air temperature is low. Perhaps the greatest drawback of the KBDI and other indices is that they only approximate the moisture content of live fuels during the growing season, although live foliage becomes a major component of available fuels during drought conditions.

Recent advances in micrometeorological sensors allow accurate and relatively inexpensive measurements of forest energy balance above the forest canopy. To date, these systems have been used extensively to estimate carbon exchange and evapotranspiration from forest ecosystems (e.g., Clark et al. 2004, Gholz and Clark 2002), but these measurements also provide the basis for a fuel moisture index based on absorbed solar radiation and sensible heat flux. Depending upon the height of the sensor and meteorological conditions, the area sampled using these sensors are ca.1-5 km^2 in size, an appropriate scale for fire managers. Using a network of towers and sensors allows landscape level estimates. In this research, we developed and evaluated a stand-level fuel moisture index using a forest energy balance approach in the Pinelands of New Jersey.

2. MATERIALS and METHODS

The energy balance of a forest can be expressed as:

$$R_{net} - G = H + LE + \Delta S + P \qquad (1)$$

Where, R_{net} is net radiation, G is heat energy flux into the soil, H is sensible heat flux into the surrounding atmosphere, LE is the energy used to drive evapotranspiration, ΔS is the change in energy storage, and P is the energy consumed by photosynthesis. $R_{net} - G$ defines the amount of radiation absorbed by the forest, R_{abs}. A growing-season fuel moisture index (and more generally a drought stress index) can be derived formally using a simplified energy balance equation:

$$R_{abs} = H + LE \qquad (2)$$

When soil water is not limiting, much of the absorbed radiation is consumed by LE. However, when soil water is limiting, live fuel moisture contents are low and the canopy is relatively "hot" for a given amount of radiation absorbed. H accounts for a larger portion of $R_{net} - G$, thus a fuel moisture index, FMI, can be calculated as:

$$FMI = H / R_{abs} \qquad (3)$$

Research sites are located at Silas Little Experimental Forest in Brendan Byrne State Forest, Fort Dix, and Greenwood WMA in the northern Pine Barrens of New Jersey (74º 35'30" W. 39º 35'00"N). Soils are derived from the Kirkwood and Cohansey Formations (Sassafras and Lakewood soils), and are sandy, well-drained, acidic, and very low in organic matter and available nutrients. Upland forests are dominated by pitch pine (*Pinus rigida*), shortleaf pine (*P. echinata*), and a number of oak species (*Quercus* spp.). The understory consists of huckleberry (*Gaylussacia bacata*), blueberries (*Vaccinium spp.*), scrub oaks (*Q. ilicifolia, Q. marlandica*), sedges, mosses and lichens.

Energy balance measurements were made from antenna-type towers at all sites, following Ameriflux protocols (http://public.ornl.gov/ameriflux). Turbulence and "speed of sound" were measured at 10 Hz using sonic anemometers mounted ca. 4 m above the forest canopy on each tower. "Speed of sound" was used to calculate sensible heat fluxes at half-hourly intervals. Net radiation and soil heat flux measurements were then used to calculate values of FM in equation (3). Energy balance closure was calculated for a subset of measurement periods by summing H, LE and heat storage components, and then comparing these to R_{abs} (e.g., Gholz and Clark 2002, Wilson et al. 2002). We evaluated this approach using fuel moisture sticks, gravimetric measurements of fuels by size class, soil moisture, and calculated KBDI values for the same time period.

3. RESULTS

Sensible heat fluxes were a linear function of R_{abs} throughout the year at the Silas Little Experimental Forest in 2004. The slope of the relationship between H and R_{abs} increased with the onset of drought stress in early July. H then became a much smaller proportion of R_{abs} later in the summer following the onset of frequent convective precipitation starting in mid-July (Fig. 1a). Closer inspection of the period between July 1-12th indicates that mean daily (10:00-17:00) FMI values increased in the first week of July, but then were reduced following a precipitation even early July 5th (12 mm; Fig. 1c). Following that event, values increased to ca. 0.6, again indicating that 60% of the absorbed radiation was reradiated as sensible heat (Figs. 1a,b). In Figure 2, mean daily values of the ratio of H to R_{abs} are compared to 10-fuel moisture sticks (Fig. 2a) and the KBDI (Fig. 2b) over the same period. In Figure 2b, the KBDI increased slowly, and did not reflect the observed variation in the fuel moisture index or 10-hr fuel moisture sticks. Comparison of our fuel moisture index to 10-hour fuel moisture sticks and manual measurements of fuel moisture content showed a high level of correspondence, while the KBDI was not as responsive

4. DISCUSSION

The example here illustrates how a useful, stand-level fuel moisture index can be derived from measurements of forest energy balance. The utility of this approach is that it is a dynamic measure of fuel moisture content, and can be calculated at half-hourly to hourly intervals. Thus, it can be used to investigate rapid changes in fuel moisture content at the stand level, which is virtually impossible on an operational basis using manual measurements. It is also difficult to use drought indices such as the KBDI or similar drought indices in the context of rapid changes in fuel moisture content, because they typically update only once every 24 hours. In addition, the KBDI and other drought indices are not transportable, because they require accurate meteorological data from the previous weeks to months. Further, the fuel moisture index developed here likely reflects the true value of live fuel moisture contents more accurately than KBDI or other fuel moisture indices.

