Linking Fuel Inventories With Atmospheric Data for Assessment of Fire Danger

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Abstract.—Combining forest fuel maps and real-time atmospheric data may enable creation of more dynamic and comprehensive fire danger assessments. The goal of this study was to combine fuel maps, based on data from the Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture Forest Service, with real-time atmospheric data to create a more dynamic index of fire danger. Fuel loadings were estimated for points on a meteorological modeling grid network (4 x 4 km) based on FIA's strategic-scale fuel inventory. In addition, fuel moisture at each grid point was predicted based on atmospheric observations over an 11-day period. A Burnable Fuels Index (BFI), combining both fuel loadings and moisture predictions, was investigated for changes in fire danger over the modeled period of time. The BFI was temporally and spatially variable due to heterogeneous forest fuel conditions and dynamic weather events. Overall, combining fuel-loading estimates with atmospheric data enables the current assessment and 1 to 2-day prediction of fire danger and greater understanding of fire danger across forest ecosystems with varying fuel loadings and weather conditions.

Fire Danger Assessment

Fire danger is defined in terms of factors affecting fire inception, spread, resistance to control, and subsequent damage (NWCG 1996). Fire danger is usually expressed as an index based on component variables and quantified using fire danger rating or prediction systems such as the U.S. National Fire Danger Rating System (NFDRS) (Deeming *et al.* 1977) and the Canadian Forest Fire Danger Rating System (Stocks *et al.* 1989). Fire behavior models employ fuel loading and fuel moisture information to predict fire behavior, which, in turn, contributes to the development of fire danger rating systems (Andrews 1986, Finney 1998). Fuel loadings are often static for time scales of hours and days, while fuel moisture is variable across time scales of an hour or less. Fuel loadings and fuel moisture are both spatially variable at small scales (e.g., stand level), but fuel moisture is difficult to measure accurately because of high variability over short time scales. As a result, spatially averaged fuel moisture observations are generally used in fire danger assessments over large areas. To better mesh the collection and integration of fuel loadings and moisture in fire behavior prediction models, NFDRS classifies fuel loadings by fuel-hour classes (Deeming *et al.* 1977). For example, a 1-hr fuel is downed woody material with moisture fluctuations at the time scale of hours and is characterized by diameters of less than 0.25 inches. Fuel hour classes with moisture fluctuations at greater time scales are larger in size. For the fire danger of any forest area to be determined, estimates of its fuel loadings and moisture need to be assessed in real time and incorporated into a fire danger index. Despite extensive work over the past decades to quantify fire behavior and subsequent fire danger, inadequate data and technology has impeded real-time assessments of fire dangers. Modern fuel inventories and recent meteorological advances may provide opportunities to determine and provide 1- to 2-day predictions of fire danger.

Large-Scale Fuel Inventories

The Forest Inventory and Analysis program (FIA) of the U.S. Department of Agriculture (USDA) Forest Service conducts a three-phase inventory of forest attributes of the United States

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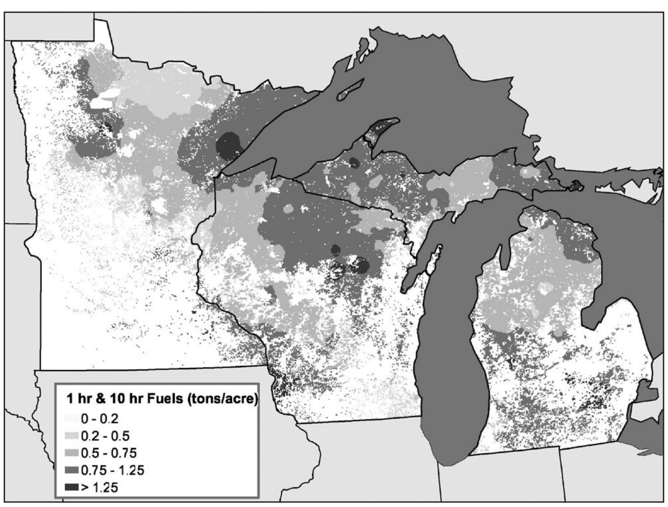
(Bechtold and Patterson 2005). The FIA sampling design is based on a tessellation of the United States into approximate 6,000-acre hexagons with at least one permanent plot established in each hexagon. In phase 1, the population of interest is stratified, and plots are assigned to strata for purposes of increasing the precision of estimates. In phase 2, tree and site attributes are measured for plots established in the 6,000-acre hexagons. In phase 3, a 1/16th subset of phase 2 plots is measured for forest health indicators such as down woody materials. Down woody components observed by the FIA program are coarse woody, fine woody, litter, herb/shrubs, slash, duff, and fuelbed depth. As defined by the FIA program, fine woody debris (FWD) are downed woody materials with transect diameters less than 3.00 inches. FWD are sampled on each FIA subplot along one transect. One- and 10-hr FWD (transect diameters between 0–0.25 and 0.26–1.0 inches, respectively) are sampled along a 6-ft transect, while 100-hr fine woody fuels (1.0–3.0 inches) are sampled along a 10-ft transect. For additional sampling design information, see Woodall and Williams (in press).

