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Classification of forest fuels in selected fire-prone ecosystems of Alberta, Canada—implications for crown fire behaviour prediction and fuel management

Nathan Phelps and Jennifer L. Beverly*

Abstract

Key message: We used clustering to construct fuel classes from fuel inventory data based on three stand attributes relevant to crown fire behaviour: surface fuel load (SFL), canopy base height (CBH) and canopy bulk density (CBD). Resulting fuel classes explained more of the stand-to-stand variability in predicted crown fire behaviour than fuel types of the Canadian Forest Fire Behaviour Prediction (FBP) System.

Context: Wildfire behaviour is partly determined by stand structure and composition. Fuel characterization is essential for predicting fire behaviour and managing vegetation. Currently, categorical fuel types based on associations with major forested or open vegetated landcovers are used nationally in Canada for fire research and management applications.

Aim: To provide an alternative description of selected forest fuels in Alberta, Canada, using direct classification in which fuel categories are constructed from data using analytical methods.

Methods: Fuel inventory data for 476 stands were used to construct fuel classes with clustering. Potential crown fire behaviour was modelled for resulting fuel class clusters (FCCs) and FCCs were compared with assigned FBP System fuel types. Tree-based modelling was used to identify stand characteristics most influential on FCC membership. Fuel treatment effects on FCC and modelled crown fire behaviour were explored for the FCC most susceptible to crown fire.

Results: Four FCCs were identified: Red (low SFL, low CBH, low CBD); Green (high SFL, low-moderate CBH, low CBD); Blue (low SFL, high CBH, low-moderate CBD); and Black (low SFL, moderate CBH, high CBD). Stand density of live conifers and FBP System fuel type were the most important variables influencing FCC membership; however, FCCs did not align directly with assigned FBP System fuel types. Fuel reduction treatments in the Black FCC were effective at shifting the stand to a less flammable FCC.

Conclusion: FCCs explained more of the stand-to-stand variability in predicted crown fire behaviour than assigned FBP System fuel types, which suggests FCCs could be used to improve fire behaviour predictions and aid fire

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managers in prioritizing areas for fuel treatments. Future technological and remote sensing advances could enable mapping FCCs across large regions.

Keywords: Stand structure, Fuel load, Fuel inventory, Fuel complex, Cluster analysis, FBP System, Fire behaviour, Crown fire initiation

1 Introduction

The physical properties of live and dead forest biomass regulate the way wildfires burn. Fuel properties include size, shape, height, depth, load, bulk density, and vertical and horizontal arrangement (Gould et al. 2011; Keane 2013, 2015; Duff et al. 2017). Descriptions of fuels have long been central to the study and management of wildland fire (Keane 2013) and fuels are considered more important to fire management than any other environmental factor (Keane 2015). Fuel descriptions are necessary to predict potential fire behaviour (Van Wagner 1983), map fire hazard (e.g. Keane et al. 2001; Fernandes 2009), and identify locations most prone to burning (e.g. Shang et al. 2020; Beverly et al. 2021). Resulting predictions and assessments can inform a wide range of fire management decisions such as where to allocate fire response resources (Taylor et al. 2013) or position proactive fuel reduction treatments (e.g. Pais et al. 2021).

Fuel descriptions are obtained either directly by field measurement or indirectly from thematic land cover maps derived primarily from remotely sensed data. Site-specific field measurements using traditional field sampling methods (e.g. McRae et al. 1979; Brown et al. 1982) are impractical for describing fuels across large areas due to the inherent variability in forest fuel complexes both within and between stands, which make field campaigns time-consuming and costly. When field-based fuel measurements are collected, they tend to be limited to localized areas such as research studies or controlled burn settings (e.g. Alexander et al. 2004). To enable broad-scale mapping of fuel characteristics across entire management jurisdictions, fuel description systems have been developed to group fuel complexes according to their similarities and differences.

Vegetation-based fuel description schemes rely on pre-existing categories defined by vegetation species to differentiate areas where the fuel complex presents with a consistent suite of properties. This *association* method for fuel description (Keane 2013) is used in the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), which associates 16 categorical fuel types with distinct fuel assemblages within major forested or open vegetated landcovers. FBP System fuel types for forested lands are based largely on stand types mirrored in readily available inventory data mapped primarily for forest harvest planning purposes.

Despite the obvious practicality, vegetation-based classifications disregard within-type variability in fuels that can exceed variation between types (Brown and Bevins 1986; Miller et al. 2003).

Natural variation in surface and canopy fuel characteristics within important fire-prone forest types found in Canada have been documented in a number of localized studies (e.g. Alexander et al. 2004; Lavoie 2004; Johnston et al. 2015). When fuels are described using the FBP System, the best representative fuel type is assigned through a systematic process that accounts for stand attributes such as species type, stand density, and percent conifer composition, among other characteristics (Frederick 2012). With just 12 different forest fuel types available to represent highly varied site conditions and stand histories expressed across diverse ecological zones, it is not surprising that fuel characteristics routinely deviate from the standard description of the FBP System fuel type assigned to represent a given stand.

The relatively recent introduction of fuel reduction treatments in Canada's northern forest ecosystems has introduced additional variability in stand structures that are not accounted for in the natural, unmanaged stand types of the FBP System (Beverly et al. 2020). Fuel reduction treatments aim to reduce potential fire behaviour in high-valued areas like communities. These treatments typically involve pruning the lower limbs of the trees and removing understory vegetation and surface biomass to increase the separation between crown fuels and the ground, as well as removing some trees to reduce stand density and separate tree crowns (Agee et al. 2000). Recognizing that potential fire behaviour before and after fuel treatments cannot be estimated for a given stand using FBP System fuel types, the provincial agency responsible for fire management in Alberta introduced a fuel inventory program in 2007 to characterize fire-prone forest fuel complexes in both natural and fuel-treated stands. The program spanned 13 years (2007–2019) during which 917 plots were sampled.

Fuel inventory data are well-suited to an alternative approach for developing fuel description systems described by Keane (2013) called *direct classification*. Unlike the *association* method used to define FBP System fuel types, direct classification involves constructing fuel categories from data using analytical methods such as clustering. Hierarchical cluster analysis has

been used to define fuel classes in the southwestern USA and northern Mexico (Miller et al. 2003), west Texas (Poulos et al. 2007) and northwest Montana (Berkey et al. 2021). Cluster analysis has also been used to classify fuels in China (Wu et al. 2011) and the Mediterranean (Elia et al. 2015), but to our knowledge, these methods have never been used to classify fuels in Canadian forest ecosystems.

The specific fuel attributes used for direct classification depend on data availability and the intended use of the resulting fuel classes. When defining fuel classes for crown fire behaviour prediction, fuel attributes of interest include the weight of surface fuels or surface fuel load (SFL, kg m^{-2}) available for combustion; the vertical distance of tree foliage above the ground or canopy base height (CBH, m); and the amount and compactness of canopy fuels through which a crown fire will move, measured as canopy fuel load (CFL, kg m^{-2}) and canopy bulk density (CBD, kg m^{-3}). These fuel attributes are necessary for populating well-established models used to predict potential crown fire behaviour (i.e. Byram 1959; Van Wagner 1977).

Byram's (1959) fireline intensity equation can be used to estimate the intensity of a surface fire, which will be determined in part by the amount or load of surface fuel (i.e. SFL) consumed during the passage of the flaming fire front. Some surface fires will never reach an intensity sufficient to preheat and ignite tree foliage suspended at a distance overhead. When measurements of conifer crown fuel (i.e. CBH and CBD) are available, Van Wagner's (1977) models can be used to estimate the critical surface fire intensity necessary for a fire to move vertically into the canopy fuel strata; and in the event a crown fire develops, the conditions necessary for sustained crown fire spread.

Byram (1959) and Van Wagner (1977) models are also imbedded within the FBP System, but calculations rely on fixed CBH and CFL values assigned to each fuel type (Forestry Canada Fire Danger Group 1992). For example, the C-2 Boreal Spruce fuel type has a CFL of 0.80 kg m^{-2} and CBH of 3 m corresponding to a standard, mature black spruce (*Picea mariana* (Mill.) BSP) stand. The SFL available for combustion in a given FBP System fuel type is based on this same mature stand condition and estimated with empirical statistical models of post-fire surface fuel consumption. The FBP System also uses empirical rate of spread models based on observations of experimental fires and wildfires in a given fuel type. Reliance on fixed crown fuel attributes and empirical statistical relationships in the FBP System means that uncertainty is introduced into model predictions whenever the structural components of a forest stand deviate from the fuel type description.

In this study, we used cluster analysis to construct fuel classes from fuel inventory data collected in selected fire-prone forest ecosystems of Alberta. We sought insight into the following questions: to what extent does predicted crown fire behaviour differ among data-derived fuel class clusters (FCCs)? Do FCCs align with FBP System fuel types? What underlying factors influenced stand membership in a given FCC?; and Were fuel reduction treatments effective at changing crown fire behaviour potential in the FCC most susceptible to crown fires? We constructed our clusters using three fuel characteristics widely known to impact the development and behaviour of crown fires (i.e. SFL, CBH, and CBD). We opted to focus on crown fire conditions because in northern forest ecosystems, most large fires exhibit crown fire behaviour (Amiro et al. 2004), which generally exceeds fire suppression capabilities (Murphy et al. 1991; Hirsch et al. 1998; Hirsch et al. 2004), and therefore represents a priority fire management concern. Implications of our results for fuel classification and fuel management are discussed.

