An R Function for Calculating the Canopy Bulk Density of Boreal Forest Fuels

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Abstract
Projects designed to reduce the probability of initiation and spread of crown fire are dependent on estimations of the height of the base of the canopy layer and the amount of fuel in the forest canopy per unit of volume (canopy bulk density). Treating the canopy volume as a "box" is straightforward to calculate but leads to biased estimates of where the bottom of the canopy lies and does not account for canopy layers that have more or less fuel mass. Here, an R script is presented that estimates canopy bulk density for 1-m vertical "slices" from the forest floor to the top of the tallest tree. The method uses allometric biomass equations from the International Crown Fire Modelling Experiment.

1 Background

Forest thinning treatments for hazard fuel reduction are often designed to inhibit the spread of fire from one tree crown to another. Modelling crown fire behavior typically requires estimates of canopy base height and canopy bulk density[1]. Modelling may be necessary to demonstrate a threshold reduction in canopy fuels, to validate hazard fuel thinning treatments that have been impacted by fire, or to associate observed fire behavior with

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[1]The term "canopy" refers to a collection of individual tree "crowns".

canopy attributes. Crown fire initiation is thought to depend on the vertical propagation of a surface fire into the canopy and is inhibited by distance between the forest floor and the bottom of the canopy layer [5]. Crown fire spread is depends on the horizontal continuity of canopy fuels but the specific relationships between canopy bulk density and stem or crown spacing are uncertain. Forest thinning objectives therefore usually specify thresholds in vertical (canopy base height) and horizontal (canopy bulk density) dimensions.

Estimating canopy base height and canopy bulk density has been accomplished in several ways [4, 2, 3]. The simplest way is the "box" method illustrated in Figure 1 in which the canopy fuel load ($\mathrm{kg\,m^{-2}}$) is divided by the length of the canopy (m). The top and bottom of the canopy are not well defined but if the distance between the average canopy base height and the average tree height is used, then the area under the curve is the same as the interval canopy bulk density yielded by the R function presented here. The box method comes with several assumptions. It is not particularly sensitive to the actual vertical distribution of fuel (i.e., trees do not look like boxes). More fuel is placed at the top and bottom of the canopy than are actually there and the thickest part of the canopy is under-represented. The canopy base height is determined by the observer rather than an estimate of the bulk density at a given height. For example, in Figure 1, the base of the canopy is at about 2 m using the box method. If the canopy base height were defined as the height where bulk density becomes greater than 0.1 $\mathrm{kg\,m^{-3}}$, it would be approximately 4.5 m above the ground.

More satisfying results are obtained through the more complex interval canopy bulk density method, e.g. the method described by Alexander et al. [1] used to characterize the fuelbed at the International Crownfire Modelling Experiment (ICFME). The method yields a bulk density estimate for one meter vertical "slices" of the canopy from the forest floor to the top if the stand as in Figure 1.

2 Function Overview

The function presented here uses the ICFME allometric equations for crown fuel weight but differs in the way that the crown weight is vertically distributed across individual tree crowns. A "slice" here refers to everything you would encounter slicing across the plot between e.g., 8 and 9 meters above the ground shown in Figure 2. Broadly the parts of the function are:

1. Estimating individual tree crown fuel weights from allometric biomass equations (8.8 kg for the first tree illustrated in Figure 2).
2. Dividing each tree crown fuel weight by the number of slices that contain fuel or the part of the tree between the crown base and the top of the tree. In the example, each slice of the tree crown is assigned 1/4 of the crown weight or 2.2 kg of fuel.
3. Summing the crown fuel weights (e.g., 9 trees) across each slice and dividing by the plot area. In the example, the crown fuel weight in the slice 9 meters above the ground (19.2 kg) is divided by the area of the plot to yield 0.24 $\mathrm{kg\,m^{-3}}$.

3 Inputs

The function requires a data frame similar to Table 2 with these fields:

- **diam_type**. Whether the diameter was measured at the base of the tree or at breast height. Boolean. True or 1 is breast height. False or 0 is base height.
- **diam**. Tree diameter in centimeters. Numeric.
- **cbh**. Crown base height in meters. Numeric.
- **ht**. Tree height in meters. Numeric.

The fields in the data frame must be in lower case and match exactly, e.g., df$plot, df$live. See the R documentation for the definition of a data frame. It is assumed here that dead trees (snags) contribute no fuel mass to the flame front. They should be excluded from the input tree list. While it is possible to estimate canopy fuels for recently dead trees there is no science (as of yet) to quantify it. Likewise, hardwood trees (birch, aspen, cottonwood) do not contribute to crown fire and should be excluded as well.