Once completely validated, the instrumentation to make these measurements can be installed on selected fire and cellular phone towers throughout the Atlantic Coastal Plain. Data collection and

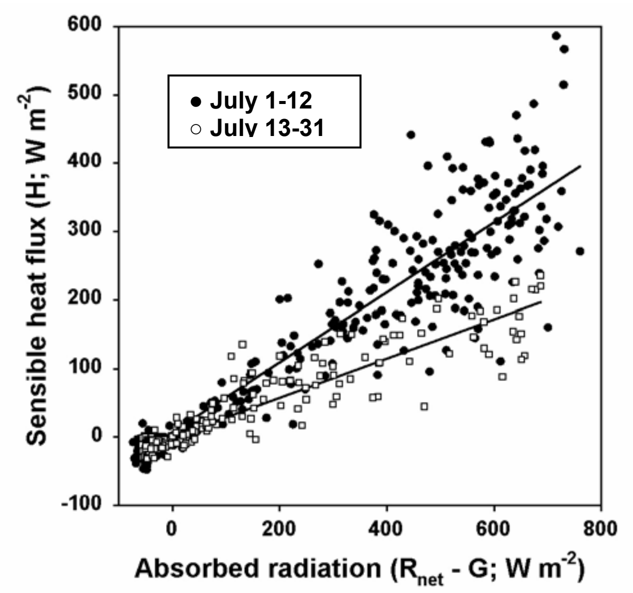
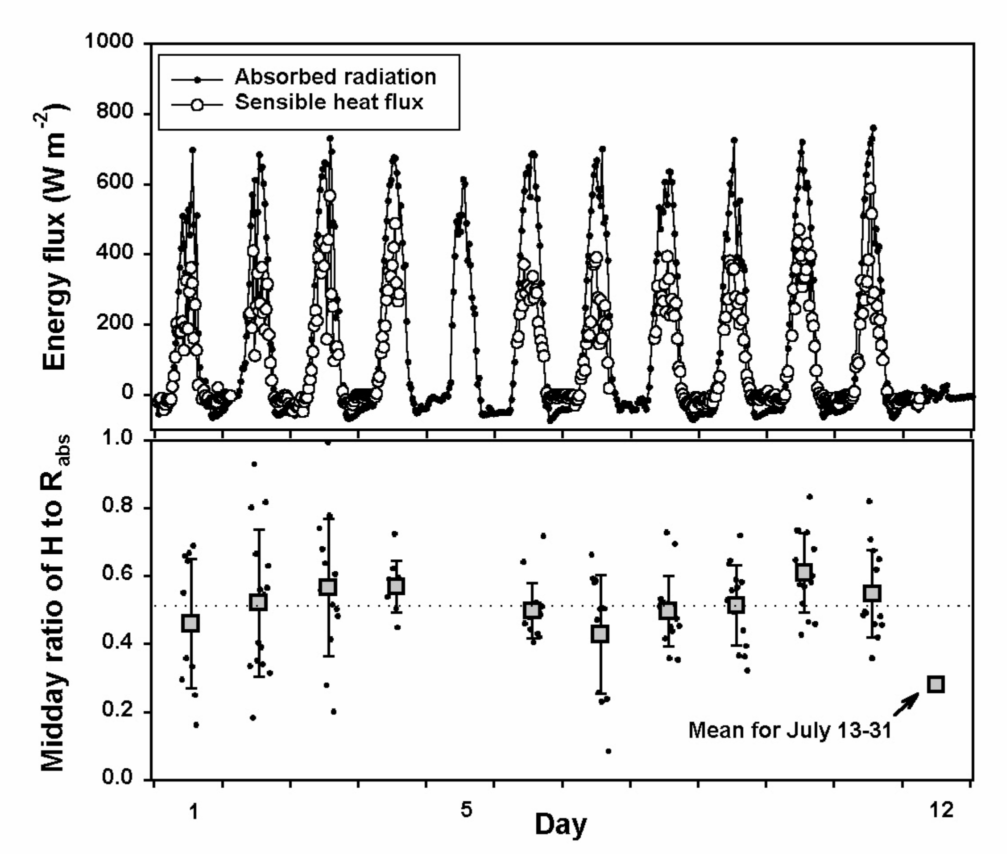


Fig. 1a. Absorbed radiation (R_{net} – G; W m^{-2}) and sensible heat flux (H; W m^{-2}) measured above the canopy of an Oak Pine forest at Silas Little Experimental Forest, New Jersey, from July 1 – 31, 2004.

