Modification of VanWagner’s Canopy Fire Propagation Model

James Dickinson¹, Andrew Robinson², Richy Harrod³, Paul Gessler⁴, and Alistair Smith⁵

Abstract—The conditions necessary for the combustion of canopy fuels are not well known but are assumed to be highly influenced by the volume through which the canopy fuels are dispersed, known as canopy bulk density (CBD). Propagating crown fire is defined as a continuous wall of flame from the bottom to the top of the canopy, implying crown fire propagation is actually independent of the vertical fuel distribution. We hypothesize that all foliar canopy fuel is available for the propagation of canopy fire. Therefore, we focus our effort on simplifying Van Wagner’s (1977) canopy fire propagation model to accept a canopy fuel metric that uses only foliar biomass per unit area (FBA) rather than the more complex and commonly used CBD. The multiplication of leaf area index (LAI) and the specific leaf area (SLA) of a given tree species results in FBA, making FBA easily related back to ecologically meaningful terms at a range of spatial scales. A variety of instruments can be used to estimate LAI with high accuracy, and SLA values have been published for many species found in fire prone forests of the West. Alternatively, allometric equations can be used to compute FBA using individual tree-level measurements. Using Van Wagner’s (1977) data we modify his propagation model and successfully match his published results. In addition, we use Forest Inventory and Analysis data from northern Idaho to compare the critical rate of spread (cROS) predicted by the modified model (using FBA) with the predictions of the original model (using CBD). We find that the two models are statistically equivalent (α = 0.10).

Introduction

Canopy fire challenges accurate modeling of fire spread because quantification of the canopy fuel stratum is difficult (Cruz and others 2003; Keane and others 2005). Particular difficulty arises, as canopy fires can exist in either ‘passive’ or ‘active’ modes. In passive canopy fires, individual trees or groups of individuals ignite and burn from the bottom to the top of the crown, resulting in mixed impacts on the environment (Ryan and Noste 1983). In active canopy fires the combustion propagates as a solid wall of flame through a landscape filled with trees in conjunction with a surface fire (Van Wagner 1977). In addition, this combination of active canopy and surface fire often burns at high intensity having significant impact on soils, vegetation, and wildlife habitat (Grier 1975; Ryan and Noste 1983; Romme 1995; Haggard and Gaines 2001). Such fires may exhibit flame lengths exceeding 30 m with rates of spread exceeding 50 m/min (Stocks and others 2004). Active canopy fire also poses great risk to fire personnel, the public, and private property (Scott 1998; Clark and others 1999; Scott and Reinhardt 2001).
For these reasons fire managers have great interest in preventative treatment of forested landscapes capable of sustaining active canopy fires (Hof and Omi 2003; Scott 2003; Peterson and others 2005) and also in predicting the behavior of these fires when they initiate (Stocks and others 2004). These management applications require knowledge of the minimal conditions sustaining canopy fire to properly plan fuels treatments or to evaluate impending conditions that threaten crews during suppression actions.

Most fire planning tools and spatially explicit fire models depend upon the original Van Wagner’s (1977) model (we refer to this model as VWcbd) to characterize the minimum conditions necessary to sustain active canopy fire (Keane and others 2000; Scott and Reinhardt 2001; Finney and others 2003; Reinhardt and Crookston 2003; Finney 2004). Other research has attempted to quantify the available canopy fuel for combustion, called canopy bulk density (CBD) to parameterize VWcbd for application (Keane and others 2000; Fule and others 2001; Hummel and Agee 2003; Riano and others 2003; Gray and Reinhardt 2003; Perry and others 2004; Riano and others 2004; Falkowski and others 2005; Peterson and others 2005; Keane and others 2005).

To date, no study has compared the effect that using different methods of CBD estimation might have on the output of the VWcbd. Therefore, this paper introduces the reader to two common methods of estimating CBD and statistically compares the outputs of the VWcbd model using these inputs. We also develop and compare a modified version of VWcbd, which we call VWfba, that utilizes a simpler metric of foliar biomass per unit area (FBA) as the fuel input.

