# Estimating Fuel Consumption for the Upper Coastal Plain of South Carolina

Scott L. Goodrick, Dan Shea, and John Blake

ABSTRACT

Recent changes in air quality regulations present a potential obstacle to continued use of prescribed fire as a land management tool. Lowering of the acceptable daily concentration of particulate matter from 65 to 35 $\mu g/m^3$ will bring much closer scrutiny of prescribed burning practices from the air quality community. To work within this narrow window, land managers need simple tools to allow them to estimate their potential emissions and examine trade-offs between continued use of prescribed fire and other means of fuels management. A critical part of the emissions estimation process is determining the amount of fuel consumed during the burn. This study combines results from a number of studies along the Upper Coastal Plain of South Carolina to arrive at a simple means of estimating total fuel consumption on prescribed fires. The result is a simple linear relationship that determines the total fuel consumed as a function of the product of the preburn fuel load and the burning index of the National Fire Danger Rating System.

**Keywords:** prescribed fire, emissions, fuel consumption

Estimates of fuel consumption per unit area (FC) and emissions of particulate matter <2.5 $\mu m$ in diameter ($PM_{2.5}$) are required to strategically manage the smoke from prescribed fire programs in the South and to assess their impacts on air quality. New federal regulations (US Environmental Protection Agency 2007) have lowered the 24-hour maximum $PM_{2.5}$ exposure for the public from 65 to 35 $\mu g/m^3$. Although the annual limit has not changed (15 $\mu g/m^3$), the cumulative impact of all sources of $PM_{2.5}$ emission may also push designated urban environments over the annual threshold and into nonattainment status. Failure to achieve air quality standards could severely restrict prescribed fire programs designed to reduce hazardous fuels, to restore red-cockaded woodpecker (RCW) habitat (*Picoides borealis*) and native pine savanna communities, and to maintain wildlife habitat for game species. The current recovery plan for the RCW (US Fish and Wildlife Service 2003) places emphasis on frequent prescribed fire in restoring and sustaining RCW habitat, and frequent prescribed fire is critical to restoration and conservation of grass-forb savanna communities (Glitzenstein et al. 2003).

The Augusta–Aiken area, between Georgia and South Carolina, is an urban zone potentially affected by prescribed burning at the Savannah River site (SRS) and other forestlands in South Carolina and Georgia. Recent assessments by the South Carolina Department of Health and Environmental Control (Lawson 2008) and the Georgia Environmental Protection Division (Johnston 2008) indicate that Augusta–Aiken area annual $PM_{2.5}$ levels are close to the 15 $\mu g/m^3$ annual standard. Similar to many other federal agencies in the South, the Department of Energy has a goal to recover the RCW, restore pine savanna communities, manage wildlife habitat for game species, and manage hazardous fuels (US Department of Energy 2005). To achieve these goals, the objective for the annual prescribed fire program is 22,500 ac, a significant increase from the historical average of 13,000 ac (Kilgo and Blake 2005). Therefore, assessing the impacts of the fire program on air quality and identifying strategies to mitigate those impacts are critical. Current regional smoke management guidelines (US Forest Service 1989) and smoke management regulations within South Carolina (South Carolina Forestry Commission 2005) are designed to limit undesirable smoke impacts. However, they do not provide data to estimate FC and the resulting $PM_{2.5}$ emissions.

The basic method to estimate $PM_{2.5}$ emissions from prescribed fires involves three independent variables: FC, area burned, and the contaminant emission factor. If these variables are measured or can be calculated, then the following equation is used: $PM_{2.5}$ (mass) = FC (mass per unit area) × Area × $PM_{2.5}$ emission factor (mass/mass).

$PM_{2.5}$ emission factors for wildland and prescribed fire are summarized by Battye and Battye (2002). Urbanski et al. (2008) recently published emission factors for a large number of southern prescribed fires, including five fires at the SRS. Emission factors vary by combustion stage and fuel type, but the bulk values for individual burns are far less variable than FC. The FC term integrates the fuel bed structure and total available fuel loading (TF), which is the greatest source of uncertainty in determining FC, as well as environmental conditions affecting fire behavior, and is therefore the greatest source of variation in the emission equation (Peterson 1987, Sandberg et al. 2002). Empirical estimates of FC from prescribed fires in the South are available from a limited number of studies. Hough (1968, 1978) produced a large number of FC observations and generated relationships predicting FC as a function of TF and bulk duff-litter moisture content (MC) in northern Florida and southern Georgia. Ferguson et al. (2002) related litter and duff consumption to diurnal changes in weather and moisture variables at Eglin Air Force Base in the Florida panhandle, and Snyder et al.