2 Methods

2.1 Study region and data

We used a database of fuel measurements collected from 430 plots sampled between 2009 and 2019, inclusive, during the Alberta Wildland Fuels Inventory Program (AWFIP). These data are presented by Phelps et al. (2022) and consist of a cleaned and curated subset of the AWFIP program data that is suitable for analysis, including fuel load calculations for surface, understory, and canopy fuel strata. Detailed documentation of AWFIP data can be found in Phelps et al. (2022) along with associated data limitations, which are attributed to factors such as inconsistent field protocols, data entry errors, and incomplete or inaccurate field records. AWFIP plots were subjectively located in dominant forest types of particular relevance for exploring fuel and fire behaviour dynamics in relation to fuel management objectives, which is compatible with our study aim.

Detailed descriptions of each variable in the database are documented by Phelps et al. (2022). At each plot, four 25-m transects were used to sample shrubs, dead and down woody material, and ground cover. Destructive samples along the transects were used to measure litter, duff, forbs, grass, and mulch, when present. Stem inventories were recorded for seedlings, saplings and large trees using a variable plot radius to ensure a minimum of 20 trees were documented. Some plots were sampled on multiple occasions with the passage of time or following a fuel reduction treatment, resulting in 476 unique sampling events, each with a set of variables describing fuel and local conditions at the plot location. All variables were measured either directly by field crews or indirectly

by computing values from field measurements following data entry, cleaning, and processing and include FBP System fuel type, moisture regime classification (Resource Data Branch 2003), canopy and understory stand density, several fuel loads (i.e. surface, understory, canopy fuels), and fuel treatment status (i.e. natural or managed stands).

2.2 Computing stand attributes

Methods and standards for computing individual fuel attributes lack consensus within the fire behaviour modelling community (e.g. Cruz and Alexander 2010). Requirements of fire behaviour prediction models can provide insight into, and justification for, a given approach for computing values.

Surface fuel load (SFL) is the sum of individual fuel loads computed for multiple fuel components, generally those located beneath the canopy and of a size and type that will be consumed during the passage of the flaming fire front. We limited SFL calculations to fuels available for consumption, such that computed values could be input into Byram's (1959) frontal fire intensity equation. Commonly, SFL consists of the weight of the fuel in the top layer of the forest floor in combination with fine woody debris, shrubs, and low-vegetation (i.e. herbaceous material), but may also include bridge fuels between the ground and canopy fuels such as loose bark, dead lower branches, lichen, and small understory conifers (Van Wagner 1977; Beverly et al. 2020). Shrubs may or may not be consumed during the passage of a surface fire, depending on the shrub species involved as well as season and local fire environment factors. To explore the sensitivity of our results to assumptions about SFL composition, we computed two variants, with and without shrubs. Both SFL formulations included litter (i.e. needles, leaves, moss, lichen), forbs, grass, understory trees, mulch, and fine woody debris with a diameter less than 1 cm.

To compute CBH and CBD, the canopy fuel strata must first be defined. For modelling purposes, Van Wagner (1977) pictured a simplified crown fuel layer with a uniform height above ground. In northern forest ecosystems, the height of crown fuel above ground can be expected to vary from tree to tree. The presence of saplings that extend well into the crown layer of overstory trees can introduce further variability by lowering crown base height in some locations. Phelps et al. (2022) defined the canopy as all large trees with a height of at least 1.3 m and a diameter at breast height (DBH) of 9 cm or greater; and saplings (i.e. trees with a height of at least 1.3 m and a DBH less than 9 cm) that were at least 3 m taller than the average live crown base height (LCBH) of the live large conifer trees in the stand. The requirement for a 3 m extension of saplings

into the canopy was used to ensure continuity of the canopy fuel strata, given the uneven vertical distribution of crown fuel (e.g. Alexander et al. 2004). To account for variability in LCBH from tree to tree, an average was computed individually for both large trees and saplings. An overall CBH was then calculated as a weighted average based on the number of observations in each category (i.e. large tree versus sapling, only considering live conifer trees).

CBD can be computed from CFL for foliage alone or in combination with small branchwood. CFL used in this study was computed with allometric equations from Lambert et al. (2005) and Ter-Mikaelian and Korzukhin (1997) using the foliage biomass component, which aligns with Van Wagner's (1977) crown fire initiation model. Small branchwood also contributes to canopy fuel load (e.g. Stocks et al. 2004); however, allometric equations for branchwood biomass components were unavailable by diameter class for the full suite of tree species inventoried.

2.3 Cluster analysis

Clustering is an unsupervised learning approach designed to create groups within a set of observations (e.g. Xu and Wunsch 2008). In clustering, the similarity of observations is measured with a user-selected metric, in our case Euclidean distance. Prior to analysis, data were standardized to remove the impact of differing variances among the features. Presence of outliers was then assessed and in the event outliers were removed, the data were then re-standardized.

In an ideal situation, clustering will place similar observations in the same group and dissimilar observations in different groups. In reality, these objectives are sometimes mutually incompatible, such that different clustering approaches place more emphasis on one objective than the other (Ben-David 2018). In classifying fuel characteristics, we considered two different clustering philosophies: agglomerative hierarchical clustering and K-means clustering.

In agglomerative hierarchical clustering, clusters are formed using a "bottom up" approach where each observation initially forms its own cluster (i.e. a singleton), which is then joined with other clusters continually until all observations form a single cluster. Different approaches are used to select the clusters joined in each step. We considered four of these linkage methods: Ward's method (Ward 1963), which has been used in a number of previous fuel classification studies (e.g. Miller et al. 2003; Poulos et al. 2007; Wu et al. 2011; Elia et al. 2015; Berkey et al. 2021); and three additional methods (i.e. single linkage, average linkage, and complete linkage).

We also applied an alternative clustering philosophy, K-means clustering (Hartigan and Wong 1979), in which K points are randomly initialized in vector space and each observation is assigned to the point to which it is closest. The cluster centroids are then computed and the process is repeated until none of the points moves to a new cluster.

All analyses were performed in R (R Core Team 2017). For each clustering method, we used the NbClust package (Charrad et al. 2014), which uses several measures to suggest an appropriate number of clusters. We used this recommendation as a guideline, but also considered other numbers of clusters that were of interest. To determine if the resulting clusters were meaningful and useful, we analysed scatter plots of SFL, CBH, and CBD values colour-coded by cluster, as well as the total within-cluster sum of squares. K-means clustering minimizes the total within-cluster sum of squares, and is therefore favoured by our procedure; however, it would not be chosen if deemed unsuitable based on visual analysis of the scatter plots. For our purposes, a meaningful set of clusters contained few clusters that were composed of very few observations.

2.4 Fire behaviour modelling

We classified fuel characteristics to inform predictions of potential crown fire behaviour in a given fuel class and assessed the degree to which crown fire behaviour can be expected to differ by fuel class. Two aspects of crown fire behaviour are of particular importance to fuel management: crown fire initiation and crown fire spread. When a surface fire successfully moves vertically into the crowns of conifer trees, it can generate firebrands that travel aloft, above the stand, and deposit on nearby structures (Albini 1979; Caton et al. 2017; Suzuki and Manzello 2021). When those individual burning conifer crowns also ignite adja-

Surface fire intensity (I , kW m⁻¹) of the flaming fire front (Byram 1959) is

$$I = H \bullet w \bullet ROS \tag{1}$$

where the constant H is the fuel's low heat of combustion (18,000 kJ kg⁻¹), w is the quantity of surface fuel consumed in the active flame front (kg m⁻²), and ROS is the linear rate of fire spread (ms⁻¹). Critical surface fire intensity (CSI, kW m⁻¹) for the development of a crown fire (Van Wagner 1977) is

$$CSI = 0.001 \bullet CBH^{1.5} \bullet (460 + 25.9 \bullet FMC)^{1.5} \tag{2}$$

where CBH is the live canopy base height (m), and FMC is the per cent foliar moisture content; and the critical minimum rate of spread (ROS_{CM} , m min⁻¹) necessary to sustain a crown fire is

$$ROS_{CM} = \frac{S_o}{CBD} \tag{3}$$

where S_o is the mass flow rate of fuel and CBD is canopy bulk density (kg m⁻³). S_o is typically estimated as 3.0 kg m⁻² min⁻¹ following field observations reported by Van Wagner (1977). Cruz and Alexander (2010) note that S_o is based largely on a single experimental fire in red pine plantation; however, the model was confirmed robust by Cruz et al. (2005) using a dataset of 37 experimental fires conducted in a variety of conifer forests.

To model fire behaviour, each FCC was represented by its centroid. In all cases, we assumed a 100% FMC, a mass flow rate of 3.0 kg m⁻² min⁻¹, and consumption of all surface fuels included in SFL calculations during the passage of the active flame front.

We also computed the probability of crown fire occurrence (Eqs. 4 and 5) and active crown fire rate of spread (Eq. 6) using empirical statistical models estimated by Cruz et al. (2004, 2005):

$$g(x) = 4.236 + 0.357WS - 0.710FSG - 4.613I(SFC < 1.0\text{kg m}^{-2}) - 1.856I(1.0\text{kg m}^{-2} < SFC < 2.0\text{kg m}^{-2}) - 0.331(EFFM) \tag{4}$$

cent trees and crown-to-crown fire spread is sustained, fire intensities will exceed direct suppression by ground crews (Murphy et al. 1991; Hirsch et al. 1998; Hirsch et al. 2004). Fuel treatments therefore aim to inhibit both the initiation and sustained spread of a crown fire.

