Supplementary Document S1

Detailed fuel model descriptions

In order to more fully understand the impact of forest thinning in black spruce on wildfire behaviour, it is imperative that the simulation of the boreal spruce fuel bed is correct and realistic both in terms of its physical structure, but also incorporating the specific ecology of boreal spruce ecosites. While boreal spruce occupies a large range of climatic and soil drainage conditions, in the high-frequency wildfire regime of the boreal forest of western North America, black spruce often occupies more poorly-drained ecosites. As a result of this slow growth in wet areas, boreal black spruce stands contain attributes such as abundant arboreal lichens and vegetative regrowth through "layering" that promotes specific stand structural characteristics that differentiate it from non-boreal and drier conifer forests. In this study, we detail the unique ecological properties of black spruce stands (and the thinning practices therein) and propose a series of best practices for incorporating black spruce stands into physics-based fire behaviour models such as FIRETEC.

* 1. Stem Mapping

Stems with a height greater than 1.4 m are mapped using the BETA algorithm (Kettridge et al., 2013), where seed trees are randomly placed on the landscape, and subsequent trees are placed at a distance (minimum of 0.2 m) from the seed tree based on a folded normal distribution until the desired stem density is reached. The goal of this non-random placement is to simulate the observed patterning in boreal black spruce stands, where dominant trees reproduce by layering. We determined an approximate stem density of 9400 trees per ha using Alberta Wildfire Fuel Inventory Program (AWFIP) data for one of the Red Earth Creek AB sampling sites, which includes only trees taller than 1.4 m. Seedlings are modeled as homogeneous surface fuel and are discussed further in section A.8.

* 1. Diameter at breast height

Unlike the original formulation of the BETA model, here we instead assign a log-normal distribution of diameter at breast height (DBH, breast height is 1.4 m) rather than top height (H) when placing trees in the domain. DBH is assigned independently from stem location. Standard deviation and mean for the log normal distributions are 4.16 cm and 5.42 cm respectively. Observed large tree (DBH > 9 cm) and small tree (DBH<9cm) data are separate in the AWFIP database; although we use only one model for the height and DBH of all trees greater than 1.4 m.

* 1. Height

Tree heights, H, are modeled from DBH based on relationships found in the AWFIP data,

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| --- | --- | --- |
|  |  | (1) |

In Equation 1, the units for H, DBH and SE (standard error) are m, cm and m respectively. The model standard error (1.4 m in the case of black spruce) is added as a normally distributed error with mean of 0. Generated trees with heights greater than 13 m (larger than found in most Alberta lowland black spruce stands) and less than 1.4 m are excluded from height modelling and removed from the domain.

* 1. Live crown base height

Live crown base height, LCBH (unit m), is calculated using a generalized linear model based upon data from AWFIP:

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|  |  | (2) |

where the SE is added from a normal distribution with a mean=0 and a standard deviation of 1 m and is the mean height of the stand. LCBH is limited to a maximum of 80% of tree height, however, for the sparse fuels, it is assigned a value of 0.

* 1. Crown width

Crown width (CW, unit m) is modeled using the same data and demarcation of DBH and LCBH (large tree data is from Alberta Fuel Inventory data), with slightly different model inputs:

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|  |  | (3) |

Here is the height percentile for the tree and the standard deviation used in the SE assignment is 0.31 m.

* 1. Fuel loading

Canopy fuel load for the purpose of FIRETEC simulations only includes thermally thin fuels that are consumed in the flaming front. We follow the 1 cm threshold used by other studies (Alexander et al., 2004). In lowland black spruce trees, fuels loads are calculated for branch wood, foliage, and arboreal lichens separately using the equations from Johnston et al. (2015). Live and dead branch wood are lumped together in this fuels model. Since the fuel load models for black spruce from Johnston et al. (2015) are based on basal diameter (BD); stem diameter at the soil surface) rather than, we applied the stem taper equations from Kozak (1988) to adjust diameters at 1.4 mdown to 0 m, as seen in Equation 4,

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|  |  | (4) |

From these basal diameters the fuel load is calculated for branch wood (BR), foliage (FOL) and lichen (LICH) as follows:

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|  |  | (5) |
|  |  | (6) |

and

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|  |  | (7) |

In Equation 5, Johnston et al. (2015) includes branch wood up to 2.99 cm in diameter. Fuels greater than 1 cm cannot be considered thermally thin; therefore, the branch wood fuel loading is multiplied by 0.6 to account for the fraction of thermally thin branch wood. This fraction was calculated from the International Crown Fire Modelling Experiment (ICFME; Alexander et al., 2004, Stocks et al., 2004) black spruce crown fuel weight regression equations.