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(2005) made FC measurements for various fuel types in the Florida Everglades. Ottmar et al. (2006) measured TF and FC for individual fuel bed components in conjunction with woody fuel and duff MC on 30 prescribed fires in the South. Prichard et al. (2007) used this data to derive fuel consumption relationships for each individual fuel bed component as a function of loading, duff MC and the fraction of soil exposed after burning to improve FC estimates from the model CONSUME 3.0. Sparks et al. (2002) related FC to fire behavior for a shortleaf pine forest in Arkansas, and Waldrop et al. (2004) reported FC measurements for a Piedmont forest in South Carolina. Scholl and Waldrop (1999) provided fuel loading and FC for eight forest stands in the Upper Coastal Plain of South Carolina, and Sullivan et al. (2003) published litter and duff consumption in conjunction with a fire effects study in the same area. In agreement with Sandberg et al. (2002), these FC observations for the South are highly variable, ranging from <1 ton/ac to >10 tons/ac. Unexplained variability in FC makes it difficult to estimate FC and subsequently emissions from a prescribed burning program.

Research on FC within other regions shows FC is related to TF and some measure or index of fuel or duff MC, and occasionally fire behavior (Sandberg 1980, Little et al. 1986, Kauffman and Martin 1989, Brown and Reinhardt 1991, Brown et al. 1991, Botelho et al. 1994). The relationship between MC of 1,000-hour fuels or dead and down wood with a diameter of 3–8 in. is used as the environmental driver for FC in the model CONSUME 3.0, based on western US regional data (Prichard et al. 2007). Various empirical equations from the western United States and rules of thumb are used in the submodel BURNUP as part of FOFEM (Reinhardt et al. 1997, Reinhardt 2003) to estimate FC. With the exception of the recent work by Ferguson et al. (2002) and Prichard et al. (2007), the relationships between FC and TF, duff MC, and other environmental variables have received limited attention in the South since the work of Hough (1968, 1978), which showed a strong predictive relationship between average duff MC, TF, and FC. Ferguson et al. (2002) showed duff and litter MC by volume to be closely associated with percentage of litter and duff reduction in four burns conducted in longleaf pine. Actual duff MC is difficult and expensive to obtain; however, indices of duff or fuel MC can be measured or calculated from local weather observations using the National Fire Danger Rating System (NFDRS) (Cohen and Deeming 1985, Burgan 1988).

Our objectives include (1) determining whether FC can be reliably predicted from measurements of TF and environmental variables collected during fire research studies at SRS; (2) determining whether simple weather measurements, estimated fuel MC, or NFDRS indices can function as alternatives to direct measurement of duff-litter MC; and (3) combining FC with recently published emission factors for $PM_{2.5}$ from the southeast to evaluate the impacts of a prescribed fire program and to identify strategies for reducing $PM_{2.5}$ emissions. The NFDRS indices of primary interest are the burning index (BI), energy release component (ERC), and the Keetch-Byram drought index (KBDI), as these quantities are commonly used to assess wildfire potential in the South and are significantly related to the conditional probability of a wildfire at SRS (US Forest Service 2005).

## Methods

The SRS is a 198,000-ac Department of Energy facility and National Environmental Research Park located in Aiken, Barnwell, and Allendale counties in South Carolina. The environmental and forest stand conditions at the SRS have been described in detail, including the prescribed fire and wildland fire history (Kilgo and Blake 2005). Typical of the southern region, a large portion of the SRS was farmed following European settlement. Between 1951 and 1970, about 40% of the land base was reforested with various southern pine species. Currently, about 65% of the area is in upland pine or pine-hardwood plantations (129,000 ac), 8% mixed hardwood, and about 22% bottomland hardwoods and cypress-tupelo forests. A significant prescribed fire program was initiated in the late 1970s on a nominal 5-year cycle. Since 2005, over 20,000 ac/year of understory prescribed burning has been accomplished.

We analyzed FC data collected from three separate understory prescribed fire studies conducted at the SRS between 1995 and 1997 (Scholl and Waldrop 1999, Sullivan et al. 2003, Urbanski et al. 2008). All three studies were performed in the eastern half of the SRS in the RCW management area (US Department of Energy 2005). In the first study, Scholl and Waldrop (1999) collected pre- and postburn data on eight forest stands prescribed burned in 1995 to develop a pre- and postburn photo series for managers. Scholl (1996) established 10 plots in each stand. At each plot, a 50-ft planer transect (Brown 1974) was used to obtain a nondestructive estimate of live fuels (grasses, forbs, shrubs, and vines) on four 10.8-$ft^2$ plots, and litter and cone dry weight on 0.54-$ft^2$ subplots. Down and dead woody fuel, including 1-hour (<0.25-in. diameter), 10-hour (0.26–1.0-in. diameter), 100-hour (1.01–2.99-in. diameter), and 1,000-hour fuels, were measured along the transect line. Nondestructive live fuel percentage cover and height were converted to biomass from equations developed from a separate series of destructive harvests on 100 plots of 10.8 $ft^2$ each. The second study is a subset of the data from a large emissions project conducted in 1996 that spanned 40 sites in the southeast (Urbanski et al. 2008). As part of this effort, five prescribed fires at SRS were monitored to estimate FC and emission factors for various combustion products, including $PM_{2.5}$. Detailed methods are given by Ottmar and Vihnanek (1997). For each burn, pre- and postburn fuel measurements were collected on 10 transects (50 ft each) centered on each of the three emissions towers. A total of 16 pre- and postburn plots (10.8 $ft^2$ each) were located along each transect. Within each plot, litter, duff, cones, 1-hour, 10-hour, and live vegetation components (grasses, forbs, shrubs, and vines) were harvested to estimate biomass. In a third study, conducted in 1997, a comprehensive fire effects experiment was performed by Sullivan et al. (2003) to determine how fire intensity and FC related to root damage and mortality in old-field longleaf pine (*Pinus palustris L.*). The data were collected on four 5-ac replicates of three burn intensities for a total of 12 burns. Within each 5-ac stand, 10 transects (50 ft each) were established, similar to the second study, and 16 plots (10.8 $ft^2$ each) were also systematically established. In contrast to the second study, each plot was subdivided into four subplots to measure pre- and postburn live fuels (grasses, forbs, shrubs, and vines), litter and duff, cones, and 1-hour and 10-hour fuels.