4 Crown Weights

Crown weights for each tree are estimated from allometric equations based on diameter using Equation 1 and the coefficients in Table 1.

$$W = aD^b \tag{1}$$

where W (kg) is crown fuel weight, D is diameter at either breast or basal height, and a and b are coefficients from Alexander et al. [1]. Crown fuel is the weight of all material <5 mm in a single tree crown. Estimates are made for several classes of crown fuel: needles, live roundwood <5 mm, and dead roundwood <5 mm. There are coefficients for fuels with diameter >5 mm but they are not used in the function. Separate equations are used for trees with a diameter at breast height (1.4 m) and shorter trees with basal diameters (Table 1).

The ICFME canopy bulk density method for vertically proportioning the crown fuel weights is not used. Instead, measurements of crown base height and tree height are used to represent the vertical length of the bole occupied by fuel. For example, for a tree 10.3 m tall with a crown base height of 3.4 m, slices 3 through 11 are considered to contain fuel. This process is illustrated in figure 2 which shows the slices of the 16 trees in Table 2 that contain fuel. The first tree contains fuel in slices 9-12. The 16th tree contains fuel in slices 4-6.

The crown weight of live foliage, live roundwood, and dead roundwood estimated for each tree is proportioned across the vertical slices that are determined to hold fuel. For the example, slice 9 has 9 trees that include fuel. The slices are then summed across the plot (19.2 kg in the example) and divided by the plot area to yield a bulk density estimate ($\mathrm{kg\,m^{-3}}$) for each slice above the ground (0.24 $\mathrm{kg\,m^{-3}}$ in the example).

5 Coefficients

6 Example Input Data

7 Output

Table 3 shows the function output of canopy bulk density for spruce components <5 mm diameter for the example tree inputs shown in Table 2. The outputs could be used directly although some authors use a moving average of the slices, making the plot-level canopy bulk density somewhat less than than that of the maximum slice. Note that the canopy bulk density output in units of $\mathrm{kg\,m^{-3}}$ is also a canopy fuel load in units $\mathrm{kg\,m^{-2}}$ since each slice of the output from the function is one meter.

Table 1: Crown fuel weight coefficients from the ICFME [1].

Fuel Class	a	b
Trees <1.4 m in height		
Needles	0.233	1.25
Live roundwood <0.5 cm	0.133	1.12
Live roundwood 0.5-1.0 cm	0.0500	1.30
Dead roundwood <0.5 cm	0.0555	1.12
Dead roundwood 0.5-1.0 cm	0.000167	3.81
Trees <1.4 m in height		
Needles	0.0153	2.36
Live roundwood <0.5 cm	0.0120	2.09
Live roundwood 0.5-1.0 cm	0.00673	1.96
Dead roundwood <0.5 cm	0.00588	1.99
Dead roundwood 0.5-1.0 cm	0.000000439	5.67

Table 2: Example dataset of 16 spruce trees from a plot with area 81.7 m^2. Note several trees with a basal diameter (the "diam_type" field is marked "0"). The R script requires all the variables shown here except species which is assumed to be either black or white spruce.

species	diam	ht	cbh	diam_type
PIMA	12.7	11.9	8.0	1
PIMA	14.1	8.2	4.3	1
PIMA	17.4	14.7	7.0	1
PIMA	11.7	9.8	5.9	1
PIMA	7.8	7.8	5.6	1
PIMA	8.3	8.6	4.9	1
PIMA	4.3	4.4	2.3	1
PIMA	4.6	5.6	1.8	1
PIMA	7.1	7.5	5.6	1
PIMA	11.6	11.6	8.5	1
PIMA	23.2	15.0	4.8	1
PIMA	15.7	10.9	5.7	1
PIMA	12.8	8.7	5.0	1
PIMA	10.1	9.6	6.4	1
PIMA	19.6	12.8	5.6	1
PIMA	10.5	6.9	3.8	1

