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- Kelly Osbourne, Fire Science Forester, BCWS, FLNRORD
- Tim Salkeld, Team Lead- VRI Data Management, Forest Analysis and Inventory Branch, FLNRORD
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- Rory Colwell, Forest Protection Officer (Central Cariboo Zone), BCWS, FLNRORD
- Brian McIntosh, retired (previously Fuel Management specialist, Coastal Fire Centre and Superintendent of Fuel Management, BC Wildfire Management Branch)
- Stan Harvey, retired (previously Senior Protection Officer-Operations, Prince George Fire Centre, BC Wildfire Management Branch)
- Judi Beck, former Fire Science Officer and Manager, Fire Management, BC Wildfire Management Branch (now with Natural Resources Canada)

Introduction

"Fire managers must rely upon the fuel type descriptions to equate FBP System fuel types to existing forest inventory/site classification schemes […], including the production of FBP System fuel type maps." [1]

1. Background: fire behaviour prediction and the CFFDRS in British Columbia

This document provides the technical description for the British Columbia (BC) provincial Fuel Type Layer (FTL) used by the British Columbia Wildfire Service (BCWS) as well as forestry and wildfire researchers and consultants. The FTL is a geographic dataset (spatial layer) used to inform fire behaviour prediction at multiple scales and in various contexts within the realms of wildland fire management and research.

Fire behaviour prediction is the science and application of predicting characteristics of wildland fire such as ignition, spread rate and intensity (Pyne et al. 1996, Canadian Interagency Forest Fire Centre (CIFFC) 2003). The main variables affecting wildland fire behaviour are fuels, current and antecedent weather, and topography — all characteristics that comprise the fire environment (Countryman 1966). Broadly, the term 'fuels' encompasses vegetation and biomass structure, biomass loading, dominant species (especially for treed landscapes), and other features such as forest floor characteristics and forest health issues (e.g. outbreaks of bark beetles or other insects) that affect the flammability and availability of biomass for combustion.

Fuel properties are recognized as critical to wildland fire behaviour. While weather and climate effects have been shown to be the major determinants of large fire development across North America (Skinner et al. 1999, Gedalof et al. 2005), fuel composition and structure remain highly significant. To paraphrase the opening statement from a recent review – while fires can occur without the influence of topography and in diverse weather conditions, without fuels there is no fire (Parsons et al. 2016). The importance of fuels in fire behaviour is recognized at fine and coarse scales. A recent continent-scale comparison of fire radiative power between North America (including BC) and Eurasia noted higher fire intensity values in Canada than in Russia; this difference was attributed to Canadian spruce-pine forests supporting crown fire much more readily than Siberian larch forests, despite similar fire weather in the two regions (Rogers et al. 2015). Other modelling studies have discussed at length the importance of fuels in determining burn probability and landscape flammability in Canada and across North America (Amiro et al. 2001, Parisien et al. 2011, Parks et al. 2012). Managers tend to focus on fuels as they represent the only element in the fire behaviour triangle that can be manipulated to mitigate fire behaviour (Fernandes and Botelho 2003).

Because of the diversity of terrestrial ecosystems in BC, describing fuels for fire behaviour prediction purposes is a complex task, and one that can be approached in different ways. Fuels can be described qualitatively (using discrete fuel types) or using various quantitative variables related to fuel structure or the amount of available fuel: total dead fuel loading, fuel load by particle size class, tree height, crown base height, live biomass load, and other characteristics (Keane 2013). Across Canada, the primary modeling system used by operational fire management agencies for fire behaviour prediction is the Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al. 1989, Taylor and Alexander 2006), which uses the fuel types described in the Fire Behaviour Prediction (FBP) System, a sub-component of the CFFDRS (Forestry Canada Fire Danger Group 1992, Wotton et al. 2009). The FBP System represents a primarily qualitative approach to fuel classification, one which matches the structure and assumptions of its overall empirical (as per Sullivan 2009b) modelling system approach (i.e., the CFFDRS). The FBP System fuel types, though limited in number, are generally considered effective at covering most fire-prone areas of Canada, including BC. Many documents have been published demonstrating the effectiveness and relative accuracy of the CFFDRS and FBP Systems in characterizing fire behaviour in wildfire events in BC and across North America (e.g. Alexander 1991, Hély et al. 2001, Alexander et al. 2013, Perrakis et al. 2014b), particularly for crown fires in conifer and mixedwood forests.

A full review of fuel measurement and characterization, including the benefits and limitations of different modeling systems, is beyond the scope of this document. As the operational agency tasked with managing wildland fire in the province, the BC Wildfire Service (BCWS)[2] relies on the CFFDRS for many aspects of wildland fire management, including operational fire behaviour prediction (decision support related to safety, suppression efficiency, tactics, aircraft and equipment use, etc.); fire season preparedness and resource pre-location; regulation of industrial and recreational activities; participation with national and interagency resource exchanges and working groups; training for suppression staff; and modeling of fire hazard and risk for planning and risk mitigation purposes outside the fire season. The depth of experience among BC fire management personnel with the current and past versions of the CFFDRS spans decades for senior members. Thus, one fuel and fire behaviour prediction system is used provincially for the vast majority of fire management tasks in the province. In step with other fire management agencies across Canada, that system is the CFFDRS/FBP System (Taylor and Alexander 2006), and is likely to remain such for the foreseeable future. A brief discussion of alternatives to the CFFDRS can be found in Section 9, although these are not emphasized in this report.

The focus of this document is the description of the process by which the entire geographic surface of BC is categorized into one of the FBP fuel types for wildland fire behaviour prediction purposes. Those areas considered non-flammable – primarily water bodies, alpine rock and ice, developed agricultural (irrigated),

1 From B.J. Stocks, B. D. Lawson, M. E. Alexander, C. E. Van Wagner, R. McAlpine, T. J. Lynham, and D. E. Dube. 1989. The Canadian Forest Fire Danger Rating System: an overview. The Forestry Chronicle 65:450-457 (p. 454).

2 The BC Wildfire Service is a branch of the Ministry of Forests, Lands, Natural Resource Operations and Rural Development; see http://bcwildfire.ca.

urban, or fully cleared surfaces – are included in this process and typed as non-fuel or water, as described in detail in Section 5.5.

1.1 History of FBP fuel typing in BC

The present process builds upon a number of similar initiatives previously conducted in BC and elsewhere aimed at categorizing the provincial landscape for fire behaviour purposes. As the first version of the CFFDRS was being documented, Stocks et al. (1989) initially suggested that fire managers should use the FBP fuel type descriptions to develop agency fuel type maps based on forest inventory data. Hawkes et al. (1995) developed the first such scheme for classifying portions of BC into FBP fuel types, using spatial data at a 4 km^2 resolution as part of an early fire threat analysis. Taylor et al. (1998) followed with an effort that included succession modeling of stand and fuel changes over time in southern interior BC.

Between approximately 1999 and 2001, with the increasing availability of GIS platforms and spatial data, a full provincial fuel type spatial data layer (FTL) was produced by J. Beck and G. Eade (unpublished files, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), Victoria, BC) that provided FBP fuel type information across the province at a 0.25 hectare resolution based on the then-new Vegetation Resource Inventory initiative (see Section 2, below). The Beck and Eade layer was static thereafter, not reflecting any disturbances, forest growth, or land cover changes since it was developed. After several years that included major disturbances (significant wildfire years and the largest mountain pine beetle epidemic in provincial history, among others) the limitations of the existing layer became apparent, as was the need for a dynamic process that included periodic updates. A Fuel Typing Task Group (see Acknowledgements section, below) was established in 2009, made up of personnel from the BCWS (at the time called the BC Ministry of Forests Protection Branch), but the group was dissolved in early 2011 when it became apparent that the detailed steps of the fuel typing algorithm were not conducive to the 'committee conference call' approach. In 2011, the responsibility was turned over to the present authors to produce a draft decision matrix for a new FTL, which at that time was 10 years old and seen as outdated.

After several iterations and revisions, the BCWS (then called the Wildfire Management Branch) adopted a trial version of FTL for operational use in 2013 in calculations using the Spatial Fire Management System and other software applications (see Section 3). An informally-published version of the present document describing the FTL was finalized in early 2016 (with the analysis and results based on the 2015 vegetation data, reflecting 2014 conditions) and posted to the BC Wildfire Service website (Perrakis and Eade 2016). The present document represents a more formalized and updated version of the FTL including important changes in the treatment of areas burned in the past decade or so (see Section 5.5).

1.2 FBP Fuel typing across Canada

In addition to BC, most provincial and territorial wildfire management agencies in Canada have developed schemes for fuel typing their lands under fire management responsibility. Several of these approaches are available as published reports. For example, the Province of Quebec (Pelletier et al. 2009), the Yukon Territory (Ember Research Services Ltd. 2002), several areas managed by Parks Canada (e.g. Wilson et al. 1994, Achuff et al. 2001) and a number of national schemes[3] (e.g. Nadeau et al. 2005) have been documented and present best-fit FBP fuel type maps for large areas of Canada. The principal problem throughout these various efforts has been how (or even *if* it is appropriate) to assign the most representative FBP fuel type to the wide variety of vegetation types and structures that comprise a particular administrative area. The challenge exists given that vegetation communities defined and described by forest inventory variables are usually aimed at informing timber management objectives rather than fire behaviour prediction. This results in a certain degree of subjectivity associated with fuel type assignments, since the forest inventory data is often lacking the details needed to assign FBP fuel types using purely objective or scientific criteria. This is discussed in greater detail in Section 5.3.

1.3 The challenge and subjectivity of FBP fuel typing

Similar to these other fuel typing schemes, the present process was based as much as possible on objective criteria, including scientific studies, experimental burn data, wildfire documentation, and informed assumptions from fire behaviour theory. However, much of it was ultimately based on the experience of the authors and those of our colleagues[4] from observing fire behaviour in the field, as well as our ability to express in computer code various informal heuristic practices, generally recognized by practitioners as 'rules of thumb' (see also Section 5.3). Although we have striven for clarity and transparency as much as possible in this document, the FBP fuel typing process is inherently subjective, and the vegetation communities of BC frequently fall through the cracks between the FBP fuel types. Empirical fire behaviour prediction systems require a very large dataset of studied fires, and in a large and diverse province such as BC, many additional fuel types would need to be studied and defined to encompass the variety of terrestrial ecosystems. The broad goals for all of these efforts are to improve fireline safety and fire management efficiency; secondary objectives include overall institutional accountability and transparency, and facilitating continuous improvement in fire behaviour prediction and wildfire management in general.

2. Objective – BC Provincial Fuel Type Spatial Data Layer (FTL)

The objective of the fuel characterization process was to produce a spatial data layer that classified the provincial area into FBP fuel types. The resultant product is termed the Provincial FBP Fuel Type Layer (FTL), and consists of polygon and raster

3 The Canadian Wildland Fire Information System (CWFIS), which consists of online publicly-available tools and an interface for monitoring wildfire activity across Canada, includes an up-to-date national fuel type layer produced by the Natural Resources Canada-Canadian Forest Service; see http://cwfis.cfs.nrcan.gc.ca/home. Contact Brian Simpson at the Northern Forestry Centre (brian.simpson@canada.ca) for more information.

4 Additional contributors and reviewers are listed in the Acknowledgements section.

datasets that provide forest fuel type information for all of BC for fire behaviour prediction and related purposes. The FTL was assembled primarily from FLNRORD forest inventory data from the provincial Vegetation Resource Inventory (VRI) program[5]. The VRI dataset, in turn, consists of a set of polygons and their respective land cover attributes[6] covering all of BC. The resulting dataset consists of over 4.7 million VRI polygons (and consequently, fuel type polygons in the FTL) representing over 94 million hectares of land area, which were finally processed into a raster grid for further treatment in fire behaviour software modeling systems.

The basis for converting VRI polygons to FBP fuel types was an extensive set of decision rules (called the ‘fuel type layer algorithm’), fully documented in Appendix 5. These decision rules describe the conversion details between vegetative, ecological, and stand history variables, including forest harvesting and other disturbances and management activities, and best fit FBP fuel types, and represent the technical heart of the fuel typing process.

The algorithm has been assembled based on the authors’ experience in implementing the FBP System in British Columbia, with considerable input from other members of the BCWS Fire Behaviour Specialist Working Group (FBS WG). The FBS WG is continually involved in the process of updating and refreshing the algorithm, as new evidence is incorporated including observations from wildfires and prescribed burns, published case studies, and new research findings. The results of this effort are shown in this document as tables and simplified maps of the final output layers (Section 8). However, the main benefit is the use of these products by the BC Wildfire Service and other contractors and professionals for operational forecasting, planning, and simulations. These specific uses are discussed in Section 3.

The FTL is refreshed annually following the VRI update cycle, which typically occurs during the winter or early spring. Since the process is labour-intensive, a biennial (every two years) update schedule is being considered for future updates.