The original data in the first study by Scholl and Waldrop (1999) were modified by eliminating the 100-hour and 1,000-hour components, since these components are rarely consumed during prescribed fires in the southeast, and comparable data on these fuels were not available in the other studies. Data on cones, 1-hour and 10-hour fuels, and live fuels not previously reported by Sullivan et al. (2003) for the third study were included in the current analysis. The unpublished observations on TF and FC data from the second study (Urbanski et al. 2008) were provided by the US Forest Service

Missoula Fire Laboratory for analysis. The calculated FC for all studies was determined by subtracting TF for the described components pre- and postburn.

Although specific weather and ignition variables were collected in all three studies, only direct fire behavior observations and fuel MC measurements were made during the second study (Ottmar and Vihnanek 1997). Therefore, a common set of environmental and fire behavior variables from historical weather records are used for the analysis. Variables for each prescribed fire were obtained for the SRS Remote Access Weather Station (383101-SAVRIV) from the National Interagency Fire Management Integrated Database (NIFMID) database. Weather observations and NFDRS indices were calculated using Fire Family Plus, version 3.0.5.0. The primary indices of interest in this study included the ERC, KBDI, and BI. The ERC can be viewed as a composite fuel moisture index that accounts for the fuel MC of the various common fuel bed components (1-hour fuels, 10-hour fuels, etc.). The KBDI is a simple measure of drought designed as an indicator of duff and upper soil MC (Keetch and Byram 1968). The KBDI is also an integral component of the 1988 revision of NFDRS designed to improve performance for the southern United States (Burgan 1988). The BI provides an overall measure of fire behavior as it integrates fuel conditions (ERC) and the potential for fire spread (as indicated by the NFDRS's spread component). The BI and ERC were calculated for each day of ignition based on fuel model P, which is representative of many parts of the southeast coastal plain, including SRS, and fuel model G, which is commonly used as a reference fuel model across the United States, as it is the only fuel model to have fuel loads in all fuel bed components. Values for BI and ERC were calculated on the basis of the 1978 and 1988 model formulations (Burgan 1988). The KBDI was also calculated for each day. The observed 10-hour fuel moisture (10HR), the calculated 1,000-hour fuel moisture (1,000HR), and the observed relative humidity (RH) at midday were also obtained from NIFMID data. Days since last rain >¼ in. (DSR) were obtained from the SRS annual meteorological reports (Parker and Addis 1993).

The data were analyzed with SAS (SAS Institute 2003). Pearson's correlation and ordinary least-squares stepwise linear regression were used to test the significance of main variables (TF, BI, ERC, KBDI, DSR, RH, 10HR, and 1,000HR) on FC at an $\alpha$ level of 0.05. The effect of the three research studies on the slope and intercept of the regression relationships was determined by creating a new variable, Study, and coding it as a dummy variable (0, 1, or 2) for each study. When initial examination of residuals suggested a possible interaction between TF and some of the environmental indices, four new variables were created (TF × BI, TF × ERC, TF × DSR, and TF × KBDI), and the analysis was repeated. We performed the regression analysis with TF in separate groups for each of the NFDRS indices (BI, ERC, and KBDI), including the 1978, 1988, and model P and G formulations of BI and ERC. The FC analysis was run with independent variables TF, BI (1978, fuel model P), DSR, 10HR, 1,000HR, and RH, followed by TF, BI (1988, fuel model P), DSR, 10HR, 1,000HR, and RH, until all of the various BI and ERC values were used. Similarly, the FC analysis was run with independent variables TF, KBDI, DSR, 1,000HR, and RH, but not 10HR because of the very strong correlation between KBDI and 10HR. The regression analysis to predict FC was also run with each non-NFDRS environmental variable (DSR, 10HR, 1,000HR, and RH) in combination with TF.

Although we ran identical statistical analysis using both the 1978 and 1988 formulations of NFDRS fuel models P and G, the $r^2$ values for comparable regression models were consistently lower by about 5–22% for the 1988 formulation, with the difference generally smaller for model G than for model P. The largest reason for this difference in performance may be due to the inclusion of the KBDI as an additional variable in the BI and ERC calculations to increase available fuel in standard fuel models to improve drought representation in humid environments. The benefits from these changes on wildfire potential are greatest in summer and fall, whereas prescribed burning generally occurs in winter and spring. Coupled with additional changes in how fine fuel moisture, greening of vegetation, and wind speed are incorporated, the 1988 formulation may not be as applicable as the 1978 version to predict FC from prescribed burning at SRS. To simplify the presentation of results, only results for the 1978 formulation of NFDRS models P and G are reported.