Crown Fire Defined

Van Wagner (1977) described a conceptual canopy fire model using “a stationary wall of flame with a conveyor belt carrying fuel into the flame.” The rate of that conveyor belt must maintain a minimum critical rate of spread (cROS) to deliver a sufficient quantity of combustible fuel per unit time to maintain the wall of flame in the canopy space (Van Wagner 1977).

Van Wagner modeled canopy fire interactions for fuel, flame front rate of spread, and the minimum fireline intensity necessary to maintain canopy fire in a fashion similar to Byram’s (1959) index. This surface fire index relates fireline intensity, the rate of spread of a flame front, and the quantity of combusted fuel (Byram 1959; Scott and Reinhardt 2001). By representing the flame front as a line moving at some rate across a plane of homogenously distributed fuel mass (multiplied by a constant heat yield) the result is a fireline intensity that is the product of the rate of flame movement and the homogeneous fuel (Byram 1959). Like Byram’s (1959) index, the VWcbd assumes a homogeneously distributed fuelbed, albeit through a volume rather than across an area (Van Wagner 1977). The assumption of a homogeneous fuel bed with a constant heat yield per unit of fuel makes VWcbd identical to Byram’s (1959) index in form.

The Van Wagner (1977) model differs only in form by its calibration to the minimal conditions necessary for active canopy fire to persist. Van Wagner assumed that the fuel present in a stand would have a constant heat of ignition (per unit mass), and thus avoided the necessity of calculating the energy in the propagating heat flux. This changed the crucial element to a simple
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The argument that relates only the critical quantity of fuel consumed per unit time required for flame maintenance, divided by the available fuel quantity (equation 1). The result of this equation is the critical rate of spread (cROS, represented by ‘\( R_o \)’ in equation 1) required for the fire to consume the available fuel (‘\( d \)’) such that the critical mass flow rate (‘\( S_o \)’) is satisfied.

\[
R_o = \frac{S_o}{d} \quad \text{(Van Wagner 1977)}
\]

Where:  
- \( R_o \): cROS for active canopy fire (m.s\(^{-1}\))
- \( S_o \): critical mass flow rate for canopy fire, (0.05 kg.m\(^{-2}\).s\(^{-1}\))
- \( d \): foliar (canopy) bulk density (kg.m\(^{-3}\))

Van Wagner’s definition of canopy fire as a wall of continuous flame from bottom to top of the canopy must be met to satisfy the implicit assumption that canopy fire has initiated (Van Wagner 1977; Scott and Reinhardt 2001). The use of a single value to represent a distribution of fuel through the canopy space removes any effect that a vertical distribution of fuel may have upon canopy fire, requiring a second implicit assumption that horizontal canopy fire propagation occurs regardless of the vertical distribution of the fuel. The quotient resulting from the division of the available fuel by volume (the definition of CBD) is simply a fraction of the total fuel load (the sum of which is still available for combustion) and is irrelative to the effect that the vertical distribution may (or may not) have on canopy fire.

Regardless of how a metric might incorporate the vertical distribution component, it must be input to a model calibrated for that fuel metric. Likewise, a metric with no vertical distribution component used in a properly calibrated model, would not preclude the use of vertical distribution as a parameter in the model. It would simply require the incorporation of the vertical distribution to be explicitly included in the model. The fuel input to such a model would be useable at a range of scales depending only upon the method used to calculate the available canopy fuel.

Our overarching assumption is that the Van Wagner (1977) model appropriately relates the basic properties necessary to describe the lower boundary conditions required for active canopy fire combustion. Namely, that an active canopy fire spreading between two points on the landscape must consume a minimum quantity of fuel per unit time in order to persist as a canopy fire. The quantification of fuel is vital to a model of the combustion process but need not incorporate the vertical distribution into the fuel metric as traditional canopy fuel methodologies have done.

