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Estimating Ladder Fuel Contributions to Crown Fire Initiation

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Introduction

Crown fires in boreal and sub-boreal conifer forests represent a significant safety hazard for fire managers and nearby communities. Crown fires typically involve high rates of spread and energy release, and have been associated with catastrophic community losses.

For predicting the onset of crowning, Van Wagner (1977) described a model (VW77) that remains in wide use today, based on empirical data and physical convection theory. His model was based on the surface fire intensity needed for flames to bridge the gap between surface fuels and the base of a continuous canopy layer, the live canopy base height (LCBH). Small-diameter fuel elements that occupy an intermediate position between the surface and canopy fuels are termed ladder fuels (LF); they are believed to be disproportionately important in facilitating crown fire initiation, but the effect has been difficult to quantify.

Here we show how the VW77 model can be rearranged to present a solution for estimating the effects of ladder fuels in crown fire occurrence, a simple but nuanced solution to a longstanding problem.

Rearranging the VW77 model

The VW77 model was originally formulated to solve for critical surface intensity (I_0) in a single-storied conifer stand, as follows:

$$I_0 = (chz)^{1.5}$$

[1], where h is heat of ignition, z is live crown base height (LCBH), and c is an empirical constant. This model has been implemented in full or in part in several popular modelling systems, notably in Canada (Forestry Canada Fire Danger Group (FCFDG) 1992) and the USA (Scott and Reinhardt 2001).

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The structure of the VW77 model permits a vertical rescaling that relies on an implied proportionality between surface fuel consumption (SFC) and *z* (LCBH). When we replace I_0 (eq. 1) with Byram's (1959) fireline intensity, as noted above, we get the following well-known equation:

$$H \cdot SFC \cdot ROS = (ch)^{1.5} z^{1.5}$$

[2], where H is the heat of combustion, SFC is surface fuel consumption, and ROS is rate of forward spread.

This relationship has often been evaluated in terms of identifying critical ROS for crown fire initiation (e.g. FCFDG 1992). However, we will presently solve eq. 2 for a critical SFC (SFC_0), assuming surface fire conditions near the crown fire initiation threshold:

$$SFC_0 = \frac{(ch)^{1.5} z^{1.5}}{h \cdot ROS}$$

[3]. This relationship places the emphasis on the mass of available surface fuel as the fire intensity engine that drives crowning.

Algebraically, it is apparent that SFC_0 can also be compared between LCBH levels. If we consider z_1 and z_2 to be different vertical distances between surface and canopy fuels, then the following ratio is evident:

$$\frac{SFC_2}{SFC_1} = \frac{\left[\frac{(ch)^{1.5} z_2^{1.5}}{h \cdot ROS}\right]}{\left[\frac{(ch)^{1.5} z_1^{1.5}}{h \cdot ROS}\right]}$$

[4], where SFC_1 and SFC_2 represent critical SFC values at the two *z* levels. This also assumes no change in surface ROS or *h* when varying LCBH, a reasonable assumption in closed conifer stands. Finally, holding terms constant, we can simplify this to yield a basic general relationship between SFC and LCBH (*z*):

$$SFC_2 = \left(\frac{z_2}{z_1}\right)^{1.5} \cdot SFC_1$$

[5].

This equation can be used as a transformation function for comparing the influence of fuel elements at different heights.

A practical example helps illustrate the logic of comparing SFC_0 at two different z values (eq. 5). Using Van Wagner's empirical heat of ignition function (Van Wagner 1977), at 90% foliar moisture content (FMC) and LCBH=2 m, eq. 1 suggests I_0 of about 417 kW/m, the intensity of a low to moderate intensity surface fire. At some moderate surface ROS value, e.g. 2 m min^{-1}, eq. 3 predicts SFC_0 of 0.695 kg m^{-2}. If LCBH were increased from 2 to 5 m, SFC_0 would then increase (eq. 5) to 2.75 kg m^{-2}. Thus, a 2.5

times increase in LCBH results in a nearly fourfold increase ($(5/2)^{1.5} = 3.95$) in the critical SFC for crowning.

For fuel elements affecting crown fire initiation, it is important to recognize that the key property is the vertical distance between a burning fuel element and the LCBH, not necessarily the height above ground. To avoid confusion, we restate eq. 5 in terms of ladder fuel structure measures. We define consumption of a LF layer as FC_L and the centroid height of a ladder fuel layer or element as C_L (e.g., the midpoint of small diameter branchwood in a dead sapling layer beneath a conifer canopy; Figure 1). The surface-equivalent ladder fuel consumption value (FC_{SE}) can then be calculated and added to actual SFC. In this case, z remains the LCBH and ($z - C_L$) represents the fuel strata gap (Cruz et al. 2004; Perrakis et al. 2023) between ladder fuel elements and the LCBH:

$$FC_{SE} = \left(\frac{z}{z - C_L}\right)^{1.5} \cdot FC_L \ , \qquad z > C_L$$

[6]. This equation finally permits the estimation of the LF influence in the right scale for comparison with expected SFC to predict crown fire.