## Results

The ranges of TF, FC, prescribed fire ignition methods, and environmental conditions are representative of prescribed burning in the Upper Coastal Plain in South Carolina (Table 1). The TF ranges from 2.6 to 12.3 tons/ac and FC from 1.0 to 8.6 tons/ac. The stands are primarily pine stands between 20 and 50 years of age. Ignition methods include both hand (head and backing fires) and aerial ignition. Burns were conducted over a period between January and May, which is the traditional prescribed burning season for this region.

The Pearson's correlation values indicate that none of the environmental or fire behavior variables are correlated with TF (Table 2) and therefore are not confounded in the results. In the regression analysis, TF has the highest correlation of any variable with FC across all studies, but the variation in the relationships suggests that other factors may influence FC (Figure 1). As single environmental variables, BI (models P and G), ERC (models P and G), and DSR are significantly correlated to FC, indicating, as in previous research, that environmental indices can explain variability in observed FC. Of the fire behavior variables, BI is most strongly associated with FC. The correlation coefficients between individual environmental and fire behavior variables are generally consistent with how they are interrelated in NFDRS calculations (Cohen and Deeming 1985). For example, BI builds on ERC by inclusion of wind speed and therefore should be correlated. The weak relationships between BI in model P and 1,000HR fuels contrast the relationship for BI in model G. The NFDRS model G incorporates substantial amounts of both 100-hour and 1,000-hour fuels, whereas model P has none. KBDI is a long-term drought index and therefore correlates well with the 1,000-hour fuels and the fuel model G indices, which are influenced by the inclusion of these larger fuels. The 10-hour fuel MC showed a strong negative correlation to KBDI and a positive correlation to RH.

The independent environmental variables RH and 1,000HR were not significantly related ($P = 0.05$) to FC in any ordinary least-squares model either alone or when TF was included. Examination of residuals did not suggest alternative model formulations such as interactions with TF. This result was not surprising, since

Table 1. **Fuel, stand, ignition, and environmental characteristics of the three prescribed fire studies at the Savannah River site.**

| Study attributes | Prescribed fire study: Scholl and Waldrop (1999) | Urbanski et al. (2007) | Sullivan et al. (2003) |
|---|---|---|---|
| Year of study | 1995 | 1996 | 1997 |
| Ignition period (month range) | January–February | February–May | February–March |
| Ignition method | Aerial | Aerial & hand | Hand (head & backing fires) |
| Stand types; age | Loblolly & longleaf pine; 20–50 years; one hardwood stand | Mature loblolly and longleaf pine; one pine pocosin | Old-field longleaf pine; 40–45 years |
| Most recent prescribed fire | 4 years; unknown (hardwood stand) | 1.5–9 years | >7 years |
| TF loading (tons/ac) | 5.9–9.1 | 2.6–12.3 | 7–9.3 |
| FC (tons/ac) | 1.4–5.0 | 1.6–8.6 | 1.0–5.5 |
| BI (model P) | 17–28 (1978) | 14–38 (1978) | 16–26 (1978) |
| | 21–35 (1988)[a] | 16–21 (1988)[a] | 16–32 (1988)[a] |
| BI (model G) | 1–18 (1978) | 20–55 (1978) | 12–31 (1978) |
| | 0–20 (1988)[a] | 21–30 (1988)[a] | 10–33 (1988)[a] |
| ERC (model P) | 22–24 (1978) | 19–29 (1978) | 21–29 (1978) |
| | 27–31 (1988)[a] | 22–28 (1988)[a] | 21–36 (1988)[a] |
| ERC (model G) | 0–5 (1978) | 24–35 (1978) | 6–25 (1978) |
| | 0–6 (1988)[a] | 25–33 (1988)[a] | 5–26 (1988)[a] |
| DSR > 0.25 in. (days) | 3–5 | 1–4 | 2–9 |
| 10HR moisture (%) | 11–12 | 8–12 | 8–12 |
| 1,000HR moisture (%) | 18–50 | 18–19 | 22–27 |
| RH (%) | 34–47 | 24–57 | 18–48 |
| KDBI | 10–18 | 60–253 | 6–138 |

[a] Represents the range of values for the 1988 formulations of models P and G.

10HR, 10-hour fuel moisture; 1,000HR, 1,000-hour fuel moisture; BI, burning index; DSR, days since last rain >¼ in.; ERC, energy release component; FC, fuel consumption per unit area; KDBI, Keetch-Byram drought index; RH, relative humidity; TF, total available fuel bed structure and loading.