Van Wagner’s (1977) published data are used here to recalibrate the model for use with FBA in place of the standard CBD input. The VWcbd and the VWfba models are applied to a regionwide nonspatial Forest Inventory and Analysis (FIA) database, and an equivalence test is used to compare the estimates of cROS from the VWcbd and VWfba models.

Methodology

In this section we introduce two methods used to calculate the fuel input necessary for VWcbd. We then modify the existing VWcbd for the use of foliar biomass to create the VWfba model. Finally, we introduce our data and the statistical methods used to test the equivalence of the VWcbd and VWfba.
**Summary of CBD Methods**

We present FBA as a more simple alternative to the several existing methods for calculating CBD (Sando and Wick 1972; Brown 1978; Cruz and others 2003; Riano and others 2003; Reinhardt and Crookston 2003; Perry and others 2004) though only the FFE (Reinhardt and Crookston 2003) and Cruz and others (2003) methods are used for comparison because they represent the two unique approaches to estimating CBD.

The widespread use of the complex FFE method by Federal land managers and researchers (Hummel and Agee 2003; Andersen and others 2005; Perry and others 2004; Falkowski and others 2005; Peterson and others 2005) is facilitated by its implementation in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) computer software (Reinhardt and Crookston 2003) and the proprietary Fire Management Analyst Plus suite of computer software (FPS 2001).

When applied to a stand inventory list, FFE calculates the foliar biomass assuming constant density of foliar biomass through the length of the individual tree-crown space. FFE calculates the amount of biomass contained in every vertical 0.3048 m (1 ft) of the volume space for each tree (Scott and Reinhardt 2001). Finally, the foliar biomass for all individuals in the stand is summed within each vertical 0.3048 m above the ground and is plotted (see fig. 1). This represents stand biomass (kg/m²) distributed by height above ground (m), as a sum of all individual trees (that is, vertical distribution of foliage within the canopy space) (Sando and Wick 1972).

**Figure 1**—FFE methodology of canopy bulk density calculation. The maximum of the 13-ft (3.96 m) running mean (marked with a star) read from the x-axis as the maximum average foliar biomass per square meter per average vertical meter, or “effective CBD” (kg/m^3).
FFE calculates the maximum 0.3048 m (1 ft) increment of a 3.96 m (13 ft) running mean applied to the vertical profile of foliar biomass (see fig. 1) (Reinhardt and Crookston 2003). This produces an effective CBD value that is not equivalent to the traditional CBD definition (Scott and Reinhardt 2001). Rather, effective CBD provides a value that is the maximum of a running average (fig. 1) and represents the greatest average fuel value, presumed to be the least resistant stratum for canopy fire propagation through a stand (Scott and Reinhardt 2001). Despite the lack of direct correspondence to the CBD definition, it is frequently used as input to VWcbd.

Cruz and others (2003) calculate the foliar biomass for all trees in a stand and divide this by the product of the average crown length multiplied by the area of the stand. Biomass is assumed to have equal distribution through the volume of the canopy. This method appears to be similar to the method used by Van Wagner (1977) for calculation of experimental fuels data. We refer to this method as the “Cruz” method for the remainder of this paper.

**Modification of Van Wagner’s Model**

Our research modifies VWcbd (equation 2a) (Van Wagner 1977) by altering the value that represents the mass flow rate ($S_o$, equation 2a), which represents the minimum quantity of fuel required to be combusted per unit time to sustain canopy fire propagation. To determine $S_o$, Van Wagner identified forested stands for canopy fire experimentation and recorded stand information including stems per hectare, basal area, tree height, height to crown base, and biomass per unit area (table 1). The stands were then ignited with three out of four fires judged to burn as active canopy fires by Van Wagner (table 1).

$$R_o (m/s) = \frac{S_o}{d} = \frac{0.05(kg/m^2 s^{-1})}{d(kg/m^3)} \quad (Van Wagner 1977) \quad (2a)$$

$$S_o = R_o \cdot d \quad (2b)$$

$R_o$ is the critical minimum rate of spread for active canopy fire  
$S_o$ is the critical mass flow rate for solid crown flame  
$d$ is the canopy bulk density