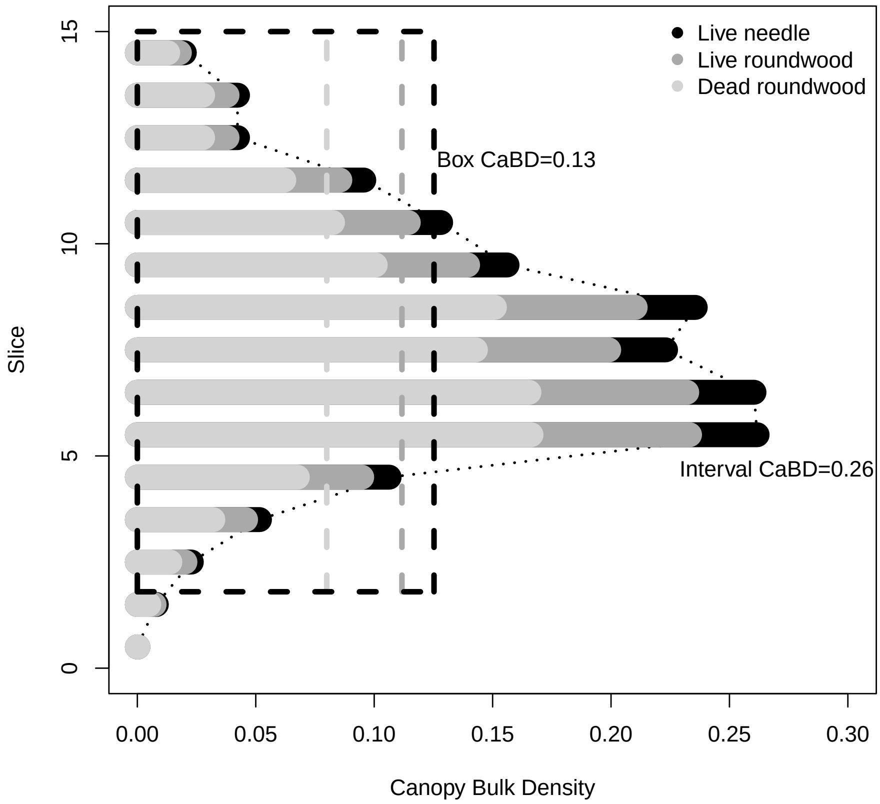

Figure 1: Two methods of estimating canopy bulk density. The horizontal bars represent the "interval" method of estimating canopy bulk density in which a separate value is calculated for each "slice" of the canopy, here slices 0 to 15 meters above the forest floor. The "box" method is shown with the square dashed lines. The box method simply takes the canopy fuel load and divides it by the length of the canopy.

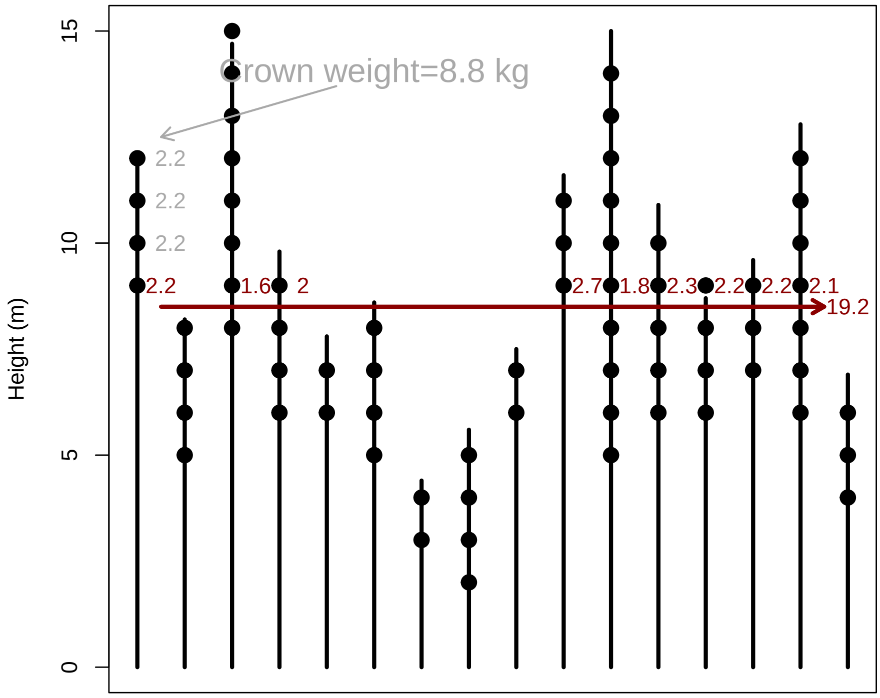

Figure 2: The example trees showing the slices that contain fuel (black dots). Shown in gray is the crown fuel weight for the first tree, 8.8 kg. This crown weight is divided across four slices of 2.2 kg each. There are nine trees with weight in slice nine and their sum is 19.2 kg. This weight, divided by the plot area yields a canopy bulk density of 0.24 $\mathrm{kg\,m^{-3}}$ for slice nine.