To assess the conditions necessary to facilitate a crown fire in each of the fuel class clusters (FCCs), we used Byram's (1959) equation to calculate an initial surface fire intensity (Eq. 1) and then used Van Wagner's (1977) equations to determine if the surface fire had a sufficient intensity to transition to a crown fire (Eq. 2) and sustain crown fire spread (Eq. 3).

where WS is the 10-m open wind speed (km h⁻¹), FSG is the fuel strata gap (m), which we approximated using live canopy base height (CBH), $I(*)$ represents an indicator variable, SFC is the surface fuel consumption (kg m⁻²), and $EFFM$ is the estimated fine fuel moisture content (%). The probability of a crown fire is

$$\text{Prob(crown fire)} = \frac{e^{g(x)}}{1 + e^{g(x)}} \tag{5}$$

and rate of spread (m min^{-1}) of an active crown fire, ROS_{AC} , is

$$\text{ROS}_{\text{AC}} = 11.02\text{WS}^{0.90} \bullet \text{CBD}^{0.19} \bullet e^{(-0.17\text{EFFM})} \quad (6)$$

where CBD is the canopy bulk density (kg m^{-3}). We explored various 10-m open wind speeds and fine fuel moisture contents and again assumed that all surface fuels included in SFL calculations were consumed in the passage of the fire front.

2.5 Comparing FCCs and FBP System fuel types

FBP System fuel types were assigned to each stand based on the species composition of the live trees that formed the canopy fuel strata, using decision rules described by Phelps et al. (2022). Fuel attributes associated with FBP System fuel types were assessed visually with scatter plots of SFL, CBH, and CBD colour-coded by fuel type. Visible groups would indicate that FBP System fuel types represent distinct and consistent combinations of SFL, CBH, and CBD in a manner similar to the FCCs. Patterns could also identify if FCCs represented subgroups within a given FBP System fuel type. To assess the similarities and differences between the FCCs and FBP System fuel types, we compared the distribution of FBP System fuel types within each FCC, and vice-versa, graphically. For all stands in the C-2 Boreal Spruce FBP System fuel type, a dominant crown fire ecosystem in Canada that is prone to high-intensity crown fires (Van Wagner 1983), we then computed the probability of crown fire occurrence and active crown fire rate of spread using empirical statistical models estimated by Cruz et al. (2004, 2005, Eqs. 4–6) and explored whether or not FCC membership explained some of the variability in predicted crown fire behaviour.

2.6 Explaining FCC membership

We sought insight into the underlying factors that influence a stand's membership in a given FCC, irrespective of differences in SFL, CBH, and CBD. In an effort to explain why a stand belongs to its FCC, we considered the stand's FBP System fuel type, proportion of live trees, moisture regime classification (Resource Data Branch 2003; Phelps et al. 2022), average litter and duff depth, canopy and understory stand density of live conifers, average age of coniferous and deciduous trees, and treatment status (i.e. managed or natural stand state). Tree-based modelling was used to explain which characteristics have the most influence on a stand's FCC membership and how these

characteristics can be used to explain which FCC a stand belongs to.

A classification tree is fit by continuously splitting the data into subsets based on one of the independent variables, with the choice of split determined by the Gini criterion (Breiman et al. 1984). Visualizing this tree provides an easily interpretable model that can help explain which values of certain attributes lead to membership in each FCC (e.g. Berkey et al. 2021); however, classification trees typically are not used to provide an assessment of the importance of each attribute. To obtain such an assessment, several studies have used a random forest (e.g. Lunetta et al. 2004; Bureau et al. 2005). A random forest (Breiman 2001) is built using many classification (or regression) trees, where each tree is fit using a bootstrapped (i.e. resampled with replacement) version of the training dataset and, at each split, only a randomly chosen subset of the variables are considered. Traditional variable importance metrics based on random forests constructed in this manner are prone to bias when some variables are continuous and others are categorical; when categorical variables differ in their cardinality (Strobl et al. 2007); or when variables are correlated (Strobl et al. 2008). Strobl et al. (2007, 2008) suggest building the random forest in a non-traditional fashion to mitigate bias, using datasets obtained from resampling *without* replacement (i.e. creating datasets that contain approximately 63.2% of the original dataset) and building individual trees using a conditional inference framework (Hothorn et al. 2006) rather than the Gini criterion, then computing conditional permutation importance.

To visualize how underlying factors influenced FCC membership, we fit a classification tree using the *rpart* package (Therneau et al. 2015) and plotted it using the *rattle* package (Williams 2009). To determine the importance of the underlying factors, we fit a random forest using the *party* package (Hothorn et al. 2015) and computed conditional permutation importance using the *permimp* package (Debeer and Strobl 2020). For the random forest, three variables were considered at each split of an individual tree and 500 trees were used. In the event that the importance scores were inconsistent (i.e. the order of variables changed) for different instances of the model, the number of trees was increased to 1000.

2.7 Exploring fuel treatment effects on fire behaviour

Results of clustering and crown fire behaviour modelling were used to identify the FCC most susceptible to crown fire, and therefore the ideal candidates

for fuel treatment interventions. A subset of these stands was subjected to a fuel treatment and then re-measured by field crews during the fuel inventory program, which enabled comparisons of fire behaviour modelling results between pre- and post-treatment stand conditions. We also examined whether or not the fuel treatment changed the stand's FCC.

3 Results

3.1 Cluster analysis

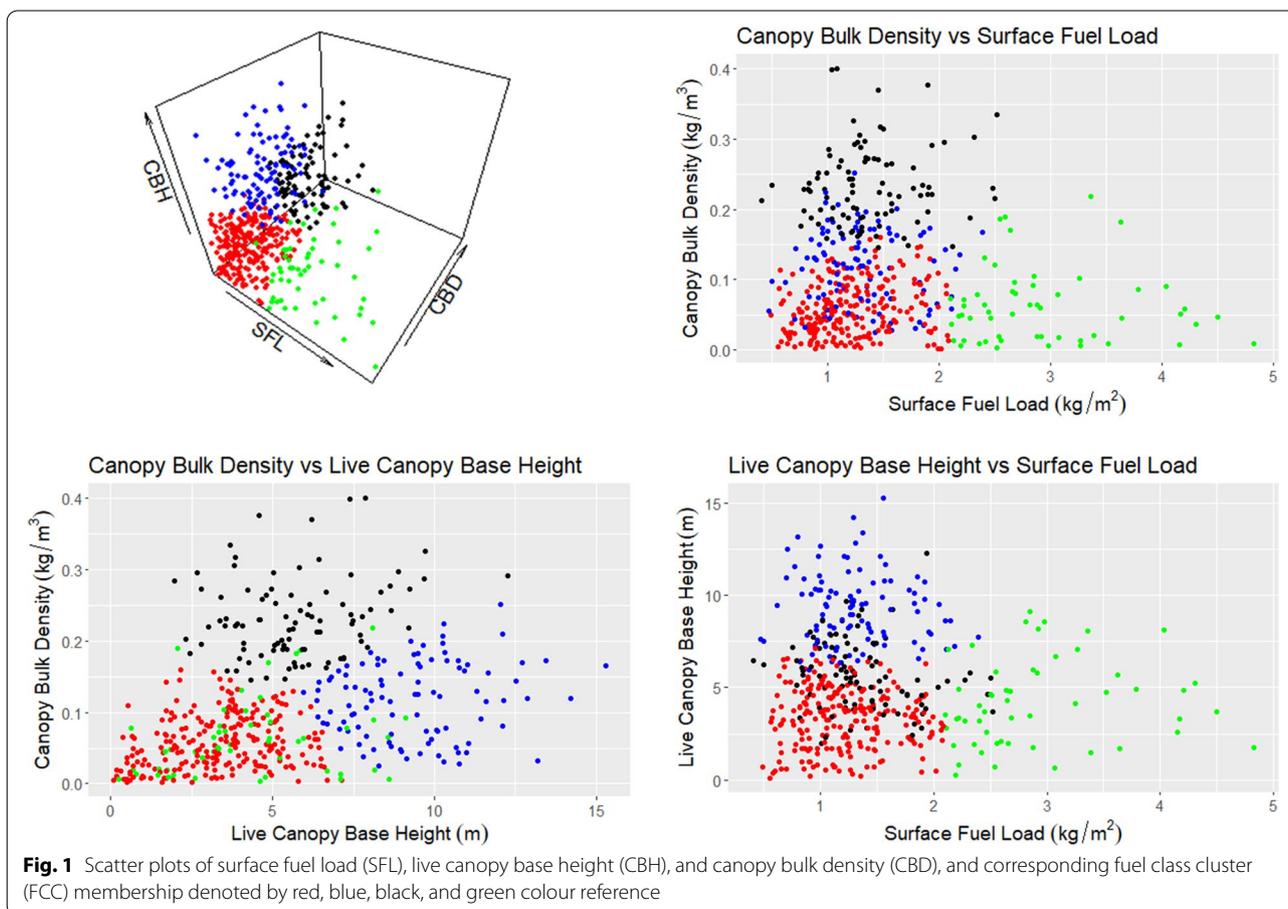
K-means clustering with four clusters was preferred to other combinations of clustering algorithm and number of clusters, regardless of whether or not shrubs were included in the SFL. We report clustering results for a single variant of the SFL calculations, with shrubs included; however, the results were similar for the SFL computation that omitted shrubs. The four clusters are visualized in Fig. 1, with each FCC corresponding to a different combination of SFL, CBH, and CBD values:

- Red FCC (n=229): low SFL, low CBH, low CBD
- Green FCC (n=54): high SFL, low-moderate CBH, low CBD
- Blue FCC (n=100): low SFL, high CBH, low-moderate CBD
- Black FCC (n=93): low SFL, moderate CBH, high CBD

Almost half (48%) of the 476 observations formed a single FCC (Red). Blue and Black FCCs each consisted of roughly 20% of the observations, while the Green FCC had the fewest observations, with just over 11%. A map showing the distribution of FCC observations across the province (Fig. 2) exhibited no obvious patterns, which suggests the spatial location of an observation does not determine its FCC.