* 1. Canopy density, moisture content, and surface area to volume ratio

Canopy volumes are computed from crown width and crown length. The shape of the canopy is assumed to be a paraboloid and is formulated using the parabolic profile approximation from the TREES program built into FIRETEC (Linn et al., 2005). Canopy fuel density (units of kg m-3) within the crown is calculated for each tree, and the median value for the entire stand is used across the domain; this equates to approximately 1.76 kg m-3. Moisture content of canopy fuels is based on the mass-weighted average from three distinct contributing fuels: branch wood, foliage, and lichen. Branch wood is assumed to have a constant moisture content of 120% (gravimetric), while foliar moisture is fixed to 86%. Foliar moisture content applied here is a compromise between Red Earth Creek measurements of 82% (Hvenegaard et al., 2016) and the Canadian Forest Fire Behavior Prediction System (FBP) field guide value fixed at 97% (Taylor et al., 1997). Arboreal lichens are assumed to be in equilibrium with the atmosphere, with a moisture content (EMC) described by Equation 8 (Van Wagner, 1987),

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|  |  | (8) |

In the above equation, FFMC is the fine fuel moisture code from the Canadian Forest Fire Weather Index system (Van Wagner, 1987) which is directly related to the moisture content in the fine surface fuels. The overall large tree moisture content is a mass weighted average of the three fuels described above; for an FFMC value of 92, moisture content in the canopy is 89.1%, and for FFMC value of 87, moisture content of the canopy is 89.9%. FFMC 92 and 87 correspond to fine fuel moisture content of 9% and 14% respectively.

The surface area to volume ratio is required in FIRETEC simulations (via a size scale, SS) and is calculated using a weighted geometric mean across the canopy, with ratios of 12.5:1 cm2 cm-3 for branch wood (assuming a simple cylinder 5 mm in diameter), 55:1 cm2 cm-3 for spruce foliage, and 635:1 cm2 cm-3 for lichen (Brown, 1970). The surface area to volume ratio is shown in Equation 9, and the size scale is shown in Equation 10:

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|  |  | (9) |

and

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| --- | --- | --- |
|  |  | (10) |

In Equation 9**,** the surface area to volume ratio is converted to m2 m-3, and the subscript indicates percent of total mass; the sum of the denominator in Equation 9 is 100%. The final size scale, SS in Equation 10 is 0.00047 m for unburned fuels, and 0.0016 m for burned fuels in the first 80 m of the domain (assuming no lichen and foliage is available to burn).

* 1. Surface fuels

For the purposes of FIRETEC simulations, surface fuels are inclusive of: (1) seedlings, trees with top heights < 1.4m; (2) shrubs; (3) litter; (4) mulch, included in mulch strips only; (5) fine woody debris and (6) the portion of any large tree canopy that falls within the bottom grid cell, or 1.5 m height. Seedlings are added homogeneously across all non-mulched and non-burned areas with a density of 0.06 kg m-3 with a depth of 1.2 m. Similarly, shrub average density is 0.3 kg m-3 with a depth of 0.4 m and shrubs are distributed in the same way as seedlings. A litter layer with average density of 11.7 kg m-3 and a depth of 0.029 m alongside a fine woody debris average density is 3.0 kg m-3 over a depth of 0.02 m were added to the lowest grid cell; both litter and fine woody debris are distributed everywhere in the domain evenly. Mulch, as discussed previously, is located only in corridors and contributes a fuel density of 120 kg m-3over a depth of up to 0.003 m. The depth of mulch was limited to 0.003 m, based on the observed mulch depth of burn in the flaming phase in laboratory tests from (Thompson et al., 2016). Mulch depths vary depending on the amount of biomass available in trees that fall within the mulched corridors. Maximum burn depth is limited to

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|  |  | (11) |

Where PD is the potential depth, is the burn rate, is the duration of flaming front and is the density of mulch. FFMC of 87 and 95 result in burn rates of 0.250 kg m-2 min-1 and 0.345 kg m-2 min-1 respectively (Thompson et al, 2016) and Equation 11 is based on the assumption that the flaming front will have a residence time of 1.5 min. For this study, we assume a burn rate of 0.345 kg m-2 min-1 for the FFMC 92 scenario.

Moisture content of seedlings and shrubs is prescribed as the same moisture content assigned to larger trees, and mulch, litter and fine woody debris moisture contents are related to the FFMC via the EMC (Equation 8). Final moisture content in each cell is determined using a mass weighting average.

The size scale applied to surface fuels is a geometric mean of all size scales for each individual component calculated in the same way as shown in Equations 9and 10. The individual surface area to volume ratios for surface fuels are as follows: litter is 55.0 cm2 cm-3, fine woody debris size class 2 is 5.3 cm2 cm-3, fine woody debris size class 1 is 13.3 cm2 cm-3, seedlings (the same as canopy) is 42.2 cm2 cm-3, shrubs (a combination of foliage and branchwood) is 27.2 cm2 cm-3 and mulch is 10.3 cm2 cm-3. This results in surface fuel size scales of 0.00042 m for fuels under the canopy and 0.0074 min the mulch.

* 1. Total fuel load

Total Fuel load for the control simulation is shown in Figure 1. Treatment fuel loads are not shown here.

Figure 1 Total fuel load for black spruce control simulations.



* 1. References

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