3. Uses and limitations of Fuel Type Layer

The FTL is used as the basis for FBP System-based fire behaviour modeling and forecasting across the province at multiple scales and in different contexts:

- At the operational wildfire incident level, the FTL can be used as a starting point for fire behaviour forecasting and tactical planning; a fuels map based on the FTL is a typical starting guide prior to more detailed field assessment of fuels
- At the regional (e.g. BCWS Fire Centre) level, modelling based on the FTL can help with wildfire regulation, including bans on industrial and recreational activity; additionally, Fire Behaviour Advisories issued to alert suppression crews based on forecast headfire intensity; and for other purposes related to resource preparedness for operational fire management
- At various spatial and temporal scales, the FTL serves as a base layer for running fire behaviour modeling software applications based on the FBP System:
  - SFMS (Spatial Fire Management System; see Figure 1) – provincial-scale daily and hourly approximations of fire behaviour and danger rating (Englefield et al. 2000)
  - Prometheus (fire behaviour simulation program, scenario-based) – for fine scale, incident-based fire behaviour prediction for operational use and planning (Tymstra et al. 2010); a batch version that can run multiple simulations at once is also available as a standalone program, called Pandora[7]
  - PFAS (Probabilistic Fire Analysis System) – long-term fire behaviour simulation program for fire incidents, for estimating probability and direction of large fire growth using climatology (Anderson 2010)
  - Burn P3 (Burn Probability, Prediction, and Planning) – regional scale fire probability and risk modeling system, using simulations of thousands of fires based on local fire history (Parisien et al. 2005, Parisien et al. 2013)
  - CanFire (Canadian Fire Effects model; formerly BORFIRE, or Boreal Fire Effects Model) – model of fire impacts, emissions, and tree mortality (De Groot 2006, 2010)
- At the regional and provincial level, the FTL has been used for producing fire risk and threat analyses. These typically incorporate fire behaviour calculations based on benchmark weather conditions (Hawkes and Beck 1997, Beck and Simpson 2007).

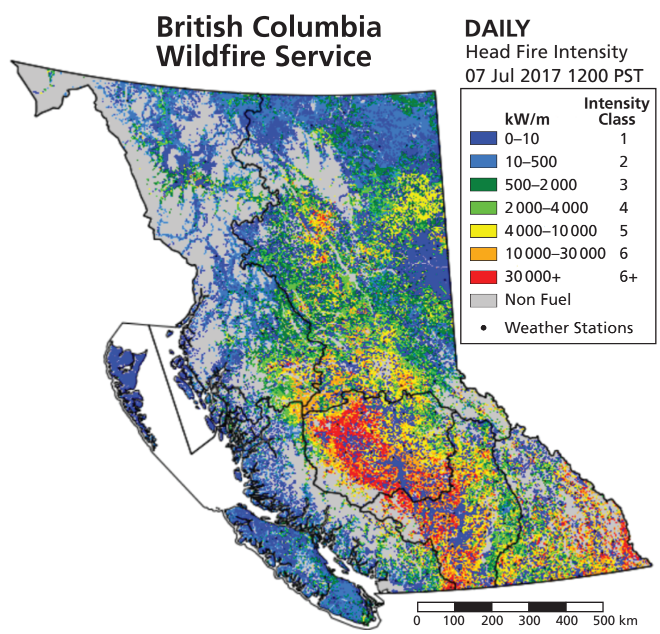

Figure 1. Example of Headfire Intensity screen from BC’s implementation of the recently updated Spatial Fire Management System (Englefield et al. 2000).

5 For a full description of the VRI program, including recent updates, see https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/data-management-and-access.

6 https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/standards/vegcomp_poly_rank1_data_dictionary_draft40.pdf.

7 See also http://firegrowthmodel.com/Prometheus/overview_e.php and http://www.firegrowthmodel.ca/pandora/overview_e.php.

Operational and long-term use of the FTL is ongoing. The BCWS recently produced a province-wide Provincial Fire Threat Analysis (PSTA) in 2016 based on a 2014 draft version of the FTL (Anonymous 2016b). However, that version of the FTL did not include any fuel type modifications due to the recent mountain pine beetle outbreak (see Section 5.4.2) or recent wildfire disturbances (see Section 5.4.6). Modifications reflecting these land cover changes, given data limitations, have been included as best as possible in the present document. An updated version of the PSTA is currently being finalized using the present FTL (Kelly Osbourne, BC Wildfire Service, personal communication September 2017).

An important decision was made early on to make the fuel type layer seamless, representing the entire land area of the province with no 'blanks' or 'white areas' on the map; this was a software requirement for running some of the modeling programs. Additionally, a seamless layer was deemed important to at least provide some minimum information on fire behaviour potential for all areas of the province. It is of little benefit to leave blanks on the map, which suggests that nothing at all is known about fuel structure in a particular area, and therefore nothing can be predicted about fire behaviour.

While every effort was made to produce a comprehensive fuel type product useful for detailed fire behaviour prediction, the FTL is not intended to replace local ground-truthing of the vegetation in the selection of best-choice fuel type. The FTL process and algorithm are updated annually and when new information becomes available; this is done at the province-wide scale, and often misses detailed stand-level information that can have a significant effect on fire behaviour characteristics. Operational fire behaviour prediction, in particular, demands proper ground-truthing of fuel type and fuel structure. A broader discussion of field verification of vegetation and fuel type attributes can be found in Section 9.2.

Methods

4. Fuel Type Layer development process

4.1 Spatial data and pre-processing

Although most of this document describes a process for selecting FBP fuel types, implementing these choices operationally involved many steps of spatial data processing and manipulation. Several procedures needed to be completed to prepare the BC VRI dataset ('Veg comp poly rank1') for fuel typing using the FTL algorithm, while other processes were developed to fill gaps in the VRI where data was nonexistent or suspect. Additional details around VRI data gaps can be found in Section 7.

This pre-processing consisted of four steps, primarily implemented by running Python (Python Software Foundation, Beaverton, Oregon, USA) scripts in an ArcGIS 10.3 (Environmental Research Systems Institute, Redlands, California, USA) environment:

- Defining a layer of recently harvested cutblocks
  - This layer is a product ('Consolidated_Cutblocks') produced by the Forest Analysis and Inventory Branch; our process used the harvest openings from the past 10 years to reflect disturbances newer than the latest VRI updates
- Dissolving VRI polygons smaller than one hectare into their larger neighbours
- Importing additional data to fill gaps in the VRI layer from Tree Farm License (TFL) and private land holdings, where possible; see Section 7
- Importing data from the Canadian Forest Service national fuel type raster (as described in Section 1.1) to fill gaps where data from private landowners and TFL areas was unobtainable; see Section 7
- Cleaning-up problem polygons that were known to cause errors when processed using the fuel typing algorithm
  - This applied to certain ocean areas, polygons with missing geometry, missing biogeoclimatic zone[8] information, very old Harvest_Date attributes (pre-1900), etc.

These pre-processing steps were much more technically involved than the cursory description provided here. Additional details can be provided upon request.[9]

After these steps were completed, the resultant polygon layer was ready for the main processing steps described in the fuel typing algorithm (shown in full detail in Appendix 5). This was implemented in a Python script to produce a final classified fuel type polygon dataset. The polygon layer was then converted to a 0.25 ha (50 x 50 m) raster layer for ready use by fire modeling applications, as previously described (Section 3).

The final step in assembling the fuel type layer was to append the fuel type raster data from neighbouring administrative areas (Yukon Territory, Northwest Territories, Alberta, and northern sections of the USA states Washington, Idaho and Montana) to the BC border. This process is described in section 5.5.

4.2 FBP System fuel type descriptions

As previously described, the FTL fuel types consist of the standard fuel types from the Canadian Forest Fire Danger Rating System, Fire Behaviour Prediction System (see Forestry Canada Fire Danger Group 1992, Wotton et al. 2009). The Appendix sections (Appendix 1 and Appendix 2), contain more detailed descriptions from these formal sources.

A brief overview of the FBP System fuel types follows, including their application for fire behaviour prediction in BC vegetation types.

8 See the BC BECWEB site for more information: https://www.for.gov.bc.ca/hre/becweb/.

9 Processing details are documented in the working document 'WMB Fuel Type Update', by George Eade, Geo-Tech Systems; latest version written in September 2017 and held by BC Wildfire Service, Prevention Section, Victoria, BC.

- There are 16 official FBP System fuel types, although some of these are seasonal variants (e.g. M-1 and M-2); one unofficial type is also frequently used (D-2; Alexander 2010); additional new fuel types (official or unofficial) may be used in near future (e.g. C-3R for red-attack mountain pine beetle-killed stands; Perrakis et al. 2014b)[10]
- In general, fuel types are defined in the FBP System by overall vegetation structure (e.g. mature conifer forest); dominant species (e.g. fully stocked lodgepole pine)[11]; and understory, ladder fuel, and forest floor characteristics (e.g. continuous feathermoss with a sparse understory conifer layer)
- Each fuel type model consists of a set of empirically-derived parameters for use in rate of spread equations and fuel consumption equations, as well as other constants (crown base height (CBH), crown fuel load (CFL), buildup effect parameters). Most of these values are meant to be constants used in calculations, applied categorically to the discrete fuel types; they are not considered 'user inputs' and are not meant to be modified, except in certain well-understood cases, as follows:
    - The M-1 and M-2 fuels have a 'percent conifer' (%C) value from 0 to 100 that must be specified
    - In many software applications, a green-up date switches between the 'leafless' (M-1, M-3, D-1) and the 'green' or 'leafed-out' (M-2, M-4, D-2) fuel type on the estimated date of deciduous bud-flush, in late spring or early summer
    - The M-3 and M-4 fuel types have a 'percent dead fir' (%DF) value from 0 to 100 that must be specified, and a green-up date can be used to switch between these two types
        - However, M-3 and M-4 are not typically used in BC, except in one specific case – red-phase mountain pine beetle-attacked pine stands; see Section 5.4 below
    - The 'Open' O-1 fuel type, typically used for grass fuels, has several parameters than can be user-selected, making it highly flexible:
        - O-1 has two variants, each with separate parameters, that define the matted (winter/spring; O-1a) and standing (summer/early autumn; O-1b) phases, respectively;
        - Some software applications use a grass green-up date for switching between O-1a to O-1b
        - A 'percent curing' (%c) value from 0 to 100 must be specified, describing to what extent the new growth has cured, or become desiccated; this is highly influential on fire behaviour
        - a grass fuel load value (0 to about 20 t/ha) can be specified which affects fire intensity (but not spread rate); alternatively, the national default value (3.5 t/ha; Wotton et al. 2009) can be used
    - The C-6 value has a 'crown base height' value that must be specified; however, this fuel type is not used at this time in BC (see section 5.4.1 below).
- Other than the quantitative constants and variables mentioned above, vegetation characteristics that define fuel types are described only qualitatively. Thus, users must rely on their own experience and training to identify and characterise forest stand structure terms such as 'well-stocked', 'moderate density', 'continuous [or discontinuous] litter', 'shallow', 'moderately deep' and so on.
- The FBP System outputs include a variety of primary and secondary fire behaviour characteristics; however, the outputs of greatest interest are usually rate of spread (ROS) and frontal intensity (as per Alexander 1982), referred to here as headfire intensity (HFI), as per FBP System convention.

Figures below show examples of predicted ROS (Figures 2–3) and headfire intensity (Figure 4) for most fuel types used in BC. For fuel types with variable user-controlled parameters, commonly used examples are provided (e.g. M-2, 50% conifer). While the HFI values go off the chart for certain fuel types (Figure 4), the relationship between fuel types is apparent from the graph.

Although the output values shown in these figures (ROS and HFI) are dependent on certain assumptions regarding weather

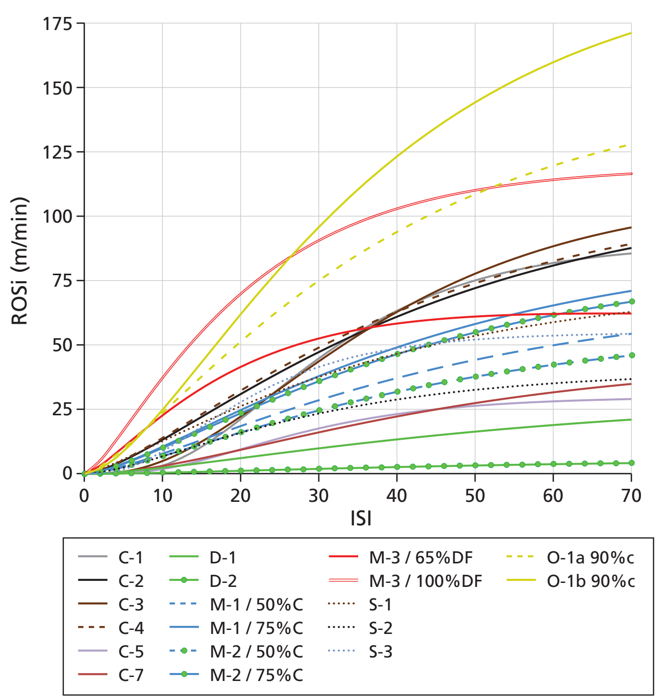

Figure 2. Initial rate of spread (ROSi) curves for most FBP fuel types on flat ground; ISI represents the Initial Spread Index; excludes Buildup Index effects on spread rate. Fuel type abbreviations are described in Section 4.2.