3.2 Predicted fire behaviour by FCC

Table 1 shows the mean values of SFL, CBH, and CBD for each of the four FCCs and the corresponding minimum rates of spread necessary for initiation



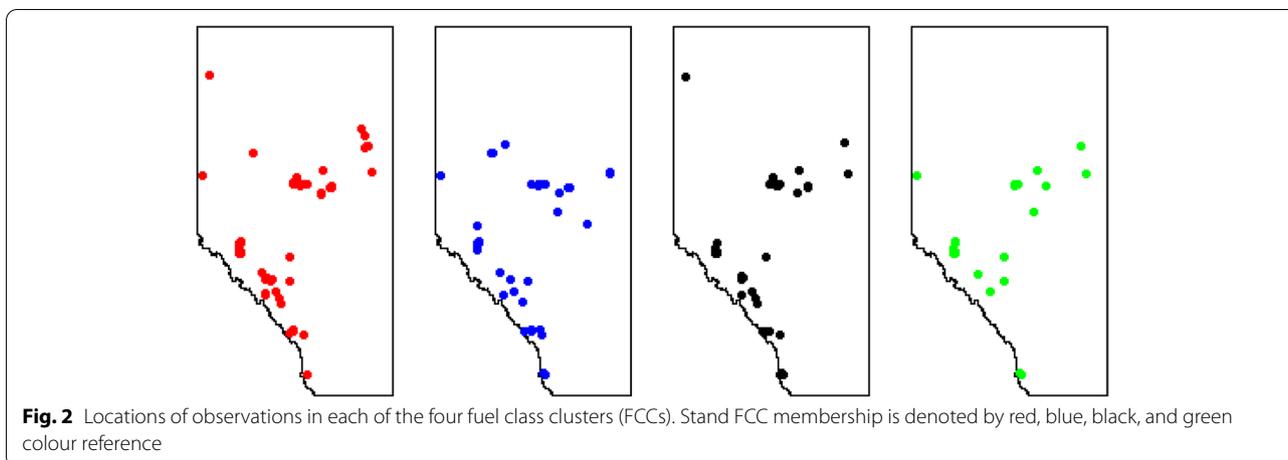


Table 1 Mean values for surface fuel load (SFL), live canopy base height (CBH), and canopy bulk density (CBD) by fuel class cluster (FCC) and the corresponding minimum rate of spread (ROS) for crowning and sustained propagation of a crown fire

| Fuel class cluster | <i>n</i> | Mean SFL (kg m ⁻²) | Mean CBH (m) | Mean CBD (kg m ⁻³) | Min. ROS for crowning (m min ⁻¹) | Min. ROS for sustained propagation of crown fire (m min ⁻¹) |
|--------------------|----------|--------------------------------|--------------|--------------------------------|--|---|
| Red | 229 | 1.21 | 3.3 | 0.059 | 2.8 | 51.2 |
| Green | 54 | 2.92 | 4.2 | 0.062 | 1.7 | 48.5 |
| Blue | 100 | 1.31 | 9.3 | 0.117 | 12.1 | 25.6 |
| Black | 93 | 1.37 | 5.7 | 0.232 | 5.6 | 12.9 |

of crowning and sustained propagation of crown fire spread based on Byram (1959) and Van Wagner (1977) equations, assuming 100% FMC. Results indicate that even under relatively low rates of surface fire spread (i.e. <15 m min⁻¹), crowning is very plausible for all four FCCs. The Blue FCC requires the highest surface fire rate of spread to initiate a crown fire, due to a comparatively low surface fuel load and high CBH. Once a fire moves vertically into the canopy fuel strata, a sustained crown fire in Red and Green FCCs will require very high rates of crown fire spread (>48 m min⁻¹) due to low CBD (<0.07 kg m⁻³). In contrast, the Blue FCC can sustain a crown fire at a rate of spread almost half that of Red and Green FCCs.

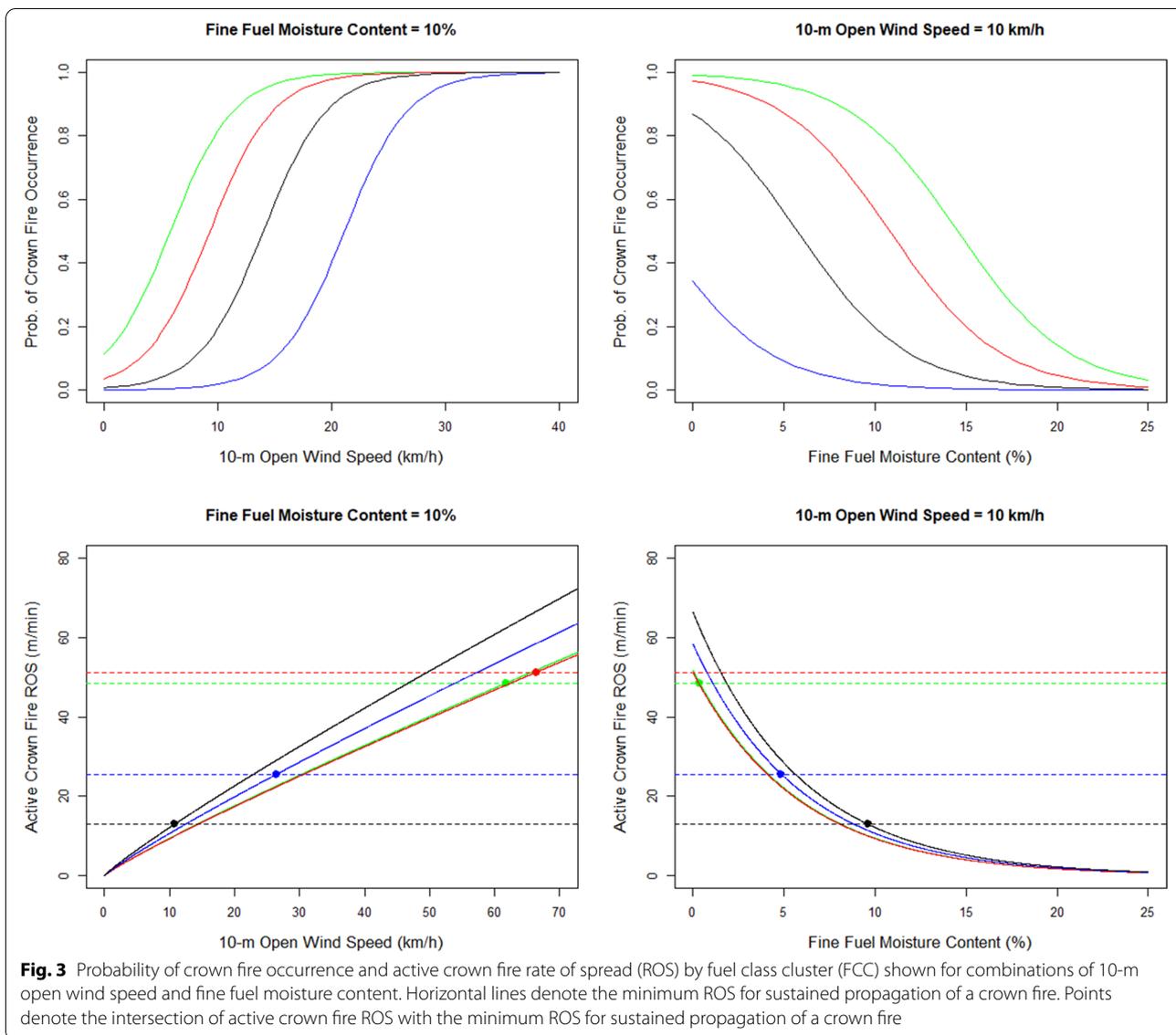
Of the four FCCs, the fuel structural properties of the Black FCC are most conducive to crown fire development and sustained spread, which can occur under relatively low surface fire rates of spread (< 6 m min⁻¹) and crown fire spread of just 13 m min⁻¹. Both Black and Blue FCCs had mean CBD values above the 0.1 kg m⁻³ threshold considered critical for active crowning (Agee 1996; Alexander and Cruz 2014).

Probability of a crown fire and active crown fire rate of spread based on the empirical statistical models estimated by Cruz et al. (2004, 2005) are shown for each

FCC in Fig. 3 for different values of fine fuel moisture content and 10-m open wind speed. Results of the statistical models produced the same general conclusions about crown fire potential in the FCCs as the coupled Byram (1959) and Van Wagner (1977) models described above. Most notably, Red and Green FCCs can support crown fire development but are not expected to sustain an active crown fire unless there are extremely high wind speeds or extremely dry conditions. The Black FCC is the most conducive to both crown fire development and sustained crown fire spread, whereas crown fire development and spread in the Blue FCC are limited by the high wind speeds required for initiating a crown fire.