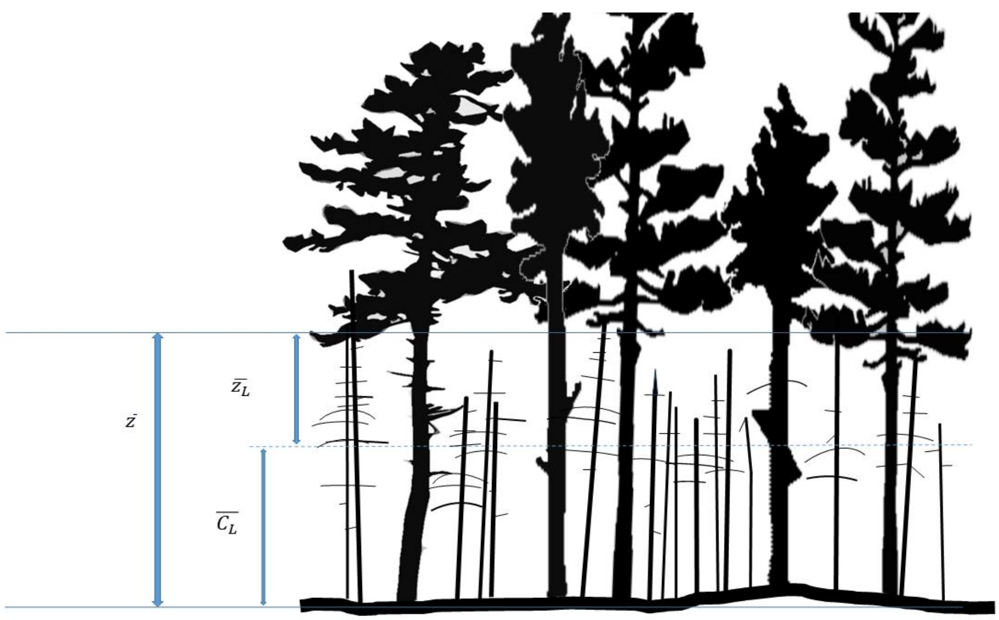

Figure 1. Simple conifer forests Diagram (not to scale) showing approximate estimation of live crown base height (z), dead ladder fuel centroid (C_L), and fuel strata gap (z_L) in a simple single-story stand, such as a developing jack pine stand.

Challenges and limitations

While logically consistent, at least three limitations are immediately apparent with eq. 6. First, the theoretical relationship between fuel elements does not account for the obvious structural differences between the surface and crown fuel complexes. Surface fuelbeds are much more compact (higher bulk density and packing ratio) than crown fuel complexes, with a much more aeration-limited combustion environment (Rothermel 1972; Schwilk 2015). The FBP System approach to SFC, where all consumed surface and ground fuels are assumed to contribute to I_0 (Van Wagner 1977; FCFDG 1992), likely overemphasizes coarse fuels (duff and coarse woody debris) that burn in post-frontal combustion, ignoring the notion of flame front residence time (Nelson and Adkins 1988; Wotton et al. 2012). In contrast, fine textured canopy and LF strata are likely to be consumed completely in the flame front. Thus, scaling FC_L to generate FC_{SE} may be insufficient to reconcile the scales of these consumption classes. This difference is not addressed here and will have to be reconciled via theoretical or empirical means.

Second, while eq. 6 specifies that the LF height cannot exceed the LCBH, it is apparent that as the difference between them $(z - C_L)$ diminishes, FC_{SE} can grow to extreme levels, eventually producing a division by zero problem at $z = C_L$. Consider, for example, FC_L = 0.1 kg m^{-2} , 1 m below a 5 m tall canopy base (z = 5; $z - C_L$ = 1); eq. 6 scales this to FC_{SE} of 1.12 kg m^{-2}. But if C_L is raised closer to z (e.g., $z - C_L$ = 0.2 m), the same FC_L generates FC_{SE} = 12.5 kg m^{-2}. This is logically consistent – burning fuels are much more likely to ignite canopy fuels if they are located immediately beneath the canopy base, and a 0.2 m gap is almost negligible at the tree or stand scale. However, this suggests that caution is needed with eq. 6 to avoid inflating the LF effect to nonsensical levels.

Finally, there is the challenge of characterizing LF in three-dimensional space in terms of one or more discrete layers comparable to surface fuel loading. Although the example here (fig. 1) considered a dead sapling cohort as a single LF layer continuous with the ground, that assumption fails for discontinuous LF elements such as bark flakes or arboreal lichens. Estimating total LF effects precisely may demand techniques such laser scanning methods (e.g., Qi et al. 2022) and summing the contributions of individual vertical tranches of combustible fuel (e.g. Alexander et al. 2004).

Conclusion

In sum, a simple theoretical model for calculating LF influence in crown fire initiation was identified and described based on the well-known VW77 model. Where LF consumption and position can be reasonably estimated, the new equation provides a solution for scaled consumption values that can be added to actual SFC. This will be useful for quantifying the effects of proposed hazard reduction treatments as well as for overall fire behaviour prediction in conifer stands.

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