10 At the time of writing, the authors are aware that operational sections within the BCWS occasionally use fuel types developed internally that have not been formally documented and are not official FBP fuel types. Thus, the 'modified C-3' and 'C-7b' fuel types are used for certain operational processes, such as preparedness planning; these are not considered here. Contact the authors for further details.

11 Common names are used for all vegetation species in this document (as per forestry conventions in British Columbia and the BC Vegetation Resource Inventory standards); see Appendix 3 for species codes and Latin names.

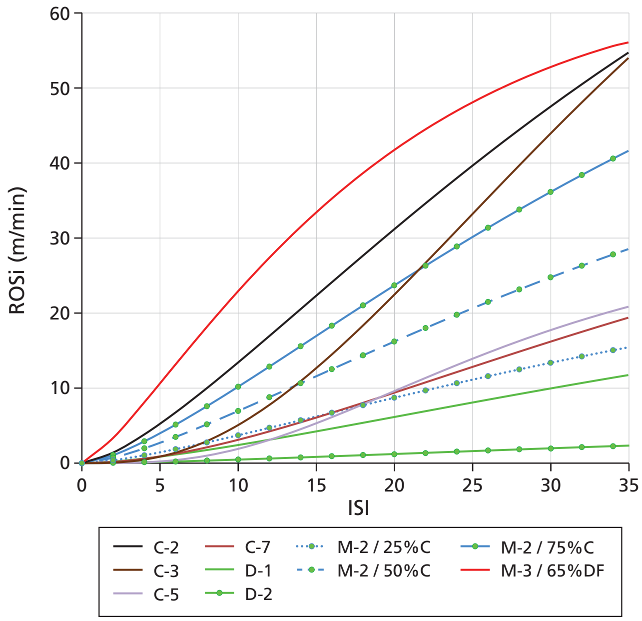

Figure 3. Initial rate of spread (ROSi) curves for most common forest fuel types on flat ground; lower ISI values only for greater detail. Fuel type abbreviations are described in Section 4.2.

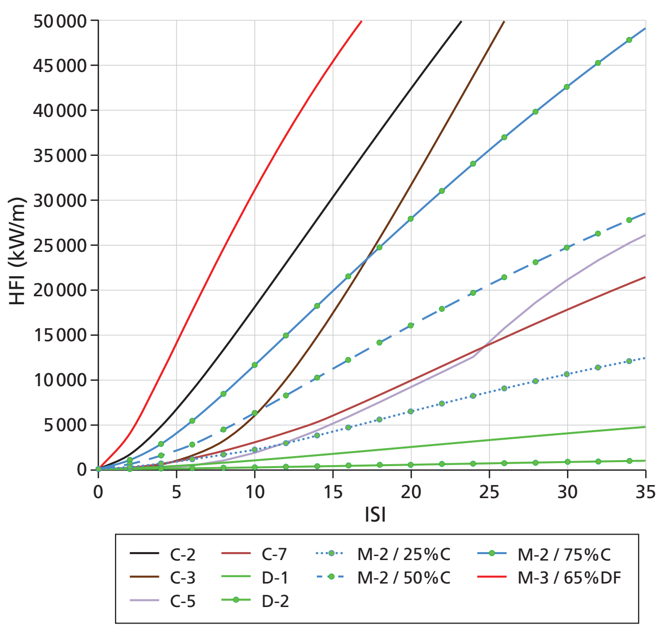

Figure 4. Headfire intensity (HFI) of common fuel types at lower ISI values; excludes BUI effects on spread rate. Assumptions: FFMC 91, BUI 70, FMC 97, flat ground; curve shapes are approximate. Fuel type abbreviations are described in Section 4.2.

and fuel moisture, particularly for HFI (Figure 4), the relative ranking of fuel types in terms of these fire behaviour characteristics is generally consistent. For example, the C-3 fuel type exhibits a faster spread rate and higher HFI than C-7, C-5, D-1 or D-2 for any given combination of fire weather index conditions. The C-2 fuel type has higher ROS and higher HFI than C-3 in most conditions, though the reverse is true at very high or extreme ISI levels (ISI >36 or so), due mostly to the higher CFL value of C-3 [12]. Similarly, the C-2 fuel type by definition has faster spread and higher HFI than any percent conifer value of boreal mixedwood (M-1 or M-2) fuel type, as these are an arithmetic blend of C-2 and the much less volatile D-1 type (Forestry Canada Fire Danger Group 1992). The only ambiguous rankings (where rankings vary depending on FWI values) between commonly used fuel types in BC are between C-5 and C-7. These fuel types have approximately similar spread rate relationships, with subtle but potentially important differences in initial spread rate at various weather index levels (Figure 2; Figure 3). The HFI ranking between C-5 and C-7 therefore depends on ISI and BUI levels, as well as the fixed CBH and CFL values (C-7: 10 m CBH, 0.5 kg/m^3 CFL; C-5: 18 m CBH, 1.5 kg/m^3 CFL; Forestry Canada Fire Danger Group 1992).

The other highly variable fuel type is O-1 (*a* and *b* variants), which varies from the fastest-spreading fuel type at high curing rates (Figure 2) to barely above zero fire spread at lower curing rates (not shown; see Wotton et al. 2009, Taylor and Alexander 2016). This makes working with the O-1 fuel type challenging, as the variables of interest, particularly curing, change constantly throughout the fire season.

These figures, showing relative spread rates and HFI values predicted by the different FBP fuel type models, as well as structural models related to the FBP system data (Cruz et al. 2004, Alexander et al. 2006) were used often in the fuel typing process as a means of comparing the various fuel type models.[13]

5. Fuel typing process, decisions, and assumptions

5.1 Fuel Typing Algorithm and BC Vegetation Resource Inventory

The fuel typing algorithm defines the detailed decision rules that were used to classify a polygon into one of the FBP fuel types (or identify it as non-fuel), based on the BC Vegetation Resource Inventory (VRI) 'Veg comp poly rank1' layer attribute data. The current algorithm, used operationally by BCWS in 2017, is shown in Appendix 5.

In order to assign the best-fit fuel type for predicting fire behaviour, vegetation inventory attributes were interpreted using a logical hierarchy of increasing detail. Attribute values for a polygon include very basic vegetation information (e.g. describing a spatial polygon as vegetated or non-vegetated – BCLCCS Level 1; see 'Coarse classification' below) as well as more detailed structural characteristics, such as the percentage of a forest stand that is dead (due to mortality from insects and pathogens), for

12 As explained in FBP System formal documentation, several common data points were used for curve-fitting the extreme end of the C-2, C-3 and C-4 fuel type ROS models. Therefore, the differences between fuel type ROS models at high ISI values is an artefact of the regression process, not an actual difference based on observations.

13 The FBP Graphing Tool, created by author DDBP, is a MS Excel-(Microsoft Corp., Redmond, Washington, USA) based tool for comparing fuel type models, available for public download. See https://www.researchgate.net/publication/295263648_FBP_Graphing_Tool.

example. Additional attributes provide detailed quantitative values from measured, projected (modelled), or interpreted sources (e.g. tree height, crown closure, percent of dominant trees of a certain species), based on VRI standards. Although the VRI data model contains over 100 attribute fields, many attributes are frequently not populated (i.e. contain null values). This is sometimes because the attribute does not apply to a particular stand or location. There are, for example, attributes for up to 6 different species of trees; stands with 1 or 2 species will have null values for Species #3 through Species #6. In other cases, the attribute could apply, but has not been populated due to decisions made or data available at the time of data entry during the inventory interpretation process. For instance, many treed stands do not have the 'Site_index' attribute populated, since this attribute (representing a modelled estimate of forest productivity) has not been studied for that location or species. Other attributes such as those describing understory characteristics (e.g. 'Herb_cover_pct', 'Shrub_height', 'Bryoid_cover_pct') are frequently null. Therefore, there was a requirement for decision rules in the FTL algorithm to accommodate both detailed information as well as complete uncertainty (null values) for many vegetation characteristics.

Decision rules for classification were established based on broad (e.g. treed vs non-treed) and specific (e.g. tree height >4 m) attributes of vegetation species, stand structure, and other characteristics believed to be structural drivers of fire behaviour (see Section 5.2, below, for the list of attributes used in the FTL algorithm). In addition to vegetative or ecological characteristics, VRI attributes also include administrative and geographic information (e.g. parcel number, name of interpreter, polygon area, etc.) that were not used in the fuel typing process.

5.1.1 Coarse classification: BCLCCS

The initial, coarsest attributes for determining overall fuel characteristics for most stands were the BC Land Cover Classification (LCCS) values. The BC LCCS comprises five levels of derived attributes that define broad cover types for the VRI polygons:[14]

- Level 1: **vegetated** (V: forest, grassland, shrubland, etc.) vs. **non-vegetated** (N: for rock, water, recently disturbed bare land, etc.)
- Level 2: **treed** (T: forest stands) vs. **non-treed** (N: < 10% crown closure)
- Level 3: **alpine** (A) vs. upland (U) or wetland (W) sites; only used to identify alpine areas in FTL
- (Level 4 describes overall vegetation lifeform (e.g. Treed Mixedwood, Shrub Tall); these are not used in the FTL)
- Level 5: vegetation density class
  - for treed polygons, classified as **Sparse** (SP: 10–25% crown closure), **Open** (OP: 26–60% closure), or **Dense** (DE: > 60% closure);
  - definitions differ for non-treed cover types (not used in FTL).

14 See the VRI data dictionary for further details; available online: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/standards/vegcomp_poly_rank1_data_dictionary_draft40.pdf.

5.1.2 Additional attributes: forest stand characteristics

Following the first stages of the BCLCCS (Levels 1 and 2), forested (treed) polygons were then divided into single-species (or nearly so) stands, where the dominant tree species cover (SPECIES_PCT_1) represented 80% or more of the tree layer, versus mixed-species stands (Species_pct_1 < 80%). To avoid errors or 'blanks' (see Section 3), decision rules encompassed all tree species found in BC, including all conifer and deciduous species (as well as appropriate classification for non-forested areas). Thus, single species stands were then classified by tree species. Mixed-species stands were classified by the percentage split between conifer and hardwood (deciduous) species, as conifers in the overstory are key determiners of crown fire potential. Further differentiation for treed stands beyond the dominant species level depended on other stand characteristics deemed important to fire behaviour, including secondary species, harvesting history (recently logged or not), tree heights, crown closure (sometimes used in addition to the BCLCCS Level 5 category), tree age (dominant cohort), mountain pine beetle attack (for lodgepole pine stands), and a few other attributes, as shown in Section 5.2.

The harvest history (Harvest_date = 'Null', or a specified harvest year) helped identify managed stands where tree harvesting, site preparation, and replanting took place and where post-harvest slash and a plantation cohort would be the dominant influence on fuel structure. Very recently harvested areas (<≈10 years, depending on biogeoclimatic zone) were assumed to behave as slash fuels in most cases, depending on the time since harvest (see Section 5.4.5). Most post-harvest stands in BC are replanted with seedlings (usually conifer trees), and after the first few years, the effects of the young plantation begin to dominate stand fuel structure. Stands were assumed to behave as forests once trees reached a height of 4 m height for fully stocked stands. The young plantation stage (≈4–12 m in height) is poorly represented by FBP fuel types, and the expected fire behaviour in these stands is heavily influenced by surface fuels left from the previous cohort; this is further discussed below (Sections 5.4 and 6).

5.2 Vegetation attributes used in fuel typing algorithm (from VRI)

The following attributes, as well as brief descriptions, from the veg_comp_poly_rank1 VRI layer are currently used in the FTL algorithm (detailed attribute descriptions and definitions can be found in the VRI data dictionary[15]). In most stands, only a few of these attributes are used for fuel typing. Categorical variable levels are noted in **bold**.

15 Descriptions provided here are interpreted in the context of fire behaviour modelling, and may be slightly different from those in the VRI data dictionary. For formal attribute definitions, see https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/standards/vegcomp_poly_rank1_data_dictionary_draft40.pdf.