Table 2. **Pearson's correlation coefficient (*r*) matrix and probability for *r* values for fuel and environmental variables across all studies.**

| | TF | BI (P) (1978) | BI (G) (1978) | ERC (P) (1978) | ERC (G) (1978) | DSR | 10HR | 1,000HR | RH | KDBI |
|---|---|---|---|---|---|---|---|---|---|---|
| FC Prob. > | 0.5816 | 0.6124 | 0.5975 | 0.6254 | 0.4710 | 0.3876 | −0.2832 | −0.2079 | −0.1006 | 0.1362 |
| | 0.0023 | 0.0011 | 0.0016 | 0.0008 | 0.0175 | 0.0556 | 0.1701 | 0.3185 | 0.6323 | 0.4357 |
| TF Prob. > | | 0.1398 | 0.1308 | 0.3025 | 0.0560 | 0.0691 | 0.2689 | 0.0762 | 0.0473 | −0.3547 |
| | | 0.5050 | 0.5332 | 0.1416 | 0.7903 | 0.7425 | 0.1936 | 0.7170 | 0.8222 | 0.0819 |
| BI (P) Prob. > | | | 0.6237 | 0.6515 | 0.2780 | 0.5577 | −0.2359 | −0.3449 | −0.1964 | 0.0183 |
| | | | 0.0009 | 0.0004 | 0.1784 | 0.0038 | 0.2562 | 0.0913 | 0.3466 | 0.9305 |
| BI (G) Prob. > | | | | 0.4499 | 0.8742 | 0.3679 | −0.5799 | −0.7319 | −0.2849 | 0.5962 |
| | | | | 0.0240 | 0.0001 | 0.704 | 0.0024 | 0.0001 | 0.1675 | 0.0030 |
| ERC (P) Prob. > | | | | | 0.3645 | 0.6320 | −0.5881 | −0.0688 | −0.6269 | 0.2811 |
| | | | | | 0.0732 | 0.0007 | 0.0020 | 0.7437 | 0.0008 | 0.1734 |
| ERC (G) Prob. > | | | | | | 0.2482 | −0.6895 | −0.6622 | −0.2253 | 0.8029 |
| | | | | | | 0.2315 | 0.0001 | 0.0003 | 0.2787 | 0.0001 |
| DSR Prob. > | | | | | | | −0.4605 | −0.1278 | −0.2920 | 0.3159 |
| | | | | | | | 0.0205 | 0.5425 | 0.1567 | 0.1239 |
| 10HR Prob. > | | | | | | | | 0.3071 | 0.6611 | −0.9025 |
| | | | | | | | | 0.1354 | 0.0003 | 0.0001 |
| 1,000HR Prob. > | | | | | | | | | −0.0081 | −0.4447 |
| | | | | | | | | | 0.9691 | 0.0259 |
| RH Prob. > | | | | | | | | | | −0.3714 |
| | | | | | | | | | | 0.0676 |

1,000HR, 1,000-hour fuel moisture; BI, burning index; DSR, days since last rain >¼ in.; ERC, energy release component; FC, fuel consumption per unit area; KDBI, Keetch-Byram drought index; prob., probability; RH, relative humidity; TF, total available fuel bed structure and loading.

RH was only one of several weather variables effecting MC of fuels, and 1,000-hour fuels represented only one minor component of southern fuel beds, such as fuel model P. Only TF in combination with BI (models P and G), ERC (models P and G), KBDI, DSR, and 10HR proved to be significant (Table 3). Higher $R^2$, $F$ values, and lower mean square errors were obtained with BI over ERC for both NFDRS models, probably as a result of incorporation of wind speed. The TF × BI (model P) variable improved the model $R^2$-value over TF and BI separately (Table 3, Equation 3 versus Equations 4 and 6), as did TF × DSR (Table 3, Equation 2), suggesting that FC may be better understood by considering the positive feedback between TF and environmental variables during prescribed burning. Although DSR was a weak environmental variable, it improved the $R^2$ for several models, including the KBDI regression model (Table 3, Equation 10).

The effect of study on the intercept and slope of the regression models of TF and BI (model P; Table 3, Equation 3) or the combined variable TF × BI (model P; Table 3, Equation 4) against FC was not significant ($P = 0.05$). Very high regression $R^2$ values were observed between TF × BI and FC for two of the individual studies (Figure 2). The $R^2$ values were 0.84 ($P = 0.0001$) in the third study, conducted by Sullivan et al. (2003) in 1997, and 0.97 for the second study, by Urbanski et al. (2008) ($P = 0.0020$). For the Scholl and Waldrop (1999) study, the $R^2$ was weak ($P = 0.1695$), but the data

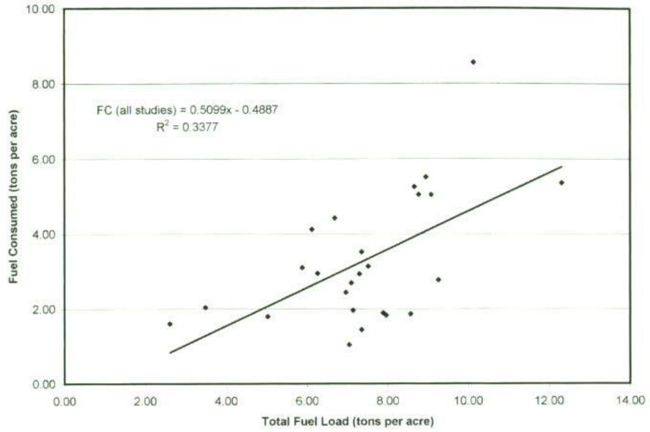


**Figure 1. Composite relationships between TF and FC for the 25 prescribed fire observations at the Savannah River site. FC, fuel consumption per unit area; TF, total available fuel bed structure and loading.**