3.3 Comparing FCCs and FBP System fuel types

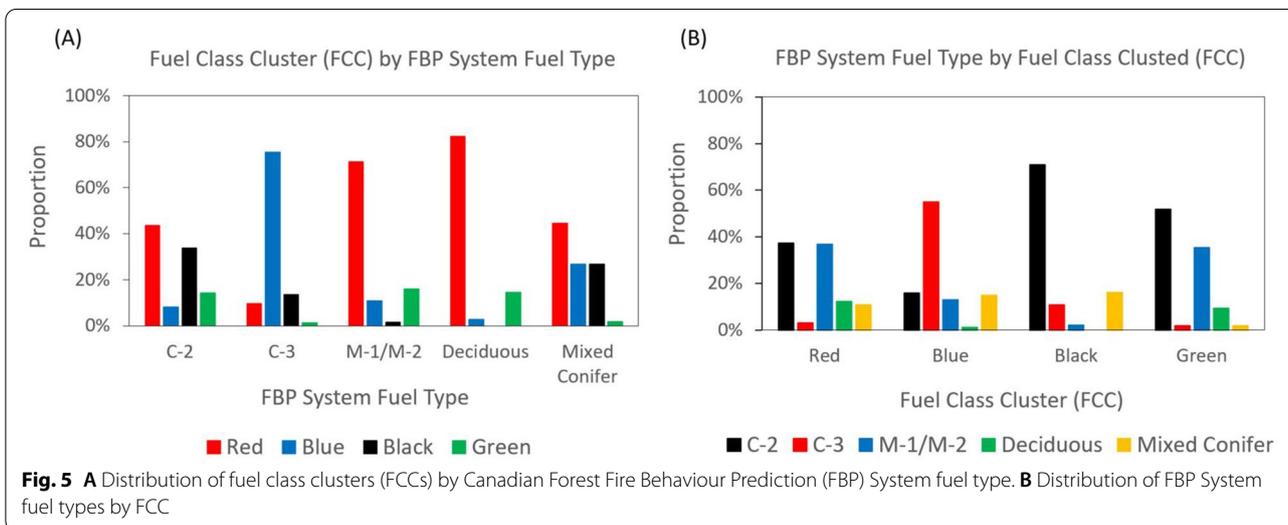
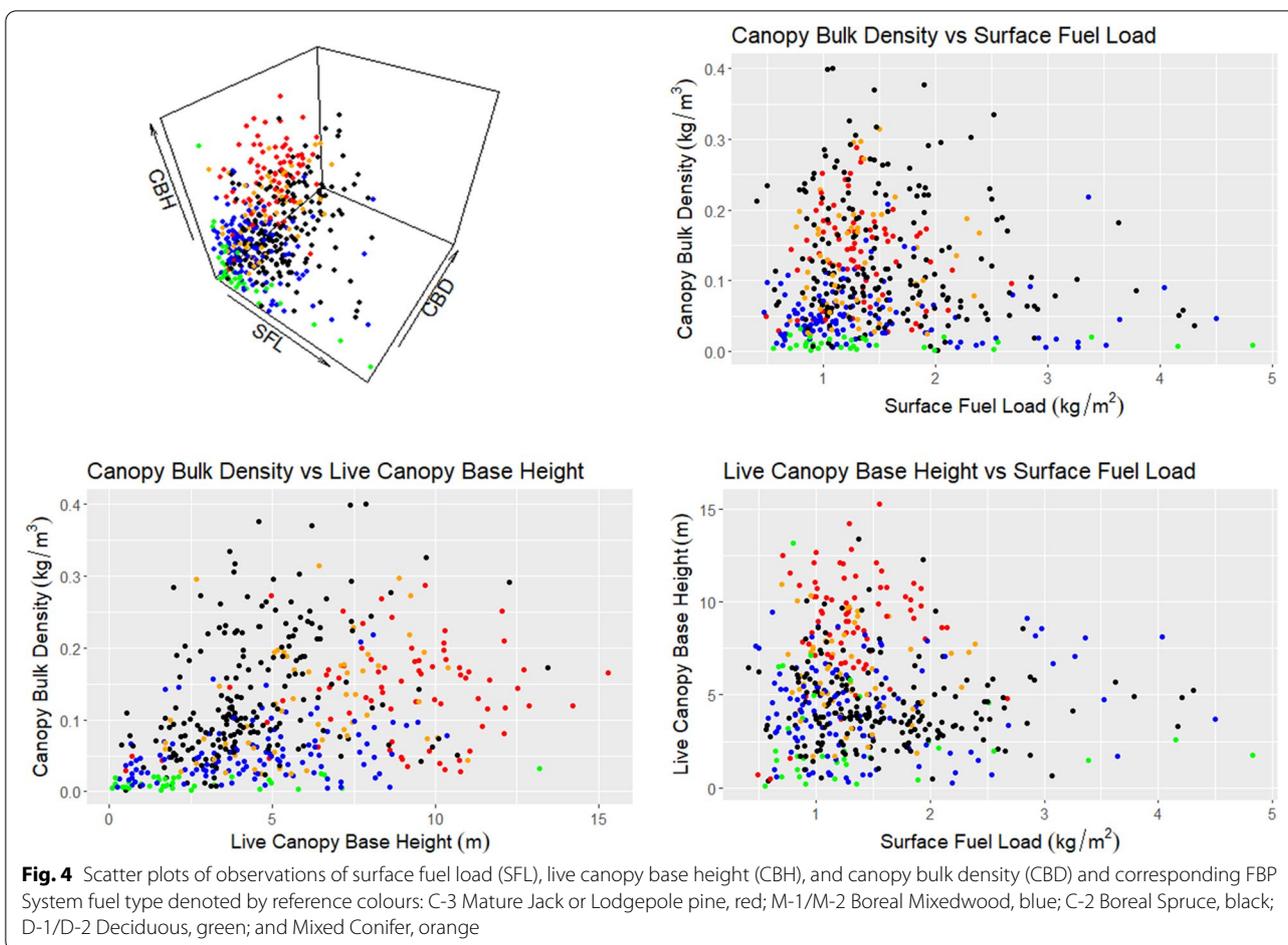
Of the 12 forested FBP System fuel types, only four types were represented in the data we analysed; however, these fuel types cover more than half of the burnable area of the province. A relatively small number of plots did not conform with any of the FBP System fuel types and were assigned a “Mixed Conifer” stand type following the decision rules described by Phelps et al. (2022). The scatter plots in Fig. 4 show the same observations as in Fig. 1, but reference colours denote the assigned FBP System fuel types and mixed conifer type, instead of FCCs:



- Green ($n=34$): D-1/D-2 Deciduous
- Blue ($n=118$): M-1/M-2 Boreal Mixedwood
- Red ($n=73$): C-3 Mature Jack or Lodgepole Pine
- Black ($n=195$): C-2 Boreal Spruce
- Orange ($n=56$): Mixed Conifer

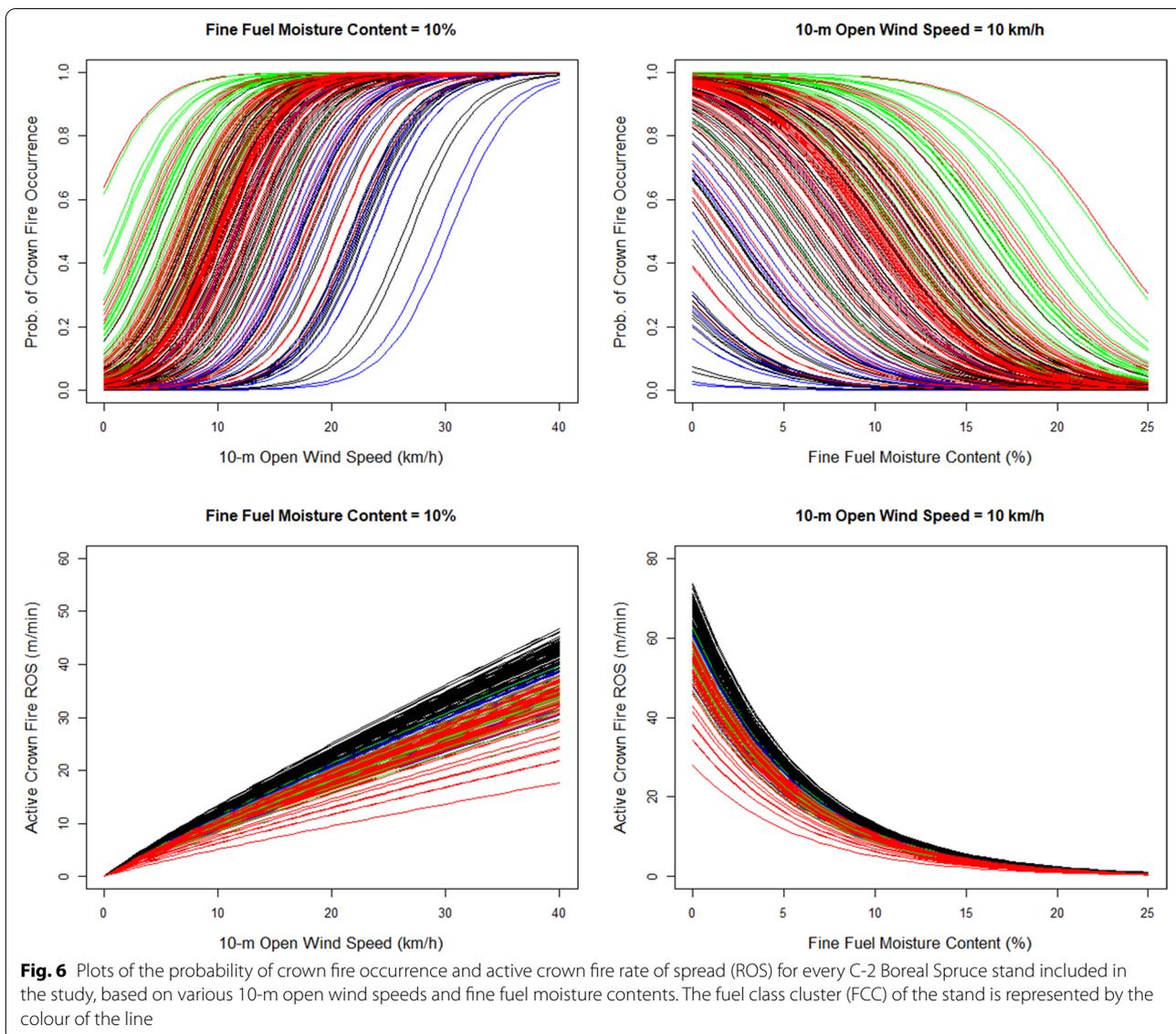
Although there are some patterns in the visualizations (e.g. D-1/D-2 Deciduous stands exhibit very low CBD), there are no clear clusters, which suggests the FCCs embody combinations of fuel characteristics that are not well-represented by the assigned FBP System fuel types. The distribution of FBP System fuel types by FCC, and vice-versa (Fig. 5) indicates that FCCs do not align with FBP System fuel types; however, we can see that there are some associations between the FBP System fuel types and FCCs.