- BC Land Cover Classification Level 1 (BCLCS_level_1): **Vegetated** (V) or **Non-Vegetated** (N); vegetated status is assigned when the total cover of all vegetation and bryoids (excluding crustose lichens) covers at least 5% of the surface area of a polygon[16]
- BCLCS_Level_2: **Treed** (T) or **Non-treed** (N); non-treed is assigned when crown cover of all trees of any size < 10%[16]
- BCLCS_Level_3: Designate various categories of broad land cover; used in FTL to designate **Alpine** (A) areas, consisting of rock and ice and very little vegetation cover
- BCLCCS_Level_5: Crown Closure category (**Dense** (DE: 61–100%), **Open** (OP: 26–60%), **Sparse** (SP: 10–25%))[16]
- Species Code 1 (Species_cd_1): species of dominant tree (based on basal area for older stands; stems/ha for very young stands) [17]; e.g. **Pl**, **Fd**, **Sx**
- Species_cd_2: species of 2nd (co-)dominant tree
- Species_pct_1: percentage cover of dominant tree species, based on percent of total area of forest cover within a polygon (Species_pct_1 through Species_pct_6 must add up to 100, regardless of actual canopy cover within a polygon)[16]
- Species_Pct_2: percent cover of 2nd dominant tree species
- Sp1 Height: (Proj_Height_1): projected height, in m, of dominant tree species
- Sp1 Age: (Proj_Age_1): projected age of dominant tree species
- Crown_closure: percentage of plot area covered by tree canopy, used to infer stand density[16]
- BEC_zone_code: Biogeoclimatic Ecosystem Classification zone[18]
- BEC_subzone: Biogeoclimatic Ecosystem Classification subzone
- Harvest_date: year of most recent harvest activity (null if never harvested)
- Earliest Non-Logging Disturbance Type (Earliest_nonlogging_dist_type): category code used to identify disturbances such as insect attack, fire, etc.
- Earliest_non-logging_dist_date: estimated year of disturbance (e.g. year of mountain pine beetle attack)
- Stand_percentage_dead: derived percentage of overstory trees estimated to be dead (new or older snags)
- VRI_live_stems_per_hectare: stand density of live overstory trees/ha
- VRI_dead_stems_per_hectare: stand density of dead overstory trees/ha
- Non_productive_code: used in older inventory data for non-forested areas to identify and differentiate brush, swamps, old burns, gravel pits, etc.
- Land_cover_class_code: used in newer inventory data for non-forested areas to identify and differentiate brush, swamps, old burns, gravel pits, etc.

5.3 Working assumptions and applied decision rules for FBP fuel typing

5.3.1 The art and science of FBP System fuel typing

It is worth mentioning at this point that the process of selecting an appropriate FBP fuel type, for operational fire management purposes, is taught in advanced fire behaviour training courses provided by the Canadian Interagency Forest Fire Centre (currently coded as S-490, Advanced Fire Behaviour and S-590, Wildfire Behaviour Specialist courses). A significant step in fuel typing, from the perspective of field and operational users, involves making a qualitative visual comparison between a given forest stand (or non-forest area) and a very small number of benchmark photographs of the various fuel types (De Groot 1993), using whatever structural data may be available. Clearly, this is not a process that can be automated or quantified, which is why fuel typing using the FBP System remains subjective. This type of fire behaviour prediction (and wildfire management, more generally) is often described as a blend of art and science (e.g. Murphy 1990), requiring the application of knowledge from both formal research as well as ‘real world’ experience in order to be proficiently applied in operational situations. This is particularly true in BC because of the limitations of the existing fuel types; with some exceptions, FBP System fuel types were developed for boreal and sub-boreal forest types that are common across most of Canada (Stocks et al. 1989, Forestry Canada Fire Danger Group 1992). Using fuel data from multiple sources, combined with calibration from observations of fire behaviour, has long been recognized as the best practice for making fire behaviour models useful in practical and operational settings (e.g. Keane et al. 2001).

In BC, the FBP System has been used with increasing success to guide fire behaviour prediction and fire response for approximately two decades now (e.g. Beck et al. 2005). This has been accomplished by learning and applying various ‘rules of thumb’ to the somewhat idiosyncratic FBP fuel types for use in BC ecosystems. This section attempts to document these working rules and create a framework for continuous future improvement in use of the CFFDRS in BC.

5.3.2 Intended vs. interpreted FBP fuel type assignments and use of informal wildfire observations

For at least some areas in the province, fuel types C-2, C-3, C-4, C-7, M-1, M-2, S-1, S-2, S-3, D-1, D-2, and O-1 were assigned more or less ‘as intended’ according to the descriptions and guidelines in the FBP System (Forestry Canada Fire Danger Group 1992). In these cases, tree species, stand structure, understory characteristics, and ladder fuels were assigned when they matched (based on the attribute data available) the characteristics

16 Note – the BC VRI data dictionary uses the terms crown closure and canopy cover interchangeably; according to the VRI Data Dictionary, ‘Tree crown closure is the percentage of ground area covered by the vertically projected crowns of the tree cover for each tree layer within the polygon and provides an essential estimate of the vertical projection of tree crowns upon the ground.’

17 Species codes in the VRI system consist of 2-letter abbreviations; these are described fully in the VRI data dictionary (see above link, p. 214–217).

18 See the BC BECWEB site for more information: https://www.for.gov.bc.ca/hre/becweb/.

of the fuel type in question (see Appendix 2, for detailed FBP fuel type descriptions). Fuel type assignments were made with relatively high confidence for these areas in BC.

In addition to these more straightforward assignments, some fuel types were interpreted and assigned with lower confidence according to a less formal heuristic process based on comparisons between fuel types (e.g. Figures 2–4). For these more challenging assignments, we attempted to harness the collective knowledge and experience of BC's fire behaviour specialists and fire management staff (and other jurisdictions, when available) using information summarized from wildfire observations. These fuel type assignments are therefore somewhat outside of the scope of the original FBP fuel types and are applied with lower levels of documentation and overall confidence. As wildfires tend to occur outside the realm of formal research and controlled conditions, there can be many variables that confound the simple fire environment conditions most sought for assembling data for empirical fuel typing. Wildfire behaviour observations are written records documenting the actual stand conditions, fire weather and topography, and relevant fire suppression or management activities that determined observed fire behaviour. These can be formal (published case studies, as per Alexander and Thomas 2003), or, more commonly, informal records, including photograph series, video clips, emailed visual reports, and (sometimes sparse or questionable) verbal descriptions from eyewitnesses. The varying quality of fire behaviour observations has been previously identified as an issue of concern by several researchers (e.g. Gould et al. 2011), but is not easily resolved. Because the density and frequency of these reports far surpasses formal research records, these records are relied upon in the absence of other information for certain stand types and cannot be ignored. Nonetheless, this remains an imperfect dataset and we hope to continue assembling our fire behaviour documentation data to validate or refute (and improve) these much less reliable fuel type assignments.

The assumption with these more speculative fuel type assignments is that a stand could coincidentally have a relatively good match with the fire behaviour characteristics (e.g. spread rate or fire type) of existing FBP fuel types, despite very different fuel structure characteristics from the benchmark fuel type. These assignments were made when at least a theoretical understanding suggested a certain pattern of fire behaviour, even if there may have been very few (if any) records of measured or observed fire behaviour in a particular fuel complex. This process becomes increasingly complex when varying ages and successional stages of developing forest stands are considered. Although the confidence associated with some of these assignments can be rather low, we have attempted to make these assignments with careful consideration of stand characteristics and most likely successional pathways. Forest ecology studies and information, including tree silvics and stand succession (e.g. Klinka et al. 2000) and direct studies of fuel succession (e.g. Van Wagner 1983, Agee and Huff 1987, Feller and Pollock 2006) were used when possible, although the links with the mostly fixed FBP fuel types were not always obvious. More theoretical and structure-based approaches to fire behaviour(e.g. Van Wagner 1977, Alexander et al. 2006; see also Section 9.3) were also used in simulations to compare predictions with standard FBP System outputs in several of these cases.

5.4 Specific fuel typing assignments

5.4.1 Main conifer fuel types:

- The **C-1** fuel type (spruce-lichen woodland) is defined by its very open structure of black spruce interspersed with *Cladonia* reindeer lichen species (Alexander et al. 1991); these stands can be found in northern boreal forests of BC. Since the lichen component is a defining component of the fuel type structure and is not easily indicated in VRI data, the C-1 type is assigned for any pure black spruce (or unspecified spruce) stands in the Boreal White and Black Spruce or Spruce Willow Birch biogeoclimatic zones where the BCLCCS Level 5 is **Sparse**. This is likely a slight overprediction of the extent of C-1, as other types of understory vegetation (e.g. grass, herb/forb, or shrub understory) are probably more common than reindeer lichen in this area. The C-1 fuel type produces spread rate prediction that are very similar to the C-3 fuel type (Figure 2).
- The **C-2** fuel type (boreal black and white spruce) is defined by dense lowland and upland sites of the eponymous species; this structure exists across the boreal plains and shield across Canada. Although these vegetation communities exist to some degree across BC, particularly in the Peace River basin in northeastern BC, this fuel type is also used, based on observed fire behaviour, for mid-elevation interior white spruce and hybrid spruce stands elsewhere in the province (R. Lanoville, unpublished reports held by BC Wildfire Service, Victoria, BC). The C-2 fuel type is also used for representing certain stages of mountain pine beetle (MPB)-affected stands; see Section 5.4.2, below.
- The **C-3** fuel type was used to represent classic stands of fully stocked, pure mature lodgepole pine (interpreted as >12 m height and **Open** or **Dense** stand structure, low levels of (or no) MPB attack). In addition, the C-3 fuel type was also used to represent several other species and stand structure combinations; the following is a non-exhaustive list:
  - Mixed stands (100% conifer) dominated by mature lodgepole pine, with spruce (any species) or subalpine fir as secondary species; also, similar stands dominated by interior spruce with lodgepole pine or fir as secondary species
  - Shorter (4–12 m tall) stands of pure lodgepole pine, density <8000 stems/ha (see C-4 fuel type description, below)
  - Certain classes of pure and mixed lodgepole pine stands (100% conifer) affected by MPB attack at low to moderately high attack densities (see Section 5.4.2, below)
  - Pure and mixed, **Dense** stands (100% conifer) dominated by Douglas-fir, 4–12 m height
  - **Open** (not **Sparse** or **Dense**) stands of pure Engelmann or interior spruce
  - **Open** or **Dense**, pure or mixed stands (100% conifer) dominated by subalpine fir
  - **Dense** pure or mixed stands (100% conifer) dominated by western redcedar, western hemlock or yellow-cedar and
    - 4–15 m height or
    - >15 m height and<60 years old

– Areas noted as non-treed that were logged >25 years ago in SBS, MS, ESSF, ICH (dry subzones) or IDF (wet subzones), where stand succession has likely occurred (i.e. inventory data is stale)

- The **C-4** fuel type (immature jack or lodgepole pine) is defined in the FBP system by immature stands of jack or lodgepole pine with horizontal and vertical fuel continuity and heavy accumulations of dead fuels (Stocks 1987, Forestry Canada Fire Danger Group 1992). Spread rate and fire intensity values predicted in C-4 fuels are nearly identical to those of the very volatile boreal spruce (C-2) fuel type (Figure 2). In the present algorithm, C-4 is assigned to forested conifer stands from 4 to 12 m in height with >8000 stems/ha (live plus dead), or 'dense' stands (>60% crown closure) 4–12 m in height with a significant (>34%) percentage of dead stems. These rules were assigned as an estimate of reasonable threshold values compared to the main experimental burn study defining the C-4 fuel type (Stocks 1987). That series of burns took place in an approximately 30-year old central Ontario stand of overstocked jack pine saplings (≈10,000 live stems/ha plus a nearly equal density of dead standing trees). A cut-off density value to discriminate between C-3 and C-4 fuel types was needed, and since dead trees are not often extensively surveyed in the VRI process, the value of 8000 stems/ha was selected; this value may change in the future if observed or measured fire behaviour in these stands suggest otherwise. In general, it is very uncommon to see stands of pine (or most other conifers) exhibit the very fast rates of spread and extreme intensity values suggested by the C-4 fuel type.
- The **C-5** fuel type (red and white pine) describes a forest type from eastern Canada that does not exist in BC (Forestry Canada Fire Danger Group 1992). However, due to the high crown base height (18 m), large and old trees, and the deciduous shrub component of this fuel type, it has been used to approximate fire behaviour in mature stands of low- to mid-elevation coastal and interior Douglas-fir, western hemlock and/or western redcedar. These forest types are known to burn rarely and typically with low intensity (Agee 1993), although this is more a function of weather than of fuel structure. The use of C-5 to model these stands was first suggested over 20 years ago by operational fire behaviour specialists in BC and has held up well over time. It is important to note that the surface fuel loading in older west coast stands can be much greater than in the benchmark red and white pine stands from Ontario, particularly if coarse woody debris are included (Agee and Huff 1987, Forestry Canada Fire Danger Group 1992). As a result, fuel consumption and fire intensity can be higher than predicted by the C-5 fuel type under drought conditions. Monitoring efforts to formally confirm or refine this fuel type assignment are slow but ongoing.
- **Conifer stands with Sparse tree cover** (BCLCCS Level 5 'SP', with 10–25% crown closure) represent challenging cases. These stands are usually transitional between forested and non-forested areas, and would probably only rarely support crown fire behaviour due to the wide gaps between tree crowns – i.e., very low canopy bulk density (Agee and Skinner 2005, Cruz et al. 2005). In these stands, the understory (herbaceous and shrub) vegetation is very important for preserving fuel continuity and determining fire spread potential. Since VRI data is often weak with respect to understory structure, biogeoclimatic zone information is often used to estimate the composition and flammability of understory fuels. Fuel types are mostly assigned to be less volatile (lower ROS and fire intensity) than would be associated with a fully-stocked similar stand, due to the lack of potential for active crown fires; for example, in an **Open** or **Dense** mature lodgepole pine typed as C-3, the similar stand with **Sparse** density would be typed as C-7 or C-5 depending on the biogeoclimatic zone.
- **Coastal forests** dominated by coastal Douglas-fir, redcedar and western hemlock at low elevations; and Amabilis fir and mountain hemlock at higher elevations, represent a unique challenge. These stands are very different in structure and vegetation composition than the boreal or sub-boreal vegetation that is addressed by most FBP fuel types. Older low elevation stands, with high canopies and low light and wind penetration, are typed as C-5, as described above. For varying ages of younger stands, research studies have suggested a U-shaped model for surface fuel hazard, where fine surface fuel loading is highest in younger (<20 years) and old-growth stages, and lower in pole-sized and mature stands (100–200 years) (Agee and Huff 1987); however, crown fire hazard was not considered. A similar pattern was also found by Feller and Pollock (2006), who examined different stand ages following harvesting in southwestern BC; however, that study, however, also included a model of crown fire hazard, which showed a very different pattern, with crown fire hazard highest in dense pole-sized regenerating stands (20–90 years). These findings have been incorporated into the present fuel typing scheme by classifying dense pole-sized stands as C-3 (see above). Amabilis fir stands have been typed as M-2 40% conifer, representing predicted ROS and HFI values somewhere between C-5 and C-3 outputs (Figure 5). In most fire weather conditions, M-2 40% conifer produces ROS near the C-3 prediction, although at high and extreme fire danger conditions (ISI >25 or so), the predicted spread rate is lower, representing more canopy openings and discontinuities which are believed to occur in these stands.
- Fuel type **C-6** (conifer plantation) is still being investigated for use in BC; use of this fuel type requires modeled or estimated crown base height, which is a variable not currently in the inventory attributes. Preliminary observations of the structure of conifer plantation in BC (Douglas-fir, lodgepole pine, white/hybrid spruce, and other species) do not seem to match the defined C-6 structure (continuous needle litter and complete crown closure); fire behaviour observations and additional research are ongoing.