Van Wagner (1977) used one stand (‘R1’ in table 1), considered ‘an incipient’ active canopy fire, for model calibration. The observed rate of spread of fire in stand ‘R1’ was multiplied by CBD to determine the required mass flow ($S_o$ in equation 2b). It was apparent that this resulting value was less than necessary for active canopy fire, so Van Wagner set $S_o$ at a constant value

<table>
<thead>
<tr>
<th>Test fire name</th>
<th>Fire type</th>
<th>Basal area (m$^2$)</th>
<th>Trees/ha</th>
<th>Tree height</th>
<th>Height to live (m)</th>
<th>Biomass per m$^2$</th>
<th>CBD (kg/m$^3$)</th>
<th>Actual ROS (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>active</td>
<td>50</td>
<td>3200</td>
<td>14</td>
<td>7</td>
<td>1.8</td>
<td>0.23</td>
<td>0.46</td>
</tr>
<tr>
<td>C4</td>
<td>active</td>
<td>50</td>
<td>3200</td>
<td>14</td>
<td>7</td>
<td>1.8</td>
<td>0.26</td>
<td>0.28</td>
</tr>
<tr>
<td>GL-B</td>
<td>active</td>
<td>25</td>
<td>1800</td>
<td>18</td>
<td>6</td>
<td>1.22</td>
<td>0.12</td>
<td>0.41</td>
</tr>
<tr>
<td>R1</td>
<td>developing</td>
<td>50</td>
<td>3200</td>
<td>14</td>
<td>7</td>
<td>1.8</td>
<td>0.23</td>
<td>0.18</td>
</tr>
</tbody>
</table>
slightly greater (0.05 kgm\(^{-2}\)s\(^{-1}\)). This established the minimum mass flow
value necessary because a slower fuel consumption rate would result in fire
behavior similar to the incipient canopy fire behavior of ‘R1’ (Van Wagner
1977).

Our alternative VWfba was created by dividing Van Wagner’s value of
\(S_o = 0.05 \text{ kgm}^{-2}\text{s}^{-1}\) by the CBD for stand ‘R1’ (0.23 kgm\(^{-3}\)) (equation 3a).
The result is a cROS of 0.217 ms\(^{-1}\) for stand ‘R1’. The cROS is multiplied
by the FBA (foliar biomass per unit area, table 1) of stand ‘R1’ resulting in
a product of 0.39 kgm\(^{-2}\text{s}^{-1}\) (equation 3b) giving the predictive equivalent to
Van Wagner’s published value using CBD of \(S_o = 0.05 \text{ kgm}^{-2}\text{s}^{-1}\) (equation
3c). The final form of the VWfba model is shown in equation 4.

\[
0.05(\text{kgm}^{-2}\text{s}^{-1}) + 0.23(\text{kgm}^{-3}) = 0.217(\text{ms}^{-1}) \tag{3a}
\]

\[
0.217(\text{ms}^{-1}) \times 1.80(\text{kgm}^{-2}) = 0.39(\text{kgm}^{-1}\text{s}^{-1}) \tag{3b}
\]

\[
\frac{0.05(\text{kgm}^{-2}\text{s}^{-1})}{0.23(\text{kgm}^{-3})} = 0.217(\text{ms}^{-1}) = \frac{0.39(\text{kgm}^{-1}\text{s}^{-1})}{1.80(\text{kgm}^{-2})} \tag{3c}
\]

\[
R_o(\text{ms}^{-1}) = \frac{0.39(\text{kgm}^{-1}\text{s}^{-1})}{d(\text{kgm}^{-2})} \tag{4}
\]

After recalibration of \(S_o\), the VWfba model was applied to the rest of the
data provided by Van Wagner (1977). The VWfba and VWcbd models pro-
vide comparable predictions of cROS. Additionally, VWfba identifies that
stand “GLB Active” (fig. 2) exceeds the cROS and is an active canopy fire
when VWcbd does not.