The FWD sampled by the FIA program match the fuel classification system (1-, 10-, and 100-hr) of the NFDRS, enabling creation of strategic-scale fuel maps that may be used to assess fire danger (Woodall *et al*. 2004). Because of the relatively sparse sample intensity of the FIA fuels inventory, inverse distance weighting interpolation techniques are often used to predict fuel loadings between sample plots. After fuel interpolation, nonforested areas are masked out of the fuel maps using classified imagery, such as the National Land Cover Data (Vogelmann *et al*. 2001), as used in this study (fig. 1). Numerous techniques are available for creating large-scale fuel maps ranging from relatively simple interpolation techniques of FIA fuels data, as used in this study, to more sophisticated efforts demonstrated by Rollins *et al.* (2004) and the USDA Forest Service's LANDFIRE program (www.landfire.gov).

Figure 1.—*Regional map of fine wood fuels based on inverse distance weighting interpolation of 500 FIA fuel inventory plots and nonforest mask (classified NLCD 1992 imagery) in the upper Great Lakes region.*

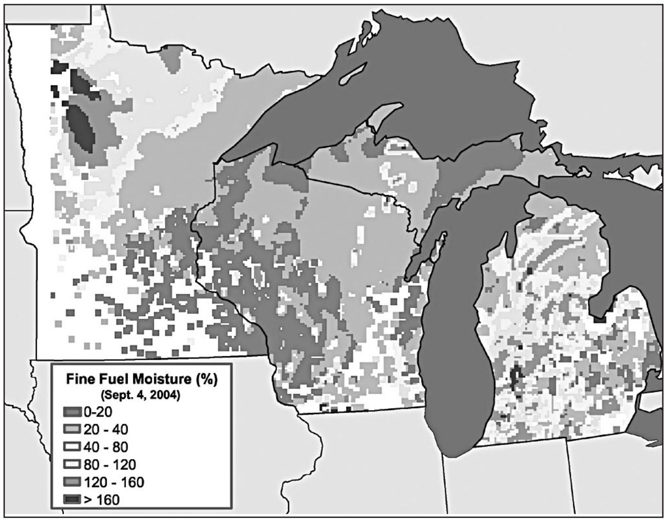


Fuel Moisture and Mesoscale Models

Estimates of surface fuels and real-time weather data are necessary to estimate fuel moisture conditions and fire danger. Numerical weather prediction models can produce daily simulations of atmospheric conditions such as temperature, winds, relative humidity, and rainfall for regions ranging in size from continents to counties. One such model, the Penn State University/National Center for Atmospheric Research Mesoscale Model called MM5, simulates the weather conditions for areas of about one-third the size of a continent down to State and county levels (Grell *et al.* 1994). The MM5 can be run daily, using observations collected and processed at the beginning of each day, to produce a sequence of 24-hr simulations of weather conditions across a region.

The Eastern Area Modeling Consortium (EAMC) is a multiagency coalition of researchers, fire managers, air quality managers, and natural resource managers conducting research and developing new products to improve fire-weather and smoke transport predictions in the north-central and Northeastern United States. The EAMC runs the MM5 daily for the north-central and Northeastern United States in support of fire-weather research and applications. One application of this atmospheric data uses the Canadian Fire Weather Index System (CFWI) (Van Wagner 1987) to calculate fuel moisture variations across the model geographic domains based on simulated temperature, relative humidity, and rainfall information. These calculations use the Fine Fuel Moisture Code in the CFWI to generate daily values for fuel moisture that roughly correspond to the expected

Figure 2.—*Fine woody (1- and 10-hr) fuel moisture map for study area, upper Great Lakes, September 4, 2004.*



variations in 1- and 10-hr fuels, as defined by the NFDRS. Fine-fuel moisture estimates from the EAMC's mesoscale models may be produced for any forest ecosystems on any given day (fig. 2).

Merging Fuels and Moisture Estimates

To create a more dynamic regional view of fire danger, we sought to combine maps of regional fuel loadings (interpolated FIA fuel map, fig. 1) and fuel moisture (EAMC mesoscale models, (fig. 2) for the upper Great Lakes. First, fuel loadings (1- and 10-hr FWD) were obtained from FIA's interpolated fuel maps for a 4 x 4-km grid (13,136 forested grid points) across the upper Great Lakes used by the EAMC's mesoscale model. Second, to address the effects of fuel loading and fuel moisture, the two estimates were combined into a single meaningful quantity that is applicable to operational fire activities. As a rule of thumb, fire danger can be considered to increase when fuel moistures fall below 30 percent, which is the fiber saturation point in dead fuels (Zhou *et al.* 2003). To accentuate the effects of this threshold, we developed the Burnable Fuels Index (BFI), formulated as follows:

$$\text{BFI} = (0.3 - m)\,FL \qquad (1)$$

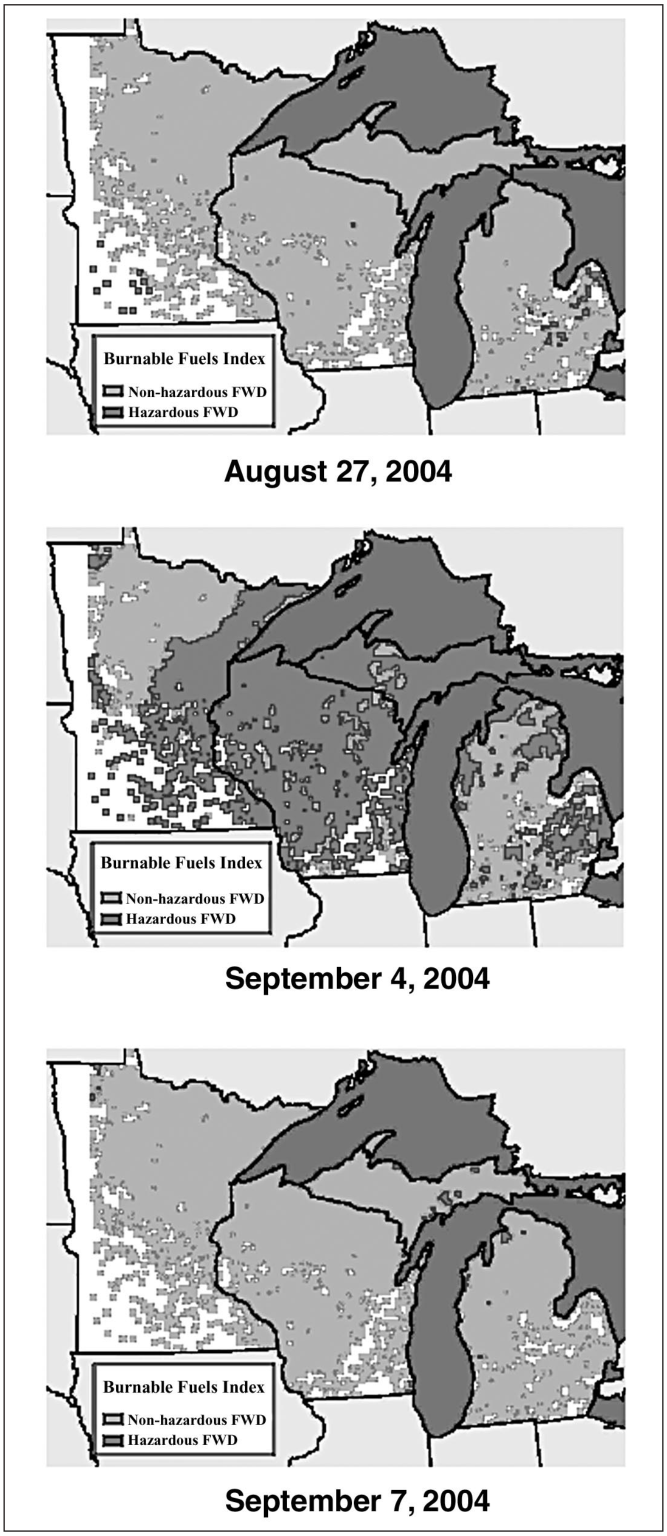
where *m* is the simulated fuel moisture between 0 and 1 (0 and 100 percent), and *FL* is the fuel loading in tons/acre. BFI is negative when fuel moistures exceed 30 percent. Conversely, BFI will increase as fuel moistures decrease below 30 percent and as fuel loadings increase. This quantity offers no insight into the probability of ignition and does not account for long-term precipitation effects on the heavier fuels. BFI is most useful, however, when used in conjunction with observations of moisture variations in the heavier fuels and local knowledge of fuel and forest conditions and at strategic scales may aid comprehension of how fire danger varies by day and user-defined areas.

Initial Results and Future Possibilities

In the upper Great Lakes region of the United States, fire danger may vary daily over a "fire season." Results from this study indicated dangers from 1- and 10-hr fuels varied from almost no danger (August 27 and September 7, 2004) to moderate danger (September 4, 2004) over a span of a few days (fig. 3). Areas with positive BFI (hazardous FWD) were typically constrained to areas that had "dried out" following the precipitation of recent weather fronts and before the arrival of a new weather front (fig. 3). Linking real-time estimates of fuel moisture with static fuel maps may allow refinement of fire behavior predictions and subsequent wildland firefighting efforts.

Because this study served as an initial examination of the techniques and outputs of merging strategic-scale fuel maps with real-time weather data, numerous refinements are needed to enable widespread application. First, BFI needs to better reflect fuel and fuel moisture relationships that are likely not multiplicative. Second, although inverse distance weighted interpolation of FIA phase 3 plots is an efficient and simple methodology for creating regional fuel maps, other techniques and data sources exist to complement and further improve regional fuel data layers. Lastly, data dissemination techniques that facilitate real-time Web updates of BFI maps are necessary to incorporate them into fire season activities. Overall, the results of this study indicate opportunities exist to refine understanding of the dynamic nature of forest fire dangers.

Figure 3.—*Burnable fuel index before (August 27), during (September 4), and after (September 7) a major weather event over a 3-day time-step during the summer of 2004, upper Great Lakes.*



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