Note: **Larch** (*Larix* spp.) is treated as a deciduous species, for fire behaviour purposes. See Section 5.4.3.

5.4.2 Mountain pine beetle-affected pine stands

The mountain pine beetle (MPB) has recently had devastating effects on lodgepole pine stands across BC, affecting more than 18 million hectares of pine-dominated stands across the province

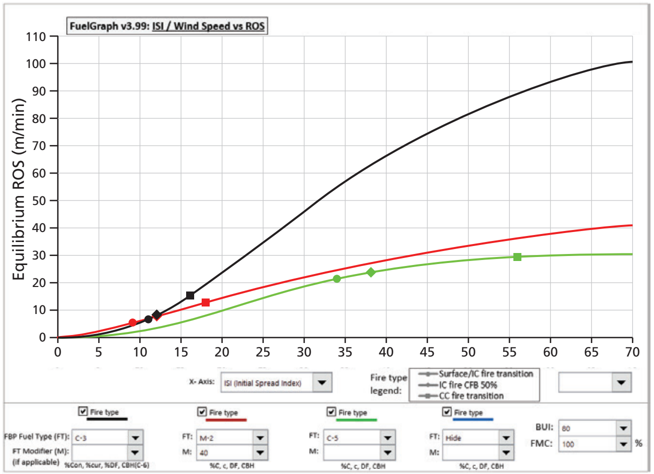

Figure 5. Example of comparison of predicted spread rate between Amabilis fir-dominated stands (typed as M-2 40%C) and C-3 and C-5 FBP fuel types, using FuelGraph Tool (footnote 13). Note selected fire weather indices.

since 1999 (Anonymous 2016a), with most severe impacts from 2002–2012 (Westfall and Ebata 2016). Several recent studies and reviews from the US have discussed the impacts of this disturbance on subsequent wildfire behaviour and effects (Page and Jenkins 2007, Simard et al. 2011, Hicke et al. 2012, Jenkins et al. 2012, Schoennagel et al. 2012, Jenkins et al. 2014, Hoffman et al. 2015), often relying only on simulations (i.e., presenting little if any actual fire behaviour data). This topic has consequently been a source of considerable controversy and confusion (e.g. Jolly et al. 2012, Moran and Cochrane 2012). Due to the importance of this disturbance in BC, MPB-affected stands have been given special treatment in the FTL. Some studies (using actual fire behaviour data) and credible observations have ultimately been completed, including in BC, and suggest that these fuels do indeed merit special caution. Mountain pine beetle impacts on a stand represent a wide variety of timing and intensity of disturbance, and consequently produce a wide range of fuel structures as described below. Research and monitoring of these fuel types is ongoing. See also Appendix 4.

- MPB-killed lodgepole pine stands in the first few years post-attack are represented by the **M-3 fuel type, with 65% dead balsam fir**; no other variant of the M-3 fuel type is used at the present time (the M-4 fuel type is not used). The research basis for this is described in Perrakis et al. (2014b). The M-3 fuel type is used only in cases when the stands consist of lodgepole pine in the 'red-attack' stage, which has commonly been observed to exhibit crown fire behaviour even under moderate weather conditions (e.g. Figure 6). In the FTL, these are identified as pure lodgepole pine or lodgepole pine-dominated (interior spruce (Sx) or subalpine fir (Bl) are secondary species), with more than 50% of standing trees killed by MPB, and with a disturbance date (Earliest_non-logging_dist_date) within the past 5 years; this represents a difference of 5 years or less between the present year (year of analysis) and the inventory year. See Table 1, below (see also Appendix 4).

Table 1. Fuel typing for mountain pine beetle-affected pine stands. 'Pure Pl' refers to Vegetated, Treed stands (crown closure ≥10%) where Species 1 is lodgepole pine and represents 80% or more cover; '2 sp' refers to stands where at least one other conifer species is present (in addition to lodgepole pine), and no single species represents more than 80% of total forest cover.

	Open stands		
			2 sp
MPB-killed pine	**Years since attack**	**Pure Pl**	**Pl/Sx or Bl**
0–24% dead	0–5 yrs	C-3	C-3
25–50% dead	0–5 yrs	C-2	C-2
51–100% dead	0–5 yrs	M-3/65	M-3/65
0–24% dead	6+ yrs	C-3	C-3
25–50% dead	6+ yrs	C-3	C-3
51–100% dead	6+ yrs	C-2	C-2
	Dense stands		
			2 sp
MPB-killed pine	**Years since attack**	**Pure Pl**	**Pl/Sx or Bl**
0–24% dead	0–5 yr	C-3	C-2
25–50% dead	0–5 yrs	C-2	C-2
51–100% dead	0–5 yrs	M-3/65	M-3/65
0–24% dead	6+ yrs	C-3	C-3
25–50% dead	6+ yrs	C-3	C-2
51–100% dead	6+ yrs	C-2	C-2

Figure 6. Mountain pine beetle stands in the red-attack stage can exhibit extreme fire behaviour even under less-than-extreme weather conditions.

- The **C-2** fuel type is also used in the present algorithm for representing certain MPB-affected stands in the gray phase of attack (≈5–20 years post-attack). Experimental burning and wildfire observation data from recent fire seasons have suggested that spread rates and headfire intensity values for grey-stage MPB-killed pine probably lie somewhere between those of the C-3 and C-2 model predictions (Kubian et al.

2009, Hicke et al. 2012, Perrakis et al. 2014a). Additionally, this fuel type has been observed during wildfires to produce copious quantities of embers and flying debris, including the lofting of large bark flakes into the burning column from hundreds of metres to several kilometres ahead of the flame front; this is a phenomenon outside the realm of the FBP System outputs. Due to the uncertainty and hazard associated with these stands, they have been conservatively typed as C-2, when MPB-caused pine mortality represents >50% of the stand (see Table 1). However, some of the rapid spread rates observed in these stands may also have been due to the presence of significant cover of regenerating spruce, subalpine (balsam) fir, or other conifer species in the understory. Since the VRI data only rarely includes the presence of these cohorts, this is a topic of considerable uncertainty and ongoing research and monitoring. See Table 1.

5.4.3 Mixedwood and deciduous fuel types:

While the fuel type algorithm must encompass all tree species found in BC, much more fire behaviour information is available for conifer stands. Consequently, broadleaf-species stands as listed below are mostly typed as D-1/2 (deciduous, leafless/ deciduous, green), indicating low fire danger in these forest types under most fuel moisture and weather conditions:

- **Larch** (*Larix* spp.), a genus of conifer trees with deciduous needles (annually shed and regrown, similar to many broadleaf species), was also classified as a deciduous group for fire behaviour purposes; larch species in BC include western larch, subalpine larch and tamarack
  - No reports have ever suggested that these species can support crown fire; since all foliage is new, foliar moisture is much higher than other conifers (>250% usually), and therefore they act similar to broadleaf species
  - Pure stands are typed as D-1/2 and are similar to pure aspen stands
    - Larch produces very little persistent litter, so the D-1 fuel type likely overestimates fire spread potential of these stands
  - In mixed-species stands with other conifers, larch is considered to contribute to the deciduous portion of the stand; this is implemented using the M-1/M-2 fuel types

Mixedwood stands of species other than boreal spruce and trembling aspen present a particularly complex case.

- The **M-1** and **M-2** fuel types were originally artificially created by blending the C-2 and D-1 fuel types based on the 'percent conifer' (%C) fraction of a stand (Forestry Canada Fire Danger Group 1992, Wotton et al. 2009, Alexander 2010). As suggested previously, this procedure is used 'as is' for forested stands of white or black spruce mixed with any deciduous tree species, with the following caveats:
  - Stands with a Species_1 cover of 80% or greater are considered single species; thus, a stand of 85% black spruce and 15% trembling aspen would be typed as C-2
  - The %C and %D are rounded to the nearest 5% for practical purposes
- For species other than white/black spruce, the %C is multiplied by a decimal proportion (between 0 and 1) to reduce the effective percent conifer; this has the effect of reducing the predicted fire behaviour (spread rate and intensity). These calculations and the specific proportions in the FTL were chosen based on the following assumptions:
  - Conifer trees in stands contribute to most fire activity; both conifer litter and conifer trees (bark and especially crowns) are much more flammable than deciduous litter and trees
  - Conifer stands (trees, overall structure) other than black and white spruce are largely less flammable and volatile than the C-2 standard that underlies the M-1/M-2 fuel types, to varying degrees that depend on surface fuel characteristics, crown base height, and various edaphic conditions
  - Therefore, adding deciduous trees to a conifer stand is assumed to reduce the rate of spread, fuel consumption, crown fraction burned, and headfire intensity compared to pure conifer stands
  - The appropriate %C for these stands was assigned iteratively, aiming for a resultant M-1/2 fuel type with lower or equal ROS or HFI than the FBP fuel type representing the original pure conifer stand (as much as is possible within the confines of the fairly rigid equations); the approach that seemed the most realistic involved different multipliers for different % conifer levels (see Appendix 5, Row numbers 197–268)
  - It is important to note that this process involved tradeoffs between the low- and high-end of fire danger; due to the use of C-2 in the calculation of M-1 and M-2 outputs, the use of these fuel types tends to overpredict spread rate and fire intensity at the low end of fire danger (ISI<10) in the interest of greater accuracy at higher fire danger levels (ISI 10–30 or so).
  - For example, a stand of well-stocked pure mature lodgepole pine might be typed as C-3 (Section 5.4.1); a similar stand height and density consisting of a blend of 65% mature lodgepole pine and 35% paper birch would hereby be typed as M-1/2, with the %C multiplied by 0.7 and rounded up – the resultant fuel type would be M-1/2 50% C. Similarly, a mature stand of 50% red alder, 40% western hemlock and 10% Douglas-fir (likely typed as C-5 if pure conifer) would be typed as M-1/2 20%C (original %C multiplied by 0.4).

Figure 7 shows ISI/ROS representing the previous two examples, as well as the equivalent pure conifer stands. Note the overprediction below ISI 15 or so using M-2, compared with the pure conifer stands (C-3 and C-5).

5.4.4 Grass and non-forested fuels:

Grasslands and shrubland vegetation communities are abundant across BC (see Section 8), and non-forested

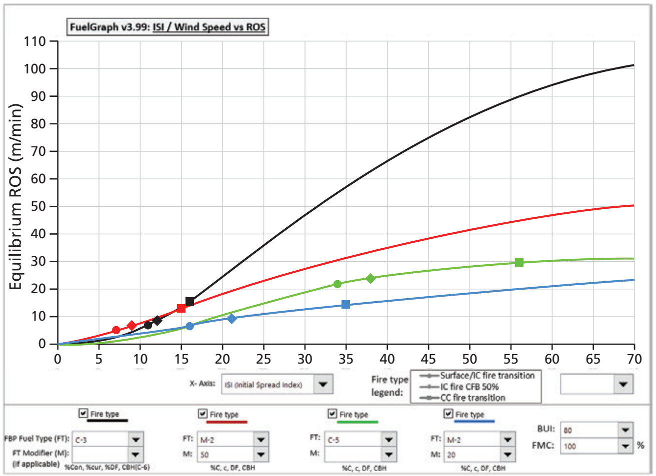

Figure 7. Comparison of headfire intensity for mixedwood fuel type examples, using FuelGraph (see footnote 13). Note selected fire weather indices.