Unsurprisingly, the FCC most susceptible to crown fire initiation and sustained crown fire spread (i.e. Black, Table 1) was composed almost exclusively of conifer-dominated stands, the majority of which were assigned the C-2 Boreal Spruce fuel type, along with a smaller proportion of C-3 (Mature Jack or Lodgepole pine) and Mixed Conifer stands (Fig. 5). It is noteworthy that more than half of the stands assigned the C-2 Boreal Spruce fuel type were not associated with the Black FCC found to be most conducive to crown fire initiation and spread. The next most susceptible FCC (i.e. Blue) consisted mostly of stands classified as C-3, with smaller proportions of C-2, Mixed Conifer and M-1/M-2 Boreal Mixedwood. The Red and Green FCCs were composed mostly of C-2 and M-1/M-2 fuel types.



While it is not surprising that mixedwood stands present with comparatively low CBD, the large component of C-2 stands in both Red and Green FCCs suggests

there is considerable within-type variation in C-2 crown fuel properties. Red and Green FCCs also had approximately 10% of their stands labelled as Deciduous, and



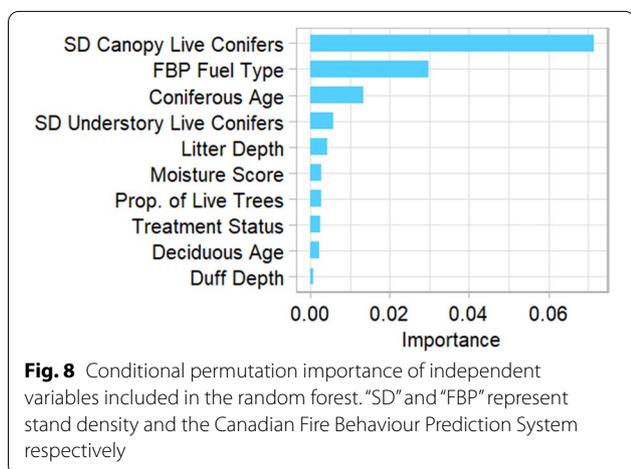
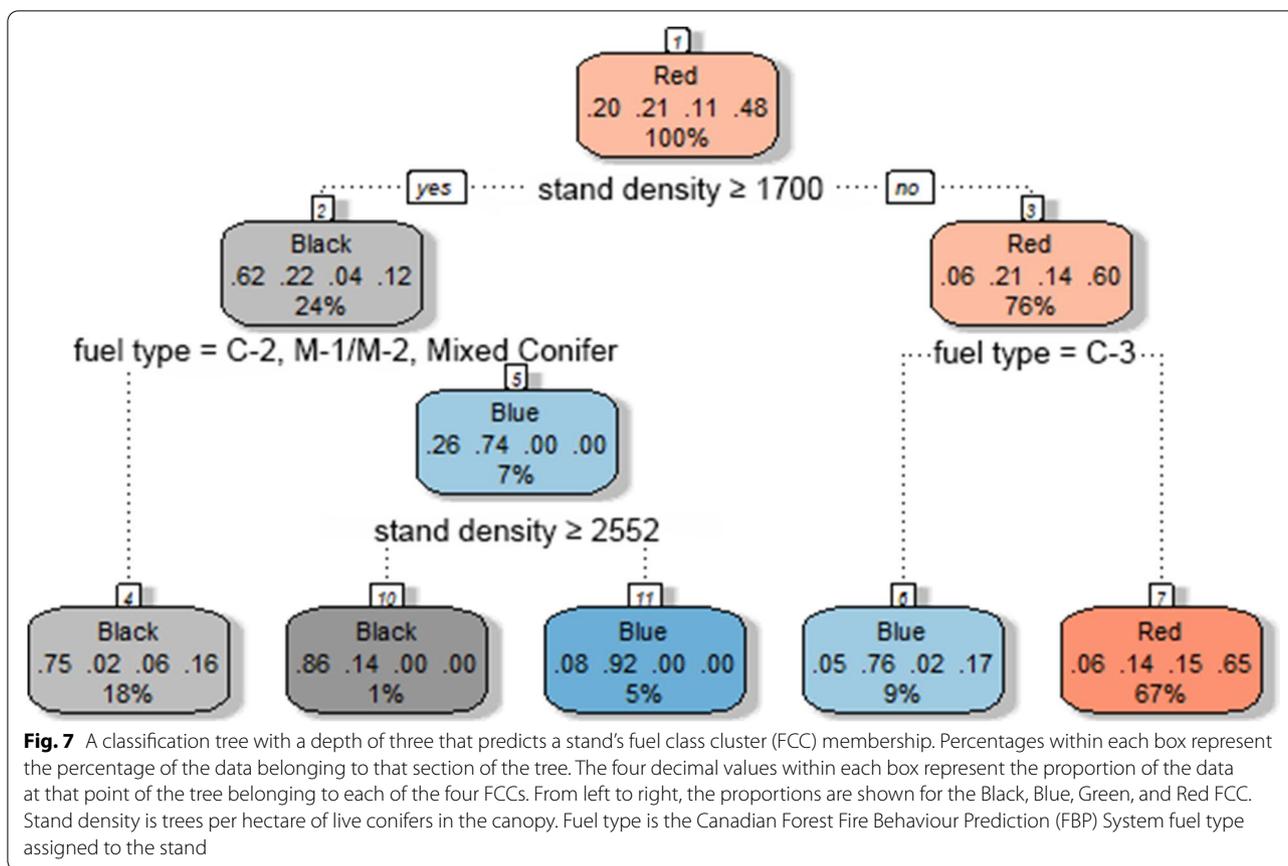
the Red FCC had roughly another 10% of its stands classified as Mixed Conifer.

Probability of crown fire occurrence and active crown fire rate of spread based on the empirical statistical models estimated by Cruz et al. (2004, 2005) for all C-2 Boreal Spruce stands in the dataset ($n = 195$) are shown in Fig. 6 for a range of fine fuel moisture contents and 10-m open wind speeds. Each line in the graph represents one field observation. If all C-2 stands had a similar structure and similar corresponding crown fire behaviour predictions, the lines in each graph would either overlap or occur very close together. Instead, the lines are spread out. This tells us that under equivalent fuel moisture and wind speeds, potential crown fire behaviour in stand types classified as C-2 can vary dramatically. FCCs are denoted by the

different line colours in Fig. 6 and these colours exhibit an obvious pattern with like-coloured lines occurring close together. The grouping of lines by FCC colour in the graphs suggests that much of the variability within the C-2 fuel type is explained by the differences in fuel structural properties represented by the FCCs.

3.4 Explaining cluster membership

We fit a classification tree with a depth of three (Fig. 7). Although there are four splits in the tree, only two attributes are used: stand density of the canopy and FBP System fuel type. The tree never predicts that a stand belongs to the Green FCC and places 67% of the stands in the Red FCC, although only 48% of the stands truly belong to this FCC. Stands with a