range was also more limited than in the other two studies. In contrast, models involving BI (model G) showed substantial reduction in residual variance by including study dummy variables (Table 3, Equations 5 and 6). The effect of study on the intercept and/or slope of the regression models of TF and ERC (models P and G), KBDI, and 10HR was also significant and generally improved the overall model $R^2$ (Table 3, Equations 7–10). Some analyses showed significant effects on model slope, whereas others showed effects on model intercept, thus making interpretation of the study effects difficult. The effect of study on the FC also limits the model utility and generalization of the results for estimating $PM_{2.5}$ emissions. The lack of significant impact of the study dummy variable on the slope or intercept of the TF × BI (model P) model allowed the studies to be pooled and treated as one data set to estimate FC (Fig 3). The adjusted $R^2$ for this combined data set is 0.69, which provides a reasonable predictive equation for managers.

Finally, we computed the FC using the equation of Hough (1978) for the five SRS fires from the second study conducted during 1996 in which duff layer MC was measured (Urbanski et al. 2008). The average observed FC was 4.1 tons/ac, which compares well with a predicted average FC of 3.66 tons/ac from Hough's equation using TF and duff MC. The Pearson's correlation coefficient was 0.81 ($P = 0.095$). Although we did not have duff MC for the other studies, this simple comparison suggests that the fundamental relationships proposed by Hough may be valid in the Upper Coastal Plain of South Carolina as well.

## Discussion

Consistent with research on FC within other regions (Sandberg 1980, Kauffman and Martin 1989, Brown and Reinhardt 1991, Brown et al. 1991, Botelho et al. 1994) and the previous studies of Hough (1968, 1978), we found TF to be a critical variable controlling FC in this study. Fuels inventory or monitoring data, published photo series (Ottmar et al. 2003), and data developed for the Fuel Characteristic Classification System in the southeast (Ottmar et al. 2007) can reduce the uncertainty in TF estimates for landowners and regulatory agencies. The relationships between natural fuel component dynamics associated with forest type, stand age, stocking, site index, and fire history may be as important as simple measures of TF to effectively use the full range of silvicultural practices required to manage hazardous fuels and emissions. Parresol et al. (2006) observed that fuel component loadings derived from sitewide inventory plots at SRS were significant functions of stand age, basal area, and site index, as well as fire history, within forest types. These observations suggest that silvicultural practices affecting species composition, stocking, and rotation age are critical in a comprehensive approach to managing TF.

The combination of NFDRS indices and TF works well in predicting FC. NFDRS calculations are driven by local weather data. Therefore, it is no surprise that variables obtained from the NFDRS, such as BI and ERC, would improve the modeling of FC (Hough 1978). The BI (model P) is a very good predictive variable for occurrence of large wildfires (>10 ac) at SRS (US Forest Service 2005). The ERC is also a significant predictive variable for wildfires at SRS, but it may not have been as effective as BI in reducing residual variability in the FC prediction because wind speed is not incorporated in the index. The KBDI is significantly related to FC in this study and generally performs as well as the BI (model G), ERC (model G), and 10HR variables, with which it is strongly correlated. The generally weaker model significance levels may be a consequence of the fact that the KBDI is designed to track drought conditions and is less sensitive to short-term weather changes that influence MC dynamics in litter and duff (Ferguson et al. 2002). We found DSR a significant but weak environmental variable for predicting FC. Empirical equations relating DSR directly to duff MC for the southeast have been developed by Hough (1978). However, the complexity of antecedent moisture conditions and the size of the prior rainfall event may limit the development of a broad-based environmental index for DSR (Ferguson et al. 2002). In contrast to studies from the western region of the United States (e.g., Sandberg 1980, Little et al. 1986, Brown et al. 1991), the calculated MC of 1,000-hour fuels was unrelated to FC despite its being correlated to other environmental variables (e.g., BI, model G) that were themselves significant in predicting FC. The environmental indices that offer the greatest predictive potential for FC during prescribed burning are those that integrate and track the MC dynamics of the available fuel bed.

Environmental indices such as 1,000HR and KBDI are not necessarily indicative of the MC of the fuel bed components that will be consumed in a prescribed burn because of their lower sensitivity to short-term weather fluctuations; in addition, NFDRS indices for fuel models representing dense forests with large dead fuel accumulations (BI model G) possess a level of inertia that limits their sensitivity to short-term weather changes because of the larger fuel classes. The 1988 NFDRS formulation, through its inclusion of KBDI, also exhibits a certain degree of inertia, as shown by the weaker relationships between FC and TF plus either BI or ERC compared with relationships for the 1978 indices. Other environmental variables, such as RH, or indices, such as the 10-hour MC, may respond faster than the MC of the available fuel bed. Whether NFDRS indices can be applied broadly in the South may depend on how the natural range of fuel loading and fuel arrangement controls fuel moisture dynamics of the available fuel bed (Nelson and Hiers 2008).