(vegetated) polygons were consequently very important in the FTL algorithm. In practice, fuel typing options are limited for these areas, as few FBP fuel types deal with non-forest. As a result, these areas were classified as one of the following:

- O-1a/b (open grassland, matted or standing); grass fuel types were assigned in the following cases:
  - Non-vegetated lands post-harvest, 7–24 years since harvesting, dry BEC zones (≥7 years post-harvest in the case of PP and BG zones) – assumes slash fuels have decomposed or been removed as part of site preparation
  - Non-vegetated, unlogged sites, with trees present, dry BEC zones – these are non-productive very dry bunchgrass ecosystems with very sparse trees
  - Vegetated, non-treed, unlogged sites with or without trees present, in dry BEC zones, defined as very short or Sparse treed stands, or other non-forest areas (brush, old burns, meadows, hayfields, open range, shrub or herb ecosystems, etc.)
  - Juniper stands
  - Very open Fd stands ≥4 m height (crown closure<26%)
- D-1/2 (deciduous forest, leafless or green (surface fire only))
  - Used for moist areas where vegetation is believed to consist mostly of deciduous herbs and shrubs
- Non-fuel, which is used for alpine areas with patchy vegetation that would not normally support fire; also for exposed rock or ice, roads or other paved or built surfaces, irrigated croplands, etc.
- Water (all water bodies, saturated marshes and bogs that would not normally support fire spread); identical to non-fuel, for modeling purposes.

Non-forested disturbed areas (affected by fire or harvesting) are dealt with specifically in the following sections.

5.4.5 Slash and post-harvest fuels:

Fuel types for harvested areas, including slash fuel types (**S-1, S-2, S-3**), were assigned based on the estimated timing of harvesting and the replanted species. Post-harvest (or other disturbance) polygons represent some of the greatest levels of uncertainty, due to site-specific factors and rapid change in the first few years.

Factors associated with forest harvesting can profoundly influence the loading and characteristics of the subsequent surface fuel. These factors include site preparation (e.g. broadcast burning prior to replanting), characteristics of the pre-harvest forest stand (forest floor depth, dominant species, etc.), and details of the harvest operation (e.g. processing at the stump vs. at the landing), among others that define the fuels available in the post-harvest environment. These variables will be most influential for a few years (5–20 in most stands), until the characteristics of the new plantation begin to dominate overall fuel structure, through processes such as litterfall, the gradual development of a canopy fuel layer, and the buildup of a duff layer (the 'F' layer of organic material on the forest floor).

Harvested blocks are assumed to consist of slash (S-1, S-2, or S-3 fuel type, depending on species planted) for a few years, depending on assumed decomposition rate (based on BEC zone); this stage is followed by the dominance of non-forested vegetation for a few more years. Where the disturbance (and update to inventory data) is more than 25 years old, stand succession is assumed to have occurred, indicating a return to a young forest (conifer in most cases) in most biogeoclimatic zones. This pattern is also the closest we can approximate the 'U'-shaped fuel succession pattern that has been detected over time in many forest stands (Feller and Pollock 2006, Lavoie et al. 2010).

Slash fuel types in the FBP System may not properly represent modern forest management practices; see discussion in Section 6.

The following assumptions were made for these stands:

- Following harvest (clearcutting is assumed), fuel structure is best represented by slash fuel types for the first 5 years post-harvest
  - Although this overpredicts in the case of post-harvest broadcast burning or other intensive hazard reduction (or site preparation) efforts, we believe this is the most likely situation where true slash fuel types will be encountered
  - Detailed site management activities (e.g. disking, mounding, fertilization, etc.) are not well represented in the VRI attributes; we are exploring links to additional data sources to incorporate this information in future analyses.

5.4.6 Recent burns – post-fire fuel succession and typing

One of the most obvious changes to vegetation cover occurs following wildfire. As suggested previously, active wildfire seasons can quickly render a fuel typing scheme obsolete if it fails to include disturbance effects on fuel structure and composition. The changes in fuel characteristics as vegetation recovers after fire are termed post-fire fuel succession (Davis et al. 2009), and predicting outcomes typically requires estimates of fire impacts as well as likely early-seral regeneration pathways. Accurately predicting post-fire vegetation and fuel succession represents a highly complex and variable endeavour that is influenced by a combination of factors, including pre-fire vegetation, soil characteristics, climate, and fire severity (e.g. Whitman et al. 2018).

As part of the 2017 VRI process, burned areas between 2004 and 2014 were identified using Burned Area Reflectance Classification (BARC)[19] techniques. Earlier fires were identified previously. This analysis used Landsat imagery before and after fires (as per Key and Benson 2006) to map burned areas and estimate ecological severity and fuel consumption; estimated changes to the vegetation and substrate were then incorporated into new VRI polygons and their attributes.

Post-fire fuel typing relied on a simple matrix, based on overall vegetation cover type (conifer forest, mixedwood forest, non-forest vegetation, non-vegetated), time since fire (TSF), and stand density (for forest areas). The first few years typically reflect the time required to rebuild the litter, duff, and overall surface fuel continuity (Agee and Huff 1987, Lavoie et al. 2010). Recent studies in boreal forests suggest that regenerating stands appear much less fire prone for several decades after fire (Bernier et al. 2016), although fuel accumulation rates are highly variable and sensitive to site factors (Thompson et al. 2017). Use of the O-1a/b fuel type for regenerating vegetation provides considerable flexibility, allowing modellers to specify both the degree of curing (affecting spread rate and thus fire intensity as well) as well as fuel loading (affecting fuel consumption and thus fire intensity); see Section 4.2. Using O-1a/b in this manner allows for communities such as herb/forb (low curing) and dry shrub (high fuel loading) to be reasonably represented.

This scheme will likely become more complex in future years as the authors and VRI analysts gain familiarity with the fire characterization process. Future fuel succession schemes will likely include measures of productivity and possibly burn severity.

Post-fire fuel typing is as follows, based on the existing (post-fire) vegetation and Time Since Fire (TSF). This information is also presented in a flowchart in Appendix 4.

- Conifer forest – dense (low fire severity; overstory mostly unchanged):
  - For 1–3 years after fire (TSF 1–3): Non-fuel (N) – although previously burned areas can sometimes support low-intensity fire immediately afterward, forests usually require at least a few years to regain fuel continuity to sustain fire spread (Lavoie and Alexander 2004)[20]
  - TSF 4–6: D-1/2 – assume that fine fuels (litter, some woody debris) have partially recovered, but duff and live vegetation cover have not; overstory structures (remnant live trees, snags) are still standing and influential. These areas will support some fire spread
  - TSF 7–10: C-5 – assume that there is a small proportion of surface fuels and ladder fuels (saplings) available for consumption and a low but non-zero crown fire hazard
- Conifer forest – open or sparse (low to moderate fire severity; open to very open stand structure)
  - TSF 1: Non-fuel (see footnote 20 above)
  - TSF 2–6: D-1/2 – assumes some grasses, herbs/forbs, shrubs recover rapidly to form light, continuous surface fuelbed that can support slow spread rates and low intensity
  - TSF 7–10: O-1a/b – assumes open stand can support graminoid species and surface fire behaviour with low fuel consumption and unlikely crown fire involvement
- Mixedwood or deciduous stands
  - TSF 1: Non-fuel (see footnote 20 above)
  - TSF 2-10: D-1/2 – assumes that aspen (or other hardwoods) will sprout post-fire, and hardwood litter, herbs/forbs, and other shrubs will form most of the surface fuels during the post-fire decade; slow, low intensity fire behaviour
- Non-forest (grass/shrub)
  - TSF 1: Non-fuel (see footnote 20)
  - TSF 2–3: D-1/2 – as above, assumes relatively modest intensity and spread rate in the first few years as vegetation regrows and fuel loading rebuilds
  - TSF 4–10: O-1a/b – assumes that the vegetation community has regrown sufficiently to burn according to the grass model
- Non-vegetated (bare ground or dead biomass alone remaining on site; very high burn severity or low site productivity)
  - TSF 1–3: N – although some vegetation will begin to resprout immediately after fire, when severity has been high, several years are often required before a continuous fuelbed redevelops
  - TSF 4–6: D-1/2 – initial vegetation community is often made of living green vegetation, with little dead material to add intensity; it takes many years before a duff layer redevelops
  - TSF 7–10: O-1a/b – eventually an open vegetation community will redevelop
- For TSF greater than 10 years (all stands), we assume that surface fuels have largely recovered, and the remaining VRI attributes represent the fuel characteristics better than is achieved by estimating fire effects.

5.5 Neighbouring lands

Through partnerships and collaboration, portions of the FBP fuel type layers of areas adjacent to BC have been acquired and

19 See http://wiki.landscapetoolbox.org/doku.php/remote_sensing_methods:burned_area_reflectance_classification_barc.

20 Note that, because of the timelines associated with the VRI process and processing the FTL, there is always a 1-year delay in the data; thus, there will never be a TSF of less than 1 year unless the workflow changes significantly.

attached seamlessly to avoid problems when modeling fuels or fires near the BC border. At the present time, the FTL includes some FBP fuel type grid data from the **Yukon Territory, Northwest Territories**, and **Alberta**. There is also some interpreted US vegetation classification data (very coarse quality) for Washington, Idaho, and Montana along the southern border of the province.

- Some of these data are required to run modeling software (e.g. Burn P3, PFAS) or are useful for fire behaviour prediction near provincial borders
- At this time, agency fuels data of approximately ≈100 km has been acquired in width to the north (Yukon), NE (NWT), and E (Alberta)
- The border of the Alaska panhandle is entirely considered 'non-fuel' due to the alpine nature of the landscape (high mountains, glaciers and exposed rock); although this is inaccurate, it is considered of minor consequence due to the westward nature of winds in the area and to the very high moisture (and low flammability) of the vegetation in the mountain passes along the border
- For the NW USA (Washington, Idaho, Montana), FBP fuel types have been crudely estimated based on publicly available landscape ecosystem maps; fuels in these areas are only presented for completeness and are a poor substitute for local data.

These data are updated much less frequently than the BC VRI polygons, and in most cases have not been verified by the authors; they are presented with no guarantees whatsoever.

6. Uncertainty and Knowledge Gaps

Some vegetation communities in BC are, at best, a poor match with any of the FBP types. The greatest uncertainty in fire behaviour is probably associated with the following:

- Shrublands and shrub-dominated communities: these are known to be very flammable in some cases (sagebrush, bog birch, juniper, Labrador tea, Scotch broom, others) and completely impervious to fire in other cases (e.g. willows, huckleberry, salal, slide alder, false azalea, and others)
- Subalpine parklands, with clumped subalpine fir and Engelmann spruce (interior) or mountain hemlock and amabilis fir (coast), separated by wet meadows and shrublands: the open herb- and shrublands tend to be dominated by forbs and graminoids (rushes, sedges, heather, etc.) and are less flammable than classic O-1 grasslands; although the conifers often have crowns extending to the ground and will burn readily under certain conditions, it is very hard to link crowning with a surface fire intensity threshold in these stands
- Young plantations: managed stands, logged and replanted with conifer seedlings; at very young ages (0–2m height), post-harvest slash and surface fuel characteristics tend to dominate fuel structure; by 3–4 m in height, depending on the species, site characteristics and stocking, planted trees begin to form a continuous canopy and crown fire can once again becomes a concern; none of these stages are well represented by FBP fuel types, with the possible exception of C-4 (representing heavily overstocked 9–10 m stands undergoing self-thinning); the C-6 (conifer plantation) fuel type sounds promising, but assumes a continuous, pure understory fuelbed of pine needle litter and completely closed canopy; although there have been no focussed studies on the subject, anecdotally the C-6 has not been found to be realistic for predicting fire behaviour in most plantations in BC (Figure 8)
  - Coastal conifer plantations represent a specific case of uncertainty, where species such as Douglas-fir and western redcedar are growing on productive sites, with abundant herbaceous and shrub species in the understory; sometimes these blocks are planted directly through untreated slash; other times, as in previous decades, slash is burned before planting; currently, these stands sometimes type out as C-5, sometimes as D-1/2, sometimes as S-3, depending on the time since harvest, tree height and tree age of the dominant cohort; in the authors' opinion none of these is a particularly good fit, and more research is needed to represent managed stands in coastal areas
- Mixed-conifer stands of the interior wet belt; species such as western white pine and western larch growing in multi-story canopies, usually associated with Douglas-fir, redcedar, lodgepole pine, or other species; these stands present similar challenges as coastal conifer plantations
- Recent clearcuts with piled slash, before or after burning (Figure 9; see also Section 5.4.5): current forestry practices