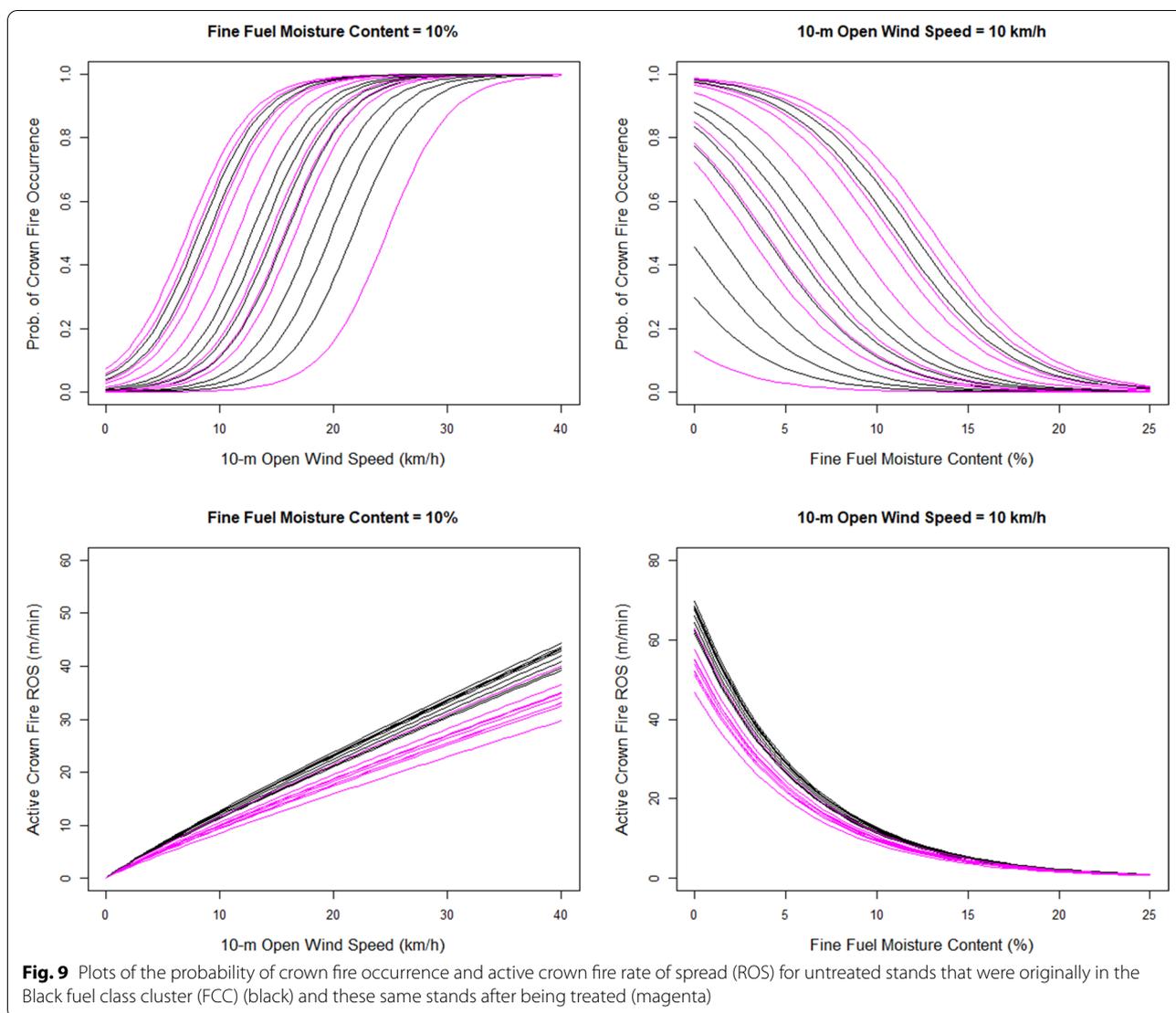
relatively low canopy stand density (less than 1700 trees·ha⁻¹) that do not belong to the C-3 FBP System fuel type are labelled as the Red FCC. Stands with a low canopy stand density that do belong to the C-3 fuel type are classified as the Blue FCC, as are stands with a larger canopy stand density (between 1700 trees·ha⁻¹ and 2552 trees ha⁻¹) that belong to either

the C-3 or Deciduous fuel types. All the remaining stands are labelled as the Black FCC.

We initially fit the random forest with 500 trees, which resulted in inconsistent ordering of the variables and was subsequently increased to 1000 trees. The resulting importance of each stand attribute is illustrated in Fig. 8. The two most important variables are the stand density of the live conifers and the FBP System fuel type, which is consistent with the classification tree since those are the two attributes that are used in the tree.

3.5 Exploring fuel treatment effects on fire behaviour

According to the conditional permutation importance, the treatment status of a stand was of very little importance in influencing FCC membership (Fig. 8); however, that does not necessarily mean that fuel treatments do not impact potential crown fire behaviour. To examine the impacts of fuel treatment modifications to stand structure, we focused on stands that belonged to the Black FCC prior to being treated, because this fuel class is most susceptible to active crown fires. There were nine stands with both pre- and post-treatment data that were originally in the Black FCC. In eight of the nine cases, FCC membership changed following fuel



reduction treatment, indicating that fuel treatment changed the fuel structure attributes relevant to crown fire behaviour. Of the eight stands that moved to a new FCC post-treatment, four stands moved to the Green FCC, two moved to the Red FCC, and two moved to the Blue FCC.

Probability of crown fire occurrence and active crown fire rate of spread based on the empirical statistical models estimated by Cruz et al. (2004, 2005) are shown for the nine pairs of pre- and post-treatment observations in Fig. 9. For ease of comparison, the original state of the stand (i.e. Black FCC) is shown with black lines and the post-treatment state consisting of several different FCCs is shown with magenta lines. Based on the intermingling of the black and magenta lines in the top panel of Fig. 9, the treatments did not have a substantial

impact on the probability of crown fire occurrence. Separation of the black and magenta lines in the bottom panel of Fig. 9 indicates that the fuel treatments reduced CBD, leading to a reduction in the modelled active crown fire rate of spread under equivalent weather conditions.

4 Discussion

Predicted crown fire behaviour differed markedly among the four data-derived fuel class clusters (FCCs), primarily due to differences in CBH and CBD. Crown fires can initiate in stands in the Red and Green FCCs, but due to low CBD, sustained crown fire spread is only predicted under the most extreme conditions where rates of spread exceed 48 m min^{-1} . In contrast, both Blue and Black FCCs have structural properties

conductive to the initiation and sustained spread of a crown fire. Compared with the Blue FCC, the lower CBH and higher CBD in the Black FCC make crown fire initiation and sustained spread possible even under relatively moderate conditions where surface fire rates of spread are $<6 \text{ m min}^{-1}$ and crown fire rate of spread are as little as 13 m min^{-1} . Of the 476 stands analysed, 20% were members of the Black FCC most capable of supporting extreme fire behaviour.

It is notable that SFL observations in Red, Blue and Black FCCs had similar ranges (Fig. 1) and mean values (Table 1). Only the Green FCC exhibited markedly higher SFL than the other FCCs. A higher SFL available for consumption during the passage of the fire front will increase fire intensity and make it easier for a surface fire to transition to a crown fire, under otherwise equivalent conditions. In the case of the Green FCC, even if a crown fire is successfully initiated, low CBD inhibits sustained crown fire spread, except under the most extreme rates of spread. Given that Red and Green FCCs differed primarily with respect to SFL, differences in the probability of crown fire initiation between these two FCCs (Fig. 3) suggest that reducing SFL in the Green FCC to levels observed in the Red FCC would only be effective for inhibiting crown fire initiation at relatively low wind speeds (i.e. $< 15 \text{ km h}^{-1}$).

Of the 476 stands included in the analysis, only 7% ($n=34$) were assigned the D-1/D-2 Deciduous FBP System fuel type and the vast majority of these (80%) were in the Red FCC which had low SFL, low CBH and low CBD. The relatively small number of deciduous stands analysed may not represent the full range of possible SFL, CBH, and CBD values characteristic of deciduous forests in Alberta. In comparison, all of the other FBP System fuel types included in the analysis had more than double the number of plots assigned to the deciduous fuel type.

Stands that we assigned to the D-1/D-2 Deciduous fuel type of the FBP System could have up to 19% conifer whereas stands assigned M-1/M-2 Boreal Mixedwood could have up to 69% conifer. It is the conifer component of the stand that was used to estimate CBH and CBD. This means that FCCs do not account for the effects of leafed-out deciduous trees on potentially inhibiting crown-to-crown fire spread during summer conditions. The FBP System fuel types and empirical models also fail to account for the effects of deciduous vegetation on crown fire behaviour, given the empirical models used to predict fire behaviour in the M-1/M-2 fuel type are based on observations of fires in C-2 Boreal Spruce and D-1 Leafless Aspen stands (Forestry Canada Fire Danger Group 1992).

FCCs are based on static fuel properties and do not describe the influence of stand structure on in-stand fuel

moisture and micro-meteorology. All of our predictions of potential crown fire behaviour are based on assumptions about the range of possible fire spread rates and expected SFC. These predictions are used solely to provide insight about potential crown fire behaviour in the FCCs and do not constitute a fire behaviour prediction system. Future observations of fires could be used to model the relationship between fuel moisture (i.e. the Build-up Index, BUI) and SFC in a given FCC. Likewise, empirical models could be used to relate fire spread observations in a given FCC to the Initial Spread Index (ISI). These empirical relationships are used in the FBP System, but model outputs are only produced for a single representative, standard fuel type condition and do not account for within-type variation in surface or crown fuel characteristics that influence in-stand fuel moisture and micro-meteorology.

In the absence of empirical fire behaviour models, the FCCs provide a means of understanding differences in potential crown fire behaviour based on well-established modelling approaches. The ability to differentiate stands according to their potential for supporting crown fire initiation and sustained crown fire spread has important management implications. Firstly, in boreal conifer vegetation, crown fires achieve intensities between 8000 and 150,000 kW m^{-1} (Van Wagner 1983) whereas direct suppression of the fire's edge by firefighters is limited to surface fires with intensities $<2000 \text{ kW m}^{-1}$ (Murphy et al. 1991; Hirsch et al. 1998; Hirsch et al. 2004). Because crown fires exceed the limits of suppression effectiveness, they pose a threat to public safety and any values in their path. Secondly, the vertical spread of fire upwards into crown foliage produces firebrands, which can be generated from individual torching trees (Albini 1979; Adusumilli et al. 2021), even if the stand does not have sufficient CBD to sustain an actively spreading crown fire. Firebrands carried aloft in the convective column pose a significant threat to any structures or values nearby (Caton et al. 2017; Suzuki and Manzello 2021). Identification of stands capable of supporting crown fire initiation and spread is therefore essential for mapping fuel hazards and identifying priority locations where fuel reduction or removal could be used to reduce risk (Beverly et al. 2020). Likewise, stands with fuel structures that inhibit sustained crown fire spread (i.e. Red and Green FCCs) could serve as strategic locations for potential fire containment lines.