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vide comparable predictions of cROS. Additionally, VWfba identifies that
stand “GLB Active” (fig. 2) exceeds the cROS and is an active canopy fire
when VWcbd does not.

![Figure 2](image)

**Figure 2**—Summary of Van Wagner (1977) published results and the VWfba recalibration applied to original data. Where the ‘Actual ROS’ line exceeds the estimated lines a canopy fire should occur. Note that only the VWfba estimate is exceeded by the GLB fire.
**Sample Data**

We use a database of 2,626 FIA plots collected from the Inland Northwest region of the United States (UIFBL, 2006). FIA routinely collects data on trees, saplings, and seedlings at each plot; however, we selected only trees at least 7.56 cm (3 inches) in diameter at breast height (1.37 m) (USDA Forest Service 1990). Each of the 40,000 tree records in this database include the variables of tree diameter, height, percent live crown ratio, species, and the tree expansion factor (number of trees per hectare that record represents) and plot level variables (such as elevation, habitat type, aspect, and slope).

**Fire and Fuels Extension Emulator**

The size and format of our 40,000 record-database is not compatible with the import tool of FFE-FVS that requires separation of the tree level data from the plot level data. A stand-alone program provided by the FVS support group in Fort Collins, CO (FMFC 2002) was also considered for use, but single stand with a maximum 2,000 tree records would not work for our database containing 2,626 plots. Therefore, with permission (FMFC, personal communication), a standalone program was rewritten within the statistical package ‘R’ (R Development Core Team 2005) to directly interface with our database.

This code provides identical CBD values in comparison to the standalone FFE program. The allometric equations we use are identical to those used in the northern Idaho and Inland Empire variants of the FFE -FVS software (Brown 1978; Gholz and others 1979). Our revised program provides us with several important values that are not readily available from FFE. It provides a CBD value identical in method to FFE, an estimate for the method of Cruz and others (2003), and an estimate of the proposed FBA alternative.

**Statistical Analysis**

Model validation is often difficult because traditional statistics require that the null hypothesis be stated such that the two models are not significantly different (Welleck 2003). The ability to demonstrate similarity rather than difference based on probability arises by changing the null hypothesis from one of similarity to one stating that dissimilarity exists, and is called equivalence testing (Welleck 2003; Robinson and Froese 2004). Though the biomedical industry has long used equivalence tests to show that two samples are statistically similar, equivalence tests have not been widely applied to ecological modeling (Welleck 2003; Robinson and Froese 2004). Robinson and Froese (2004) use equivalence tests to validate model predictions of the diameter growth model contained within the Forest Vegetation Simulator.

This variety of statistical test requires that a region of indifference (ε), or a range of difference that is of negligible concern, be established (Robinson and Froese 2004). That is, a range of difference between sample metrics that is insignificant in practical application (Welleck 2003). After establishing a region of indifference, what is analogous to two separate trials of a one sided t-test on the difference between samples is carried out, one for differences greater than the test statistic, and one trial for differences less than the test statistic (Robinson and Froese 2004). This method is called a ‘two-one-sided t-test’ (TOST), and like a regular t-test, this test gains power as the sample size increases (Robinson and Froese 2004).

The null hypothesis of dissimilarity is rejected if the range of indifference overlaps into the rejection region for a one-tailed 95 percent confidence interval of the mean of the differences (x_a - x_b = x_{diff}) (Robinson and Froese...
Modification of VanWagner’s Canopy Fire Propagation Model (2004). The mathematics behind equivalence testing do not make p-values practical, so we use both a strict (small) and liberal (large) range of indifference to bracket our confidence in the hypothesis test (Wellek 2003).