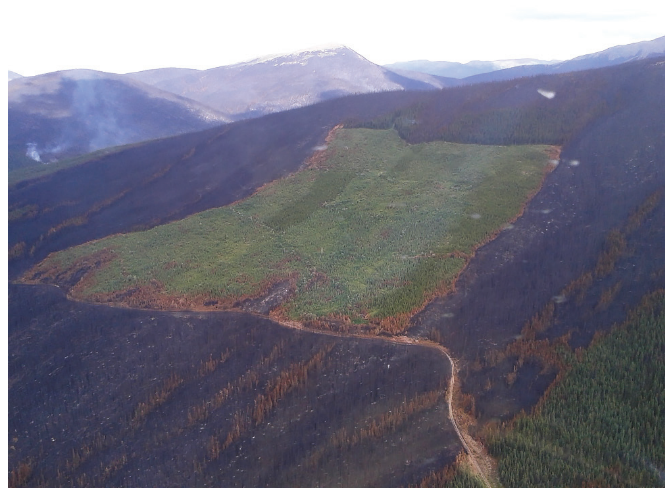

Figure 8. Young plantations represent a significant fire behaviour modelling challenge. This block in northern BC (centre) was logged in 1989, scarified and pile-burned in 1990, and replanted in 1991 with hybrid spruce and lodgepole pine. A wildfire, burning as an active crown fire, burned the surrounding stand of lodgepole pine, hybrid spruce and subalpine fir in 2014. Other than the blackened incursions along its edge, most of the plantation remained unburnt and alive. (Photo courtesy BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development)

Figure 9. Piling of coastal slash represents altered forestry practices in recent decades, where most (not all) woody fuels from harvest activities are piled at landings; slash fuel types (e.g. S-3) probably do not match this type of slash management.

often are quite different from those of the 1970s and 1980s, when the slash fuel types were developed from experimental burns in slash left scattered across cutblocks; consequently S-1 through S-3 types probably do not represent modern slash blocks adequately, but are used due to a lack of other options.

- Agricultural croplands: these represent everything from dense hayfields (with graminoids and other herbaceous species) to post-harvest stubble; flammability often depends on characteristics and timing related to agricultural practices (crop species, timing of irrigation, timing of harvest, stubble characteristics, etc.); while these areas could burn under certain conditions (e.g. fallow fields during drought conditions), they are non-fuel during most conditions; predicting the fire behaviour characteristics of these areas accurately using a provincial-scale inventory-based process is a tall order; for the time being, therefore, they are mostly treated as non-fuel.

7. Exceptions to VRI and data pre-processing

Although the VRI polygons cover the entire province seamlessly, there were certain cases where data was missing and an alternate approach was required (briefly described in Section 4.1). In these areas, all vegetation cover attribute data were absent from the VRI polygons (due to ownership or administrative reasons), resulting in great uncertainty with respect to fuel typing.

7.1 Available Tree Farm License data

In areas managed as Tree Farm Licenses (TFLs), forest industry licensees are responsible for maintaining vegetation inventory data and providing this information to the Ministry of FLNRO. Compliance with that requirement has varied considerably. In some TFLs, licensees have provided full inventory to FAIB and these data were already included in the VRI. In other cases, licensees provided some polygon data specifically for the purposes of this project (outside the VRI process) with simplified forest stand information, with many key attributes missing. For example, in many TFLs, BCLCS attributes were not assigned (these are assigned by FA&I Branch as part of the VRI process). Moreover, other attribute data that is part of the VRI standard was often missing (tree heights, crown closure, harvest information, disturbance types and dates, etc.). Other points of note regarding TFL data include the following:

- The vast majority of these areas consisted of productive conifer forest land, simplifying the logic processing somewhat
- We estimated some of these attributes during the course of this project (e.g. by making simple age-height relationships) as well as possible from the basic overstory tree species, cover percentages, and timber volume information that was provided by licensees
  - The VRI process typically uses sophisticated tree and stand modeling to produce this information, but it was not possible to have this done as part of this project
  - Accuracy of stand attributes produced by simple regression modeling (during this project) is likely less accurate than the VRI-produced estimates
  - Consequently, we assumed greater uncertainty in vegetation attributes and in fuel type modelling in these stands
- At this time (autumn 2017), the total area covered by TFL data that did not meet the VRI standard was 2,760,201 ha, or 2.91% of the provincial area
- The TFLs covered by these data are the following: 6, 19, 25, 30, 33, 37, 38, 39, 41, 44, 45, 48, 52, 61.

7.2 TFLs and private timberlands with no data provided

In some TFL areas, despite provincial requirements, no inventory information was available. This was also the case on most private forest lands, where inventory, if it existed, was not obtainable. Attribute values in these polygons (other than administrative and geographic identification attributes, polygon size, and derived attributes such as biogeoclimatic zone) were all null (no data). Over time, we may have better data for these areas as Ministry staff seek compliance from licensees in obtaining inventory data.

With few options, we used portions of a national satellite imagery-based fuels layer provided by Natural Resources Canada (Nadeau et al. 2005, and recent unpublished updates (B. Simpson, Canadian Forest Service Northern Forestry Centre, Personal Communication)) to fill in the gaps in spatial data. Furthermore, the fuel typing in these areas is based on mixed classification (classified and unclassified) image processing using benchmark sites This is a less transparent process than the VRI-based procedure used in most of the province and has not been validated. In addition, very limited metadata is available.

Cursory testing suggests that this method does adequately distinguish, for example, alpine areas classified as non-fuel from subalpine forests and valley bottom vegetation. However, the fuel typing process, decisions, and transparency in these areas are not consistent with the majority of the provincial scheme.

At this time, the total area covered by National fuels grid coverage is 2,111,261 ha, or approximately 2.23% of the province. This area is disproportionately high in certain regions, particularly southeastern Vancouver Island, due to the historically large area of private timberlands there.

7.3 Recently harvested and intensely managed areas

According to provincial regulations, all managed stands must be surveyed, with the stand attributes updated in provincial inventory using the RESULTS system. However, in many recently harvested areas (particularly the areas heavily affected by mountain pine beetle and recently salvage-logged), there appears to be a lag of several years (≈3–7) between harvest activities and updates in RESULTS; consequently, the VRI is sometimes out of date.

- The Forest Analysis and Inventory Branch creates an annual ‘Consolidated_Cutblocks’ layer, based on newly created forest openings (‘depletions’) detected by satellite imagery
- To capture some information regarding these depletions that are not reflected in the VRI, the following steps were taken:
  - The depletions were used in the present fuel typing process when the year of disturbance for a depletion polygon was greater (more recent) than the VRI polygon it covers – this shows that the VRI polygon is stale with respect to the most recent disturbance
  - Depletion polygons were then overlaid into the VRI layer and treated as harvested areas consistent with the fuel typing algorithm
  - The harvest date was then set to the depletion date, indicating the newly detected year of harvest
- At this time, the area covered by these depletions is 988,456 ha, or approximately 1.04% of the provincial area; these areas are scattered across the province in the productive forestry land base.

Results and Discussion

8. Fuel type maps and frequency tables

8.1 Fuel type maps

Overview maps show the geographic distribution of FBP fuel types across various portions of the province. The provincial overview map (Figure 10) also shows the portions of fuel type layers provided by neighbouring land management agencies, to the north, east, and south of BC (see Section 5.5).

Figures 11–16 show fuel type maps for each of the 6 BCWS Fire Centres (FC): Cariboo FC, Coastal FC, Northwest FC, Prince George FC, Kamloops FC, and Southeast FC.[21]

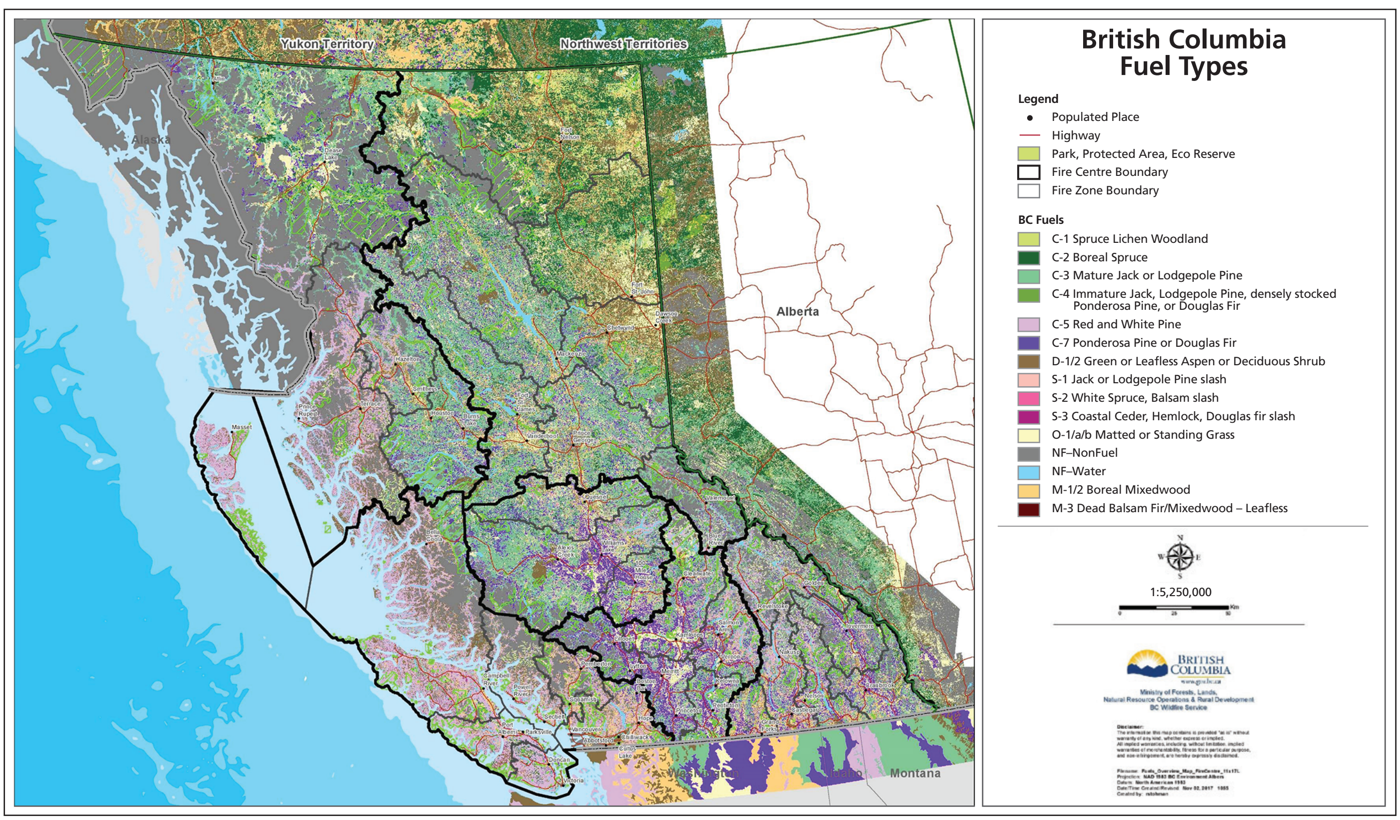

Figure 10. Provincial Overview map.

21 For further administrative information of the six Fire Centres in BC, see http://bcwildfire.ca/hprScripts/WildfireNews/FireCentrePage.asp.