Despite some success in predicting FC, predicting $PM_{2.5}$ to show the potential of reducing particulate emissions is more complex. Reducing the land area treated with prescribed fire is possible if alternatives exist that can cost-effectively achieve hazardous fuel and ecological objectives. Although the use of silviculture and harvesting practices can reduce hazardous fuels (Rummer et al. 2002, Waldrop

**Table 3. Ordinary least squares best fit regression models for FC with associated $R^2$, Probability of *F* value > and RMSE.**

| Regression model for FC (tons/ac) | RMSE | $R^2$ | Probability $F>$ | Equation no. |
|---|---|---|---|---|
| $= -0.4903 + 0.51018$ TF | 2.11903 | 0.3383 | 0.0023 | 1 |
| $= -0.6064 + 0.40101$ TF $+ 0.03149$ (TF × DSR) | 1.76275 | 0.4735 | 0.0009 | 2 |
| $= -3.1979 + 0.44374$ TF $+ 0.16001$ BI (P) | 1.25229 | 0.6259 | 0.0009 | 3 |
| $= -0.01516 + 0.02207$ TF × BI (P) | 1.00101 | 0.6874 | 0.0001 | 4 |
| $= -2.2357 - 0.21783$ TF × Study $+ 0.70378$ TF $+ 0.05581$ BI (G) $+ 0.05314$ BI (G) × Study | 0.60974 | 0.8344 | 0.0001 | 5 |
| $= 3.12084 + 0.01202$ TF × BI (G) × Study $- 1.87941$ Study | 0.81962 | 0.7742 | 0.0001 | 6 |
| $= -7.00438 + 0.49116$ TF $+ 0.31312$ ERC (P) $+ 0.06188$ TF × Study | 1.36048 | 0.6121 | 0.0001 | 7 |
| $= -1.3739 + 0.59726$ TF $+ 0.09924$ ERC (G) $- 0.91037$ Study | 1.07352 | 0.6939 | 0.0001 | 8 |
| $= 3.4804 + 0.72624$ TF $- 0.45162$ 10HR $- 0.64606$ Study | 1.2616 | 0.6403 | 0.0001 | 9 |
| $= -2.69319 + 0.72157$ TF $+ 0.01000$ KBDI $- 0.64633$ Study $+ 0.21826$ DSR | 1.35921 | 0.6309 | 0.0003 | 10 |

10HR, 10-hour fuel moisture; BI, burning index; DSR, days since last rain >¼ in.; ERC, energy release component; FC, fuel consumption per unit area; KDBI, Keetch-Byram drought index; prob., probability; RMSE, root mean square error; TF, total available fuel bed structure and loading.

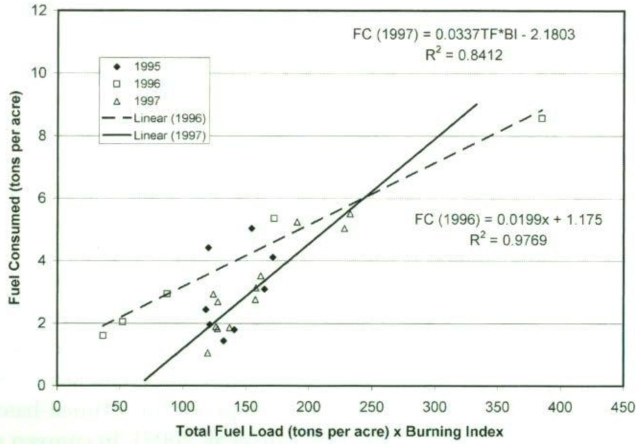


**Figure 2. Relationships between FC and TF × BI from three independent prescribed fire studies at the Savannah River site. The data and equation from the second study (Urbanski et al. 2008) are labeled 1996. The data and equation from the third study (Sullivan et al. 2003) are labeled 1997. The data from the first study (Scholl and Waldrop 1999) are labeled 1995, but the equation is not shown (*P* = 0.16). BI, burning index; FC, fuel consumption per unit area; TF, total available fuel bed structure and loading.**

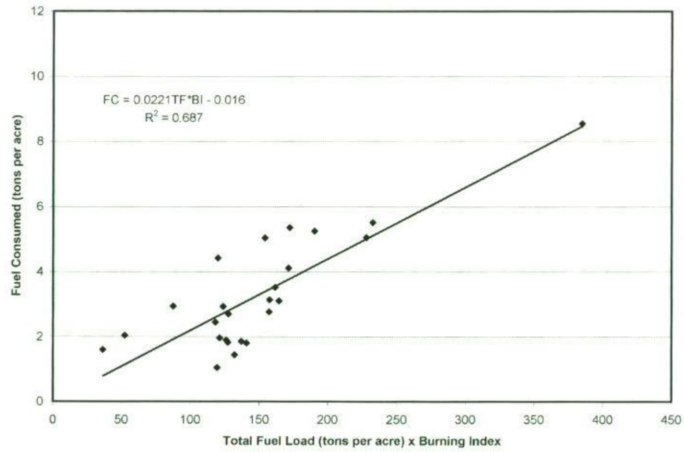


**Figure 3. Composite relationship between FC and TF × BI (model P) for 25 prescribed fire observations at the Savannah River site. BI, burning index; FC, fuel consumption per unit area; TF, total available fuel bed structure and loading.**