Fig. 1b. Absorbed radiation and sensible heat flux from July 1 – 13, 2004.

Fig. 1c. Mean daytime (10:00 – 17:00) ratio of sensible heat flux to absorbed radiation from July 1- 13, 2004. Values are means ± 1 SD, and the dotted line is 0.5.



retrieval can be automated, and transferred to fire managers via wireless technology.

Many locations on the Atlantic Coastal Plain are suitable for accurate forest energy balance measurements, due to their generally flat topography and large fetch. A number of sites are already making these measurements on a continuous basis*, and we have found that the values of the relationship between absorbed radiation and sensible heat flux converge during high fire danger for sites of very different species composition, stand age, and management histories. This suggests that a general relationship characterizes fuel moisture content and sensible

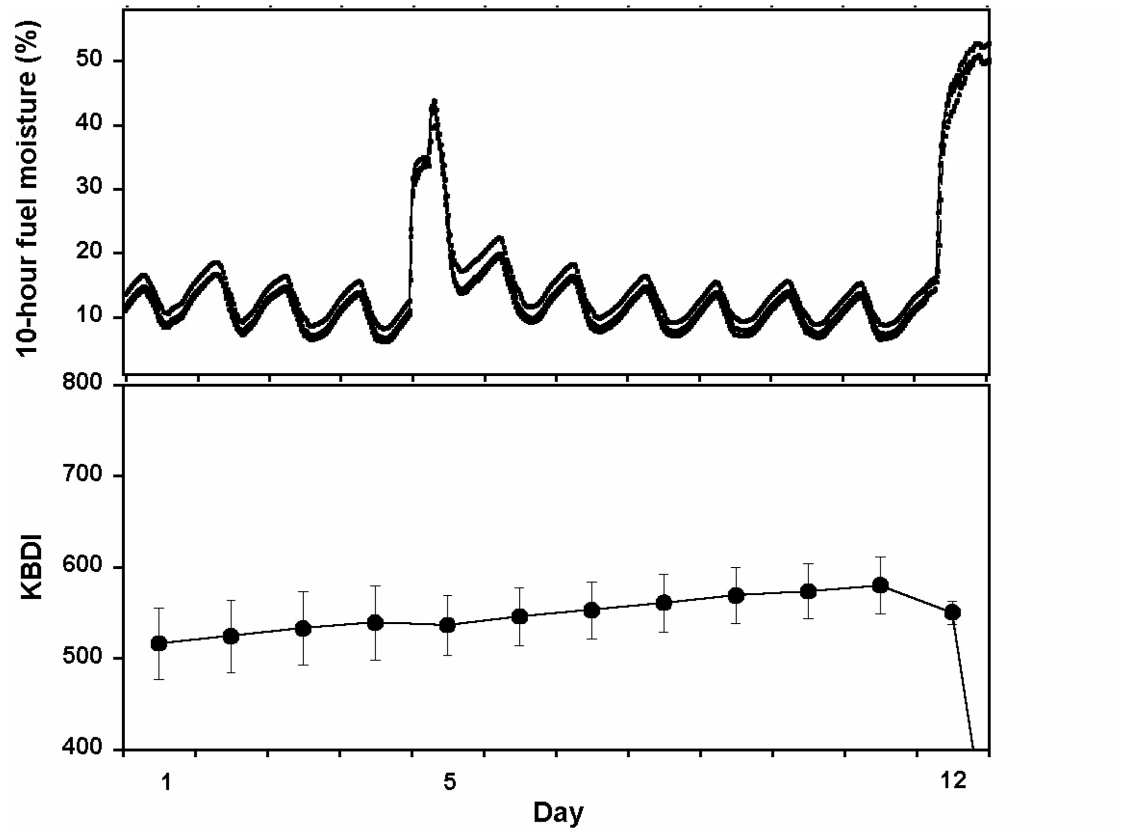


Fig. 2a. Ten-hour fuel moisture (%) measured at the Silas Little Experimental Forest during July 1-12, 2004. Fig. 2b. Keech-Byram Drought Index (KBDI) calculated from meteorological data collected during the same time period.

heat fluxes of forests, indicating that these measurements also may be transportable across a wide range of forest types.

* The Ameriflux network consists of 90+ tower sites from Costa Rica to Canada making high quality weather and carbon flux measurements since 1996 (http://public.ornl.gov/ameriflux/).

5. REFERENCES

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6. Biography

Dr. Kenneth L. Clark is a Research Forester with the USDA Forest Service-Northern Global Change Program at the Silas Little Experimental Forest, New Lisbon, New Jersey. He has a Ph.D. in forest ecology from the University of Florida. His current research interests include fire weather indices and the National Fire Danger Rating System, fuel mapping using remote sensing, the effects of wildfires and fire management on the carbon dynamics of forest ecosystems, and the effects of burrowing animals on ecosystem processes.