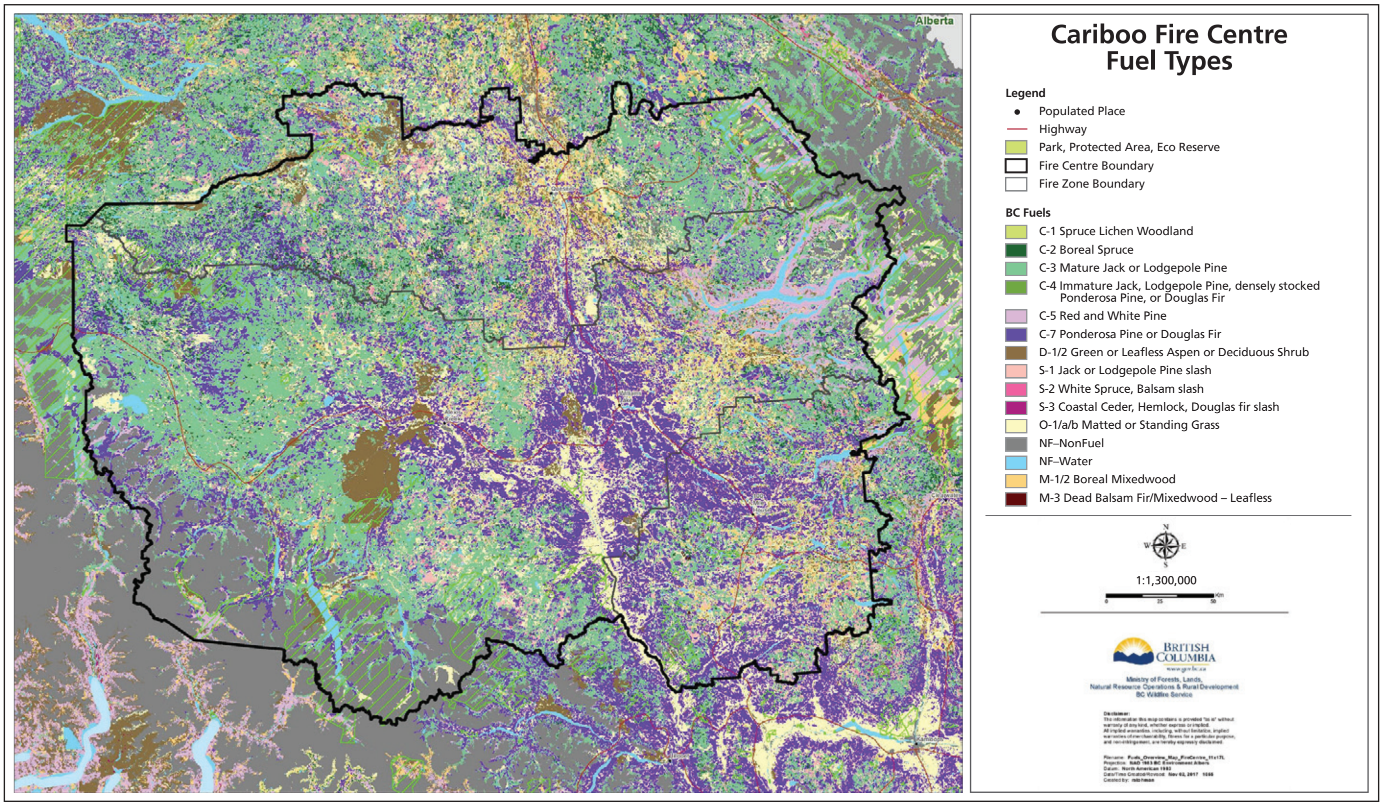

Figure 11. Cariboo Fire Centre overview.

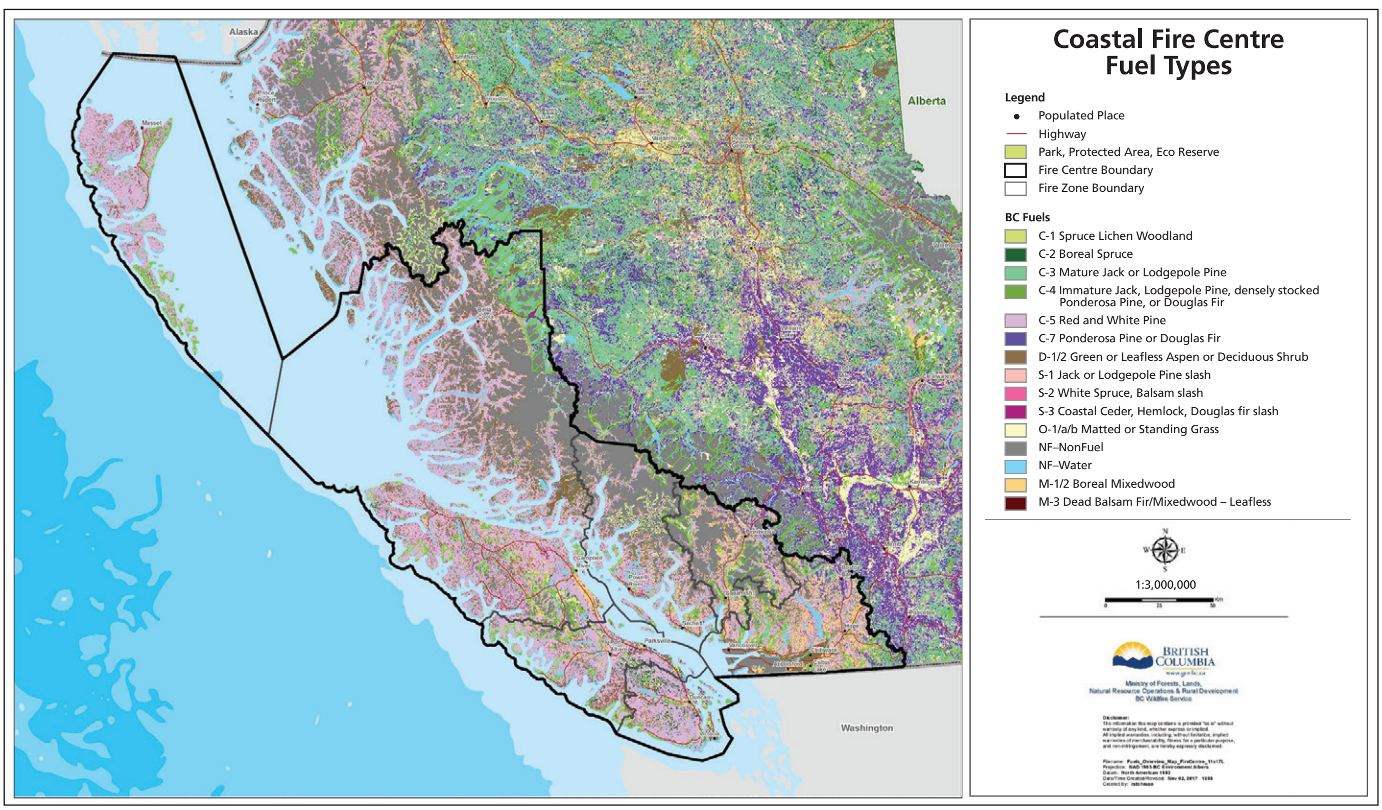

Figure 12. Coastal Fire Centre overview.

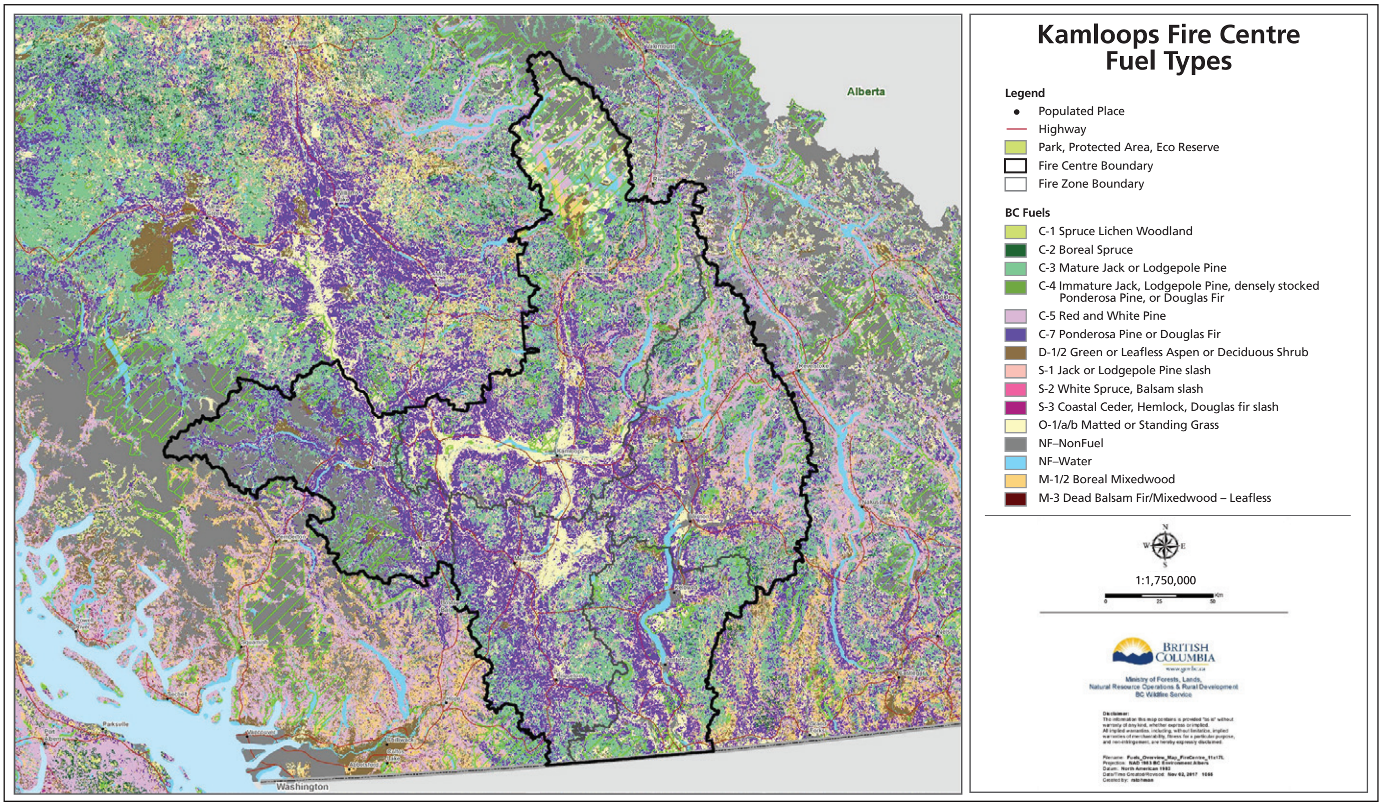

Figure 13. Kamloops Fire Centre overview.

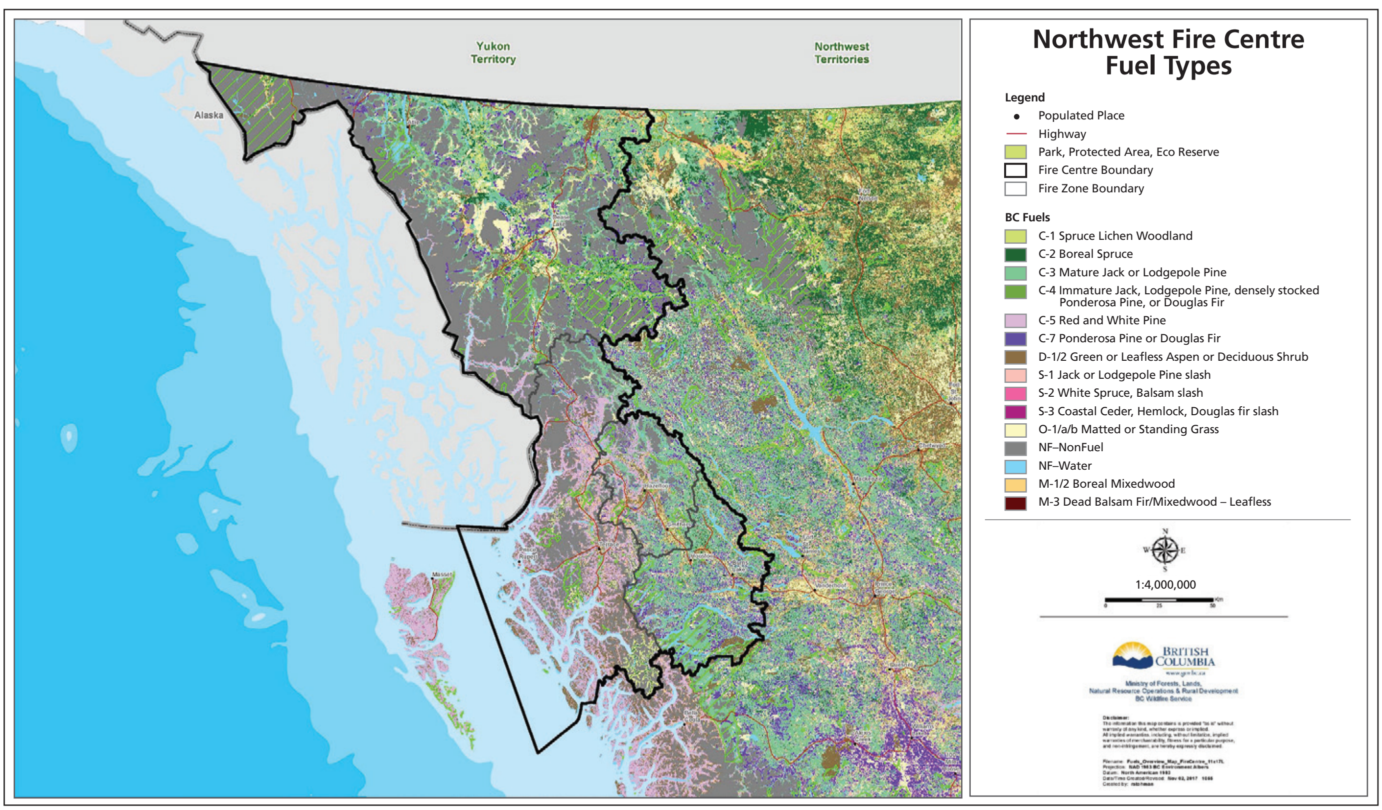

Figure 14. Northwest Fire Centre overview.