et al. 2004), the existing research does not indicate that ecological objectives for maintaining or restoring pine savanna grasses and forbs are achieved with mechanical or chemical treatments alone (Brockway et al. 2009). There is a range in observed emission factors for the southeast (Urbanski et al. 2008), but there is currently no systematic relationship identified that can be used by managers to reduce emission factors. Firing techniques such as backing fires are suggested as a means of reducing particulate emissions by increasing combustion efficiency. However, field studies show that they generally consume more litter and duff but relatively less live fuel (Hough 1968, Botelho et al. 1994, Sullivan et al. 2003). Under similar fuel and environmental conditions, the FC is very similar (Hough 1978). Backing fires also have lower fire line intensities that can limit smoke plume rise within the mixing layer, and they require longer ignition periods that can lead to smoke being trapped during inversions. The latter condition may increase the 24-hour $PM_{2.5}$ above regulated levels.

When we combine the FC modeled with variables TF and BI (Figure 3; Table 3, Equation 2) with recently published emission factors for $PM_{2.5}$ from the southeast (Urbanski et al. 2008), and the target prescribed fire goal of 22,500 ac/year (US Department of Energy 2005), the average annual $PM_{2.5}$ emissions impact from prescribed burning can be evaluated (Table 4). For perspective, the magnitude of emissions from existing plantations, when burned on a cycle of 5+ years, is approximately double the $PM_{2.5}$ emissions from a 50-year old boiler at SRS burning 154,000 tons of coal/year to generate process steam (US Department of Energy 2008). Since a long-term ecological objective for a large portion of the SRS is development of RCW habitat characterized by frequently burned open pine and grass-forb communities (US Fish and Wildlife Service 2003), the future air quality impacts should reflect these fuel bed conditions. Although these conditions are currently limited at SRS, the live vegetation TF can be approximated from SRS old-field studies (Odum 1960), frequently burned range studies in the South (Gaines et al. 1954, Brockway and Lewis 1997), and dead TF from the SRS inventory equations relating dead fuel component loading to stand age, basal area, site index, and fire frequency (Parresol et al. 2006). The total annual $PM_{2.5}$ emissions are drastically reduced under these ecological conditions as a direct result of changes in stand structure, leading to much lower TF (Table 4). Creating and sustaining these fuel bed conditions requires a more frequent prescribed fire cycle (McNab et al. 1978, Hough 1978, 1982, Hanula and Wade 2003, Glitzenstein et al. 2003); therefore, instead of burning, for example, a total of 112,500 ac on a nominal 5-year cycle (22,500 ac/year), we can treat only a total of 67,500 ac on a

**Table 4. Estimated annual $PM_{2.5}$ emissions from prescribed fires burning at the Savannah River site. Pine plantation total available fuel (TF) is the average of the 25 prescribed fire observations. Expected long-term ecological restoration fuel loads for pine savannas are derived from the literature as noted.**

| Forest condition | Emission factor[a] (lb/ton) | TF (tons/ac) | FC[b] (tons/ac) | Annual area burned (ac) | Total $PM_{2.5}$ emissions (lb) |
|---|---|---|---|---|---|
| Pine plantation | 27.96 | 7.4 | 3.25 | 22,500 | 2,045,330 |
| Pine savanna[c] | 26.06 | 2.05 | 0.89 | 22,500 | 521,852 |
| Pine savanna[d] | 26.06 | 3.25 | 1.42 | 22,500 | 832,617 |

[a] Urbanski et al. (2008). The savanna burns included FS1, ICI1, ICI2, ICI3, and SC3 from Appendix A1.
[b] Calculated from Equation 4 in Table 3; burning index = 20.
[c] Live fuel load based on Gaines et al. (1954), Odum (1960), and Brockway and Lewis (1997). Inventory equations of Parresol et al. (2006) used to estimate litter, duff, 1-hour and 10-hour loading in 50-year old longleaf pine, site index 70, BA of 30 and burned every 3 years.
[d] Live fuel load based on Carter and Hughes (1974) and dead fuel is based on Parresol et al. (2006), as in footnote *c*.
FC, fuel consumption per unit area; $PM_{2.5}$, particulate matter; TF, total available fuel bed structure and loading.

3-year cycle. Hazardous fuels reduction would require implementation of other silvicultural practices, such as biofuel harvests, or strategic placement of fuel treatments across a landscape to limit large wildfires (Finney et al. 2007).

Although the data collected have a limited geographic scope, we believe they are consistent with other research and support several important conclusions. Total fuel consumption from prescribed fires can be reliably estimated from knowledge of total available fuel loading and environmental indices. We found support for Hough's (1978) proposal that NFDRS indices may be useful surrogates for direct measures of duff MC in the southeast, but additional analysis of unpublished FC data from southeastern prescribed fires (Ottmar et al. 2006, Urbanski et al. 2008) would help validate their broad utility for FC models such as CONSUME (Prichard et al. 2007). Opportunities to reduce total $PM_{2.5}$ emissions are limited, but increasing fire frequency on a smaller area of the landscape is feasible, and it is compatible with RCW habitat and longleaf savanna restoration goal.

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