Our FCCs, which differentiate stands based on their potential crown fire behaviour, did not align well with FBP System fuel types (Figs. 4 and 5). Within a given FBP System fuel type, the stands that we analysed exhibited substantial variation with respect to SFL, CBH, and CBD (Fig. 4). If variation in fuel structures within FBP System

Fuel types was less than variation between fuel types, we would expect our data-derived FCCs to either align with FBP System fuel types or present as subgroups within a given FBP System fuel type, which was not the case. Observations of stands assigned conifer-dominated FBP System fuel types (i.e. C-2 Boreal Spruce and C-3 Mature Jack or Lodgepole Pine) included a mix of FCCs. Notably, stands assigned the C-2 fuel type were dominated by Red and Black FCCs, which represented highly polarized stand structures that were assessed as being the least and most conducive to active crown fire, respectively. Stands assigned the C-3 fuel type exhibited less within-type variation in stand structures and consisted primarily of Blue FCC stands. The mixedwood and deciduous fuel types of the FBP system were both dominated by fuel structures represented by the Red FCC. Interestingly, the Mixed Conifer fuel category that was introduced for stands that did not conform with any of the FBP System fuel types assigned by Phelps et al. (2022) also contained a mix of FCCs, distributed somewhat evenly among Red, Blue and Black FCCs. It is noteworthy that over two-thirds of the stands in both Red and Green FCCs were also conifer-dominated and composed of black spruce or lodgepole pine trees (i.e. C-2 and C-3 FBP System fuel types), which are both considered crown fire ecosystems. These results are consistent with other studies that have shown that stand structure is more important to fire behaviour than the tree species in the stand (e.g. Brown and Bevins 1986; Fernandes 2009).

FBP System fuel types have been heavily relied upon by fire researchers and fire management agencies in Canada for several decades as foundational inputs to models and decision support tools that span multiple spatial and temporal scales of analysis (Wotton 2009; Taylor et al. 2013). Our results provide compelling visual and quantitative summaries of the extent to which fuel structural conditions can vary within stands assigned a given FBP System fuel type; but they also highlight that different stand types, composed of different tree species, can present with similar fuel structural attributes. The ranges of within-type variation that we have documented for FBP System fuel types provide insight into the uncertainty of the fuel input data widely relied upon for instantaneous fire behaviour predictions, as well as spatially-explicit fire growth simulations conducted for longer time periods (i.e. several hours or days) with models like the Prometheus Fire Growth Model (Tymstra et al. 2010). Despite the overall lack of alignment between FBP System fuel types and FCCs, fuel types were one of the underlying factors that influenced stand membership in a given FCC. Results of tree-based modelling (Fig. 7) and a random forest (Fig. 8) indicated the influence of FBP

System fuel types on FCC membership was surpassed only by the stand density of live conifers.

To explore the implications of variation in stand structural attributes for crown fire behaviour prediction within a given fuel type, we focussed on the C-2 Boreal Spruce fuel type that consisted of black spruce-dominated stands, which are a prominent boreal stand type in Canada (National Forest Inventory 2013) and prone to high-intensity crown fires (Van Wagner 1983). Results indicated that under equivalent fuel moisture and wind speeds, potential fire behaviour can vary dramatically in stands characterized as the C-2 fuel type. This finding is consistent with other studies that have shown fuel-driven fire behaviour differences in black spruce stands, primarily associated with the stand development stage. Johnston et al. (2015) found that CBD in black spruce bogs in Alberta increased over time. In that study, stands had sufficient CBD to support active crown fire after 60 years of stand development, under reasonably high fire danger conditions. Analysis of containment success in stands classified as C-2 in Alberta showed that fires that occurred during the initial decades of post-fire stand development were less likely to escape fire suppression efforts, likely due to fuel-limited conditions that would be expected in younger stands (Beverly 2017). In our random forest analysis, coniferous age was the third most important factor that explained FCC membership (Fig. 8), although it was not sufficiently important to be utilized in the classification tree (Fig. 7).

Fuel treatments were effective at changing modelled crown fire behaviour in the Black FCC, which was found to be most susceptible to crown fires. Fuel reduction treatments in stands that belonged to the Black FCC prior to treatment were effective at shifting the stand to an FCC with reduced crown fire potential in all but one case. Following treatment, stands had reduced CBD, which corresponded to a reduction in the active crown fire rate of spread under otherwise equivalent weather conditions (Fig. 9). While effective for inhibiting sustained crown fire spread, the fuel reduction treatments conducted in the stands we analysed did not have a substantial impact on the probability of crown fire development. These results suggest that fuel treatments in black spruce stands, which produce unnatural fuel structures for the purpose of protecting values (Beverly et al. 2020), do not remove the potential for involvement of crown foliage in combustion and associated firebrand production that is known to pose a threat to any nearby structures (Caton et al. 2017; Suzuki and Manzello 2021).

To explore potential crown fire behaviour in our FCCs, we used two well-established crown fire modelling approaches: the combined Byram (1959) and Van

Wagner (1977) models and the Cruz et al. (2004, 2005) empirical statistical models. In the case of the latter, we equated CBH with the fuel strata gap (FSG) measurement used by Cruz et al. (2004, 2005). FSG is defined as the distance between the lower limit of the canopy fuel stratum, which includes live trees and ladder fuels, and the top of the surface fuelbed (Cruz 1999; Cruz et al. 2004). Cruz et al. (2004) note that FSG is equivalent to live canopy base height in some stands and we considered our CBH measurements an acceptable substitute for FSG for our modelling purposes. Our calculations of CBH accounted for some ladder fuels by including saplings that overlapped with the canopy fuel strata in CBH calculations (Phelps et al. 2022). In cases where the surface fuel strata extended vertically, but conifer saplings were either absent or did not overlap with the canopy fuel strata, CBH would overestimate the separation between canopy and surface fuels represented by FSG, resulting in an underestimate of potential crown fire occurrence.

Crown fire behaviour predictions in each FCC that we reported for the Cruz et al. (2004, 2005) statistical model in Fig. 3 were computed for the centroid of each FCC, which we expect would dampen the effect of any underestimates of FSG in individual stands. Comparisons of predicted crown fire behaviour in stands assigned the C-2 fuel type (Fig. 6) could potentially underestimate crown fire development in some stands if FSG was not well represented by our CBH measurements. For the comparison of treated and untreated stands in Fig. 9, we expect CBH in treated stands to conform well with FSG due to the removal of surface fuels. Accordingly, any underestimates of FSG in untreated stands would not undermine our finding that fuel treatments were ineffective at reducing potential for crown fire development. Results of the Cruz et al. (2004, 2005) crown fire behaviour predictions for our FCCs were also consistent with the results of the Byram (1959) and Van Wagner (1977) modelling results, which suggests our use of CBH as a substitute for FSG did not compromise the analysis.

We demonstrated the process of classifying fuels directly from field inventory data and used our data-derived FCCs to explore differences in potential crown fire behaviour and summarize the within-type variation in fuel structure for several FBP System fuel types. Our results provide general insight into the limitations of vegetation-based fuel classification schemes like the FBP System that use the *association* method for fuel description. Updates to the FBP System are currently under development to enable predictions for a much broader range of fuel conditions (Canadian Forest Service Fire Danger Group 2021). Central to these updates is a new mixed modelling framework that deconstructs fire behaviour processes into individual components that include

surface fire behaviour, transition to crown fire, and crown fire behaviour. This new framework has been designed to accommodate new and emerging sources of information about forest structure and composition. Fuel attributes associated with our FCCs could potentially be used as inputs to these new FBP System models to further investigate the role of stand structure on potential fire behaviour.

Unfortunately, site-specific measurements of SFL, CBH, and CBD are generally unavailable for large areas, due to the time and cost involved in conducting field inventories. Furthermore, the four FCCs we have identified do not represent all fuel types in Alberta. Despite these limitations, the FCCs presented here are representative of several important fuel types in Alberta that occur across Canada. High-resolution vegetation inventory systems, LiDAR and other technological and remote sensing advances may soon offer an alternative to field measurement for mapping fuel structural attributes and FCCs across broad areas. For example, Cameron et al. (2022) recently used data collected from an airborne laser scanning (ALS) system (i.e. LiDAR) to predict CBD and stand density for black spruce stands in Alberta. Recent research suggests that ALS also has potential for estimating SFL in coniferous forests with a dense overstory (Stefanidou et al. 2020). Compared with collecting field samples, ALS-derived fuel attributes are more cost-effective and less time-consuming. An ALS system could potentially be used to map FCCs across large regions and develop new FCCs in the years ahead. Furthermore, given that a stand's FBP System fuel type is also an important indicator of its FCC membership, FBP System fuel type could potentially be incorporated into a model to predict FCC membership in conjunction with ALS data.

5 Conclusion

Fuel inventory data collected with traditional fuel sampling methods proved well-suited to a fuel description approach in which fuel classes were derived directly from the data with K-means clustering. Data-derived fuel class clusters (FCCs) based on measurements of surface fuel load (SFL), canopy base height (CBH) and canopy bulk density (CBD) did not align with the fuel types of the Canadian Forest Fire Behaviour Prediction (FBP) System. FCCs explained more of the stand-to-stand variability in modelled crown fire behaviour than FBP System fuel types and when considering stands classified as the C-2 Boreal Spruce fuel type, potential crown fire behaviour was shown to vary dramatically due to within-type variation in fuel attributes. Fuel treatments conducted in the FCC most conducive to crown fire initiation and active crown fire spread (i.e.

the Black FCC) were effective at changing the stand's fuel class and inhibiting crown fire spread, but did not affect the potential for crown fire development. FCCs presented in this study could eventually be mapped across large areas to enable more refined fire behaviour predictions by using stand attributes derived from LiDAR or other technological and remote sensing advances expected in the years ahead.

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Code availability

N/A.

Authors' contributions

Conceptualization, supervision [Jennifer L. Beverly]; formal analysis and investigation: [Nathan Phelps]; and methodology, writing - original draft preparation [Nathan Phelps, Jennifer L. Beverly]. The authors read and approved the final manuscript.

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Availability of data and materials

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Declarations

Consent for publication

All authors gave their informed consent to this publication and its content.

Competing interests

The authors declare that they have no competing interests.

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