These ranges of indifference bracket our confidence based not on probability, but on a judgment of how large the difference could be for the models to still be considered equivalent. In this paper, we choose a strict range of indifference such that \[ |\bar{X}_{\text{diff}} \pm \varepsilon| < 0.138 \text{ m.s}^{-1} (\pm 0.50 \text{ kph}) \] for cROS, while the liberal range of indifference was established such \[ |\bar{X}_{\text{diff}} \pm \varepsilon| < 0.278 \text{ m.s}^{-1} (\pm 1.0 \text{ kph}) \]. The values were chosen as being insignificant ranges of difference from both a management and a modeling standpoint. We use a one sided type I error rate of 5 percent (\(\alpha = .05\)), which translates to two times a one-sided \(\alpha (2 \times .05 = .10)\) for our TOST test of equivalence.

It is unusual for any two models to produce identical outputs so we attempt to use the available data to explain differences that may exist between these models. To explain these differences we fit a multiple linear regression model (MLR) to the output of the VWcbd (using FFE method) and VWfba. The VWcbd and VWfba models do not exhibit consistent differences between them; for example, VWfba does not always estimate lower than VWcbd. Therefore, we evaluate the ratio of the cROS estimates from the VWcbd and VWfba models (VWcbd:VWfba) as the response variable.

Within the ‘R’ statistical package (R Development Core Team 2005) a saturated MLR model with two-way interactions was fit to the response values to find a response transformation that provides the best model fit. Evaluation of residual plots, QQ-normal plots, and Boxcox plots indicate that the best response transformation is a square root transformation.

Each predictor was then removed one at a time and we use the extra sum of squares F-test (Ramsey and Schafer 2002) using the “drop1” function (R Development Core Team 2005) to determine which estimators are significant based on their residuals.

**Results and Discussion**

Our data do exhibit some kurtosis; however, our large sample size lends resistance to any departures from normality (Ramsey and Schafer 2002). To verify that outliers were not affecting the results, we removed obvious outliers and reran the TOST. In each comparison of models, removing the outliers made the minimum region of indifference smaller. Hence, the null hypothesis was more clearly rejected with the outliers removed in each comparison, and we present our results with all data represented.

The mean of the differences between cROS for FIA plots using VWcbd-FFE and VWfba is only 0.010 ms\(^{-1}\) (table 2). Despite a comparatively large standard deviation the null hypothesis of dissimilarity is rejected. The sum of the minimum range of indifference and the mean of the difference (0.010 \(\pm\) 0.027 ms\(^{-1}\)) is substantially less than the conservative range of indifference lending strong evidence (in lieu of a p-value) that the rejection of the null hypothesis is justified (table 2).

These same patterns are repeated for the comparison of VWcbd-Cruz and VWcbd-FFE, though the mean of the difference is larger than the previous comparison (0.050 ms\(^{-1}\)) (table 2). Again, the sum of the difference and the minimum range of indifference (0.050 \(\pm\) 0.066 ms\(^{-1}\)) are well within the pre-defined conservative range of indifference leading to a comfortable rejection of the null hypothesis. In the final comparison between VWcbd-Cruz and
VWfba, the mean of differences is larger than any of the previous comparisons (0.060 ms$^{-1}$) (table 2). The sum of this large bias between the models and corresponding large minimum region of indifference (0.060 ± 0.086 ms$^{-1}$) does not allow a rejection of the null hypothesis of dissimilarity under the conservative scenario, though it is still rejected at the liberal range. In all but one of these comparisons we reject the null hypothesis of dissimilarity.

The VWfba provides the slowest estimate of cROS between these three methods. These differences 0.010 ms$^{-1}$ and 0.060 ms$^{-1}$ are interpreted to mean that on average the VWfba model estimates the cROS necessary to sustain canopy fire to be less than the cROS predicted by the VWcbd-FFE and VWcbd-Cruz, respectively. This result is likely due the VWfba utilization of all available fuel and not some fraction of the available fuel, which means that the cROS does not need to be as high as the case where less fuel is available.

The small (0.010 ms$^{-1}$) difference between the VWcbd-FFE and VWfba method is surprising considering the drastically different methods of fuel estimation used in these models. Therefore, we attempt to explain only the differences between VWcbd-FFE and VWfba models using MLR. The total variance ($R^2$) explained by the saturated MLR is 57.8 percent (294 and 2331 degrees of freedom). Only the diameter at breast height of the tree of average basal area (dbh.bar) is a significant individual predictor. Nine other variables, all interactions, are found to be significant using the extra sum of squares F-test (table 3).

Colinearity of variables limits our ability to identify the contributed explanatory power of each significant variable. Instead, we fit many regressions using each individual variable, or constituent variables (in the case of interactions), to quantify the remaining variance not explained by the predictor(s). For each variable, table 3 lists the root mean square error (RMSE) of a model that incorporates only that variable (and its constituents). The RMSE of the response variable predicted using a mean parameter was fit for comparison. An individual variable associated with a low RMSE in table 3 is a stronger explanatory variable than a variable with a larger RMSE.

The interaction between total basal area (BA.sum) and total trees per acre (TPA.sum) has the lowest marginal RMSE, but this MLR model would have had two more parameters. While this interaction can be biologically explained, it is not easily interpreted. In contrast, the dbh of a tree with average basal area (dbh.bar) is directly related to the total basal area of a stand, which is highly influenced by the total number of trees in a stand (tpa.sum). The high explanatory power of this single variable is useful to know but provides no further insight to the differences between these models.

### Table 2—Results of the equivalence test for FIA data.

<table>
<thead>
<tr>
<th>Models compared</th>
<th>Mean of difference (ms$^{-1}$)</th>
<th>SD of difference (ms$^{-1}$)</th>
<th>H$_0$: dissimilarity</th>
<th>Minimum range of indifference (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_{d}$ - $x_{b}$</td>
<td>$x_{diff}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFE - FBA</td>
<td>0.010</td>
<td>0.499</td>
<td>Reject</td>
<td>± 0.027</td>
</tr>
<tr>
<td>Cruz - FFE</td>
<td>0.050</td>
<td>0.486</td>
<td>Reject</td>
<td>± 0.066</td>
</tr>
<tr>
<td>Cruz - FBA</td>
<td>0.060</td>
<td>0.814</td>
<td>Accept</td>
<td>± 0.086</td>
</tr>
</tbody>
</table>
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The VWcbd and VWfba estimates for the regional FIA data (n=2676) are equivalent to one another well within acceptable ranges of indifference established for these tests. We demonstrate that VWfba is equivalent to VWcbd in the Inland Northwest when the sampling design of FIA is followed and the data used to describe a 0.40 ha (1 acre) stand. Rejection of the null hypothesis of dissimilarity suggests that either model can provide reasonable cROS estimates in this case study. Based on our analysis of comprehensive FIA data, we conclude that the use of VWfba is a reasonable alternative to VWcbd, in particular when compared to VWcbd-ffe. Unfortunately, MLR analysis of our data does little to explain the observed insignificant differences between the VWcbd-ffe and VWfba.

Some of the failure to quantify the accuracy of the VWcbd model may be attributed to the difficulty in measuring, evaluating, or estimating the canopy fuels (Keane and others 2005). Reinhardt and Scott (2005) report nearly 1000 person-hours required to physically measure several canopy biomass variables (including their vertical distribution) to calculate canopy fuel CBD for a single 10 m radius plot. This inability to physically measure the volume space used in CBD calculations has made it difficult to assess the utility of the model as put forth by Van Wagner (1977) (Keane and others 2005).

Table 3—Saturated multiple linear regression (MLR) model and significant predictors found using the extra sum of squares F-test.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Df</th>
<th>Marginal RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total RMSE: 0.214</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BA.sum:elevation *</td>
<td>1</td>
<td>.208</td>
</tr>
<tr>
<td>sdi:elevation *</td>
<td>1</td>
<td>.210</td>
</tr>
<tr>
<td>foliage.sum:slope *</td>
<td>1</td>
<td>.211</td>
</tr>
<tr>
<td>dbh.bar *</td>
<td>1</td>
<td>.174</td>
</tr>
<tr>
<td>foliage.sum:BA.sum *</td>
<td>1</td>
<td>.212</td>
</tr>
<tr>
<td>foliage.sum:sdi *</td>
<td>1</td>
<td>.206</td>
</tr>
<tr>
<td>foliage.sum:HAB *</td>
<td>29</td>
<td>.191</td>
</tr>
<tr>
<td>BA.sum:TPA.sum *</td>
<td>1</td>
<td>.167</td>
</tr>
<tr>
<td>BA.sum:sdi *</td>
<td>1</td>
<td>.172</td>
</tr>
<tr>
<td>TPA.sum:sdi *</td>
<td>1</td>
<td>.174</td>
</tr>
</tbody>
</table>

Note: Total RMSE represents the RMSE of an intercept parameter fit to the response variable only; it is the root mean square error left after accounting for only the mean.
In contrast, VWfba is directly correlated to the foliar biomass within a stand and does not vary based on estimated canopy volume. The accuracy of allometric equations and the increasing use and accuracy of remote sensors that can be used to estimate foliar biomass in a stand make FBA more easily measured in the field in front of potential canopy fires. This measurability will make nonexperimental field evaluation of the VWfba model a more practical endeavor.

Like CBD estimates, FBA is limited by the accuracy of the technologies used to estimate foliar biomass (total available fuel). However, CBD methods have the added difficulty of measuring the necessary volume. The ability to field test, calibrate, refine, or even observe the efficacy of the VWcbd estimates has been limited mostly because of the complex, more difficult measurement of the CBD input. The principle of parsimony (Ford 2000) might be applied in this situation leading to the adoption of VWfba as a canopy fire model because it utilizes a simpler canopy fuel input. This makes the VWfba model simpler than the existing VWcbd model while providing a statistically significant equivalent estimate when compared to the current model.

Conclusions

The adoption of VWfba may allow for consistent fuel quantifications that are less influenced than CBD, by the highly varied canopy structure of forested stands. This consistency provides a benchmark by which to adjust Van Wagner’s (1977) modified model, VWfba, for further improvement and refinement. We assert that the VWfba recalibration of Van Wagner’s model provides statistically equivalent estimates and is consistent with the original field observations of Van Wagner.

The VWfba model proposed here only quantifies the fuel conditions necessary to sustain canopy fire between two points on the landscape with the intention of matching the performance of the original Van Wagner model. This model does not require knowledge about the vertical distribution of fuel, only that enough fuel exists between two points to sustain canopy fire. Future work with the VWfba model may require a coefficient to describe vertical distribution or a number of other parameters, but these coefficients will be independent of the combustible biomass estimate. This approach leads to a more subtle refinement of the model output independent of the quantity of fuel that is truly available to the advancing canopy fire.

The VWfba model should be applied to a variety of case studies where estimates of foliar biomass can be obtained for observed canopy fires. An example of this sort of validation could be the acquisition of LANDSAT imagery over an area subsequent to a canopy fire. Using estimates of foliar biomass derived from leaf area index (LAI) and specific leaf area (SLA), the resulting VWfba prediction could be compared to fire behavior observations from that fire. This type of field validation removes the necessity of estimating the probable fire spread direction and then placing fuel sampling personnel directly in the path of impending canopy fires, allowing the required fire observations to be conducted from a safe distance. Given the lack of literature suggesting that the use of VWcbd adequately provides estimates of the cROS threshold we would not necessarily expect the VWfba model to accurately estimate cROS in these field trials, but we would expect it to perform as well as the VWcbd model, if reliable CBD data could be collected for comparison.
Ultimately, acceptance of the VWfba model may lead to the development of a canopy fire behavior model that can be related simply to LAI. This would remove the necessity of knowing the tree species necessary to assign a SLA value. This refinement would provide a practical method to take remotely sensed imagery and convert it directly to a relevant canopy fuel characteristic involving one less step than the VWfba model proposed here.

References