Table 3: Example of function output. "slice" is in meters. The slice "0.5" represents 0-1 m in stand height. "cabd" variables are in $\mathrm{kg\,m^{-3}}$.

slice	cabd_live_needle	cabd_live_round	cabd_dead_round
0.5	0.0000	0.0000	0.0000
1.5	0.0048	0.0022	0.0009
2.5	0.0137	0.0064	0.0027
3.5	0.0319	0.0138	0.0059
4.5	0.0675	0.0272	0.0116
5.5	0.1662	0.0669	0.0285
6.5	0.1654	0.0666	0.0284
7.5	0.1428	0.0563	0.0240
8.5	0.1508	0.0594	0.0254
9.5	0.1004	0.0390	0.0167
10.5	0.0824	0.0320	0.0137
11.5	0.0618	0.0237	0.0101
12.5	0.0275	0.0103	0.0044
13.5	0.0275	0.0103	0.0044
14.5	0.0128	0.0049	0.0021

8 Alternative Allometric Equations for Black and White Spruce

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- Sando RW, Wick CH (1972) A method of evaluating crown fuels in forest stands. U.S. Forest Service, North Central Forest Experiment Station, Research Paper NC-84. (St. Paul, MN, USA).
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9 R Script

The R script is printed below and available at GitHub: https://github.com/taigafire/canopy_bulk_density

```
canopy_bulk_density_function=function(plot_name, plot_area, tree_list) {
  # A function to calculate plot-level canopy bulk density from a list of trees
  # This method assumes that all the data are Alaska black spruce.  Allometric e
  # Eliminate hardwood species from the tree_list before feeding the tree_list i
  # Eliminate dead stems which are assumed to be disintegrated enough to contrib
  # The function accepts one plot at a time
  # Assumes metric units, diameter in centimeters and plot_area in meters
  # The input tree_list data frame of trees requires these variables:
  # live, Logical.  T or 1=live.  F or 0=dead
  # diam_type. Logical.  0 f basal.  1 if breast height.
  # diam, Tree diameter, centimeters
  # ht, Tree height, meters
  # cbh, Tree crown base height, meters

  # Calculate individual tree crown weights from allometric equations based on d
  # The equations and constants below come from Alexander ME, Stefner CN, Mason
```

```
# Other equations could be substituted.
tree_list$live_needle=tree_list$live_round=tree_list$dead_round=0 # create fue
# calculate crown fuel load, large trees
idx=which((tree_list$live==1) & (tree_list$diam_type==1))
tree_list$live_needle[idx]= 0.23317*tree_list$diam[idx]^1.25384 # live needles
tree_list$live_round[idx]=0.13267*tree_list$diam[idx]^1.11546 # live roundwood
tree_list$dead_round[idx]= 0.05553*tree_list$diam[idx]^1.12281 # dead roundwoo
# calculate crown fuel load, small trees
idx=which((tree_list$live==1) & (tree_list$diam_type==0))
tree_list$live_needle[idx]= 0.01534*tree_list$diam[idx]^2.36069 # live needles
tree_list$live_round[idx]=0.01202*tree_list$diam[idx]^2.09296 # live roundwood
tree_list$dead_round[idx]= 0.00588*tree_list$diam[idx]^1.99293 # dead roundwoo
# calculate crown fuel load, dead large trees
idx=which((tree_list$live==0) & (tree_list$diam_type==1))
tree_list$live_needle[idx]= 0 # live needles
tree_list$live_round[idx]=0 # live roundwood <5mm
tree_list$dead_round[idx]= 0.05553*tree_list$diam[idx]^1.12281 # dead roundwoo
# calculate crown fuel load, dead small trees
idx=which((tree_list$live==0) & (tree_list$diam_type==0))
tree_list$live_needle[idx]= 0 # live needles
tree_list$live_round[idx]=0 # live roundwood <5mm
tree_list$dead_round[idx]= 0.00588*tree_list$diam[idx]^1.99293 # dead roundwoo

# Distribute the fuel over the individual trees
# Create a data frame to hold the slices that contain fuel
# This data frame has columns for each tree and rows for the slices, e.g., 1-2
# E.g., for a 17 m tall canopy there are 18 rows or slices.
crown_occupation=dead_round=live_round=live_needle =as.data.frame(matrix(0, nr
j=1
for (j in 1:ncol(crown_occupation)) {
  crown_occupation[(tree_list$cbh[j]+1):(ceiling(tree_list$ht[j])),j] = 1 # cb
}
crown_occupation[is.na(crown_occupation)] = 0 # change any NA to zero
for (i in 1:nrow(tree_list)) {
idx=which(crown_occupation[,i]>0) # how many slices contain fuel, are 1?
live_needle[,i][idx] = tree_list$live_needle[i]/(length(idx))  # Take the crow
live_round[,i][idx] = tree_list$live_round[i]/(length(idx))  # Take the crown
dead_round[,i][idx] = tree_list$dead_round[i]/(length(idx))  # Take the crown
}
return(
data.frame(
```

```
    slice=(1:nrow(crown_occupation))-0.5, # Slice or meters above the ground.  S
    cabd_live_needle=rowSums(live_needle[,1:ncol(live_needle)])/plot_area, # Plo
    cabd_live_round=rowSums(live_round[,1:ncol(live_round)])/plot_area, # Plot-l
    cabd_dead_round=rowSums(dead_round[,1:ncol(dead_round)]/plot_area) # Plot-le
  )
  )
} # end function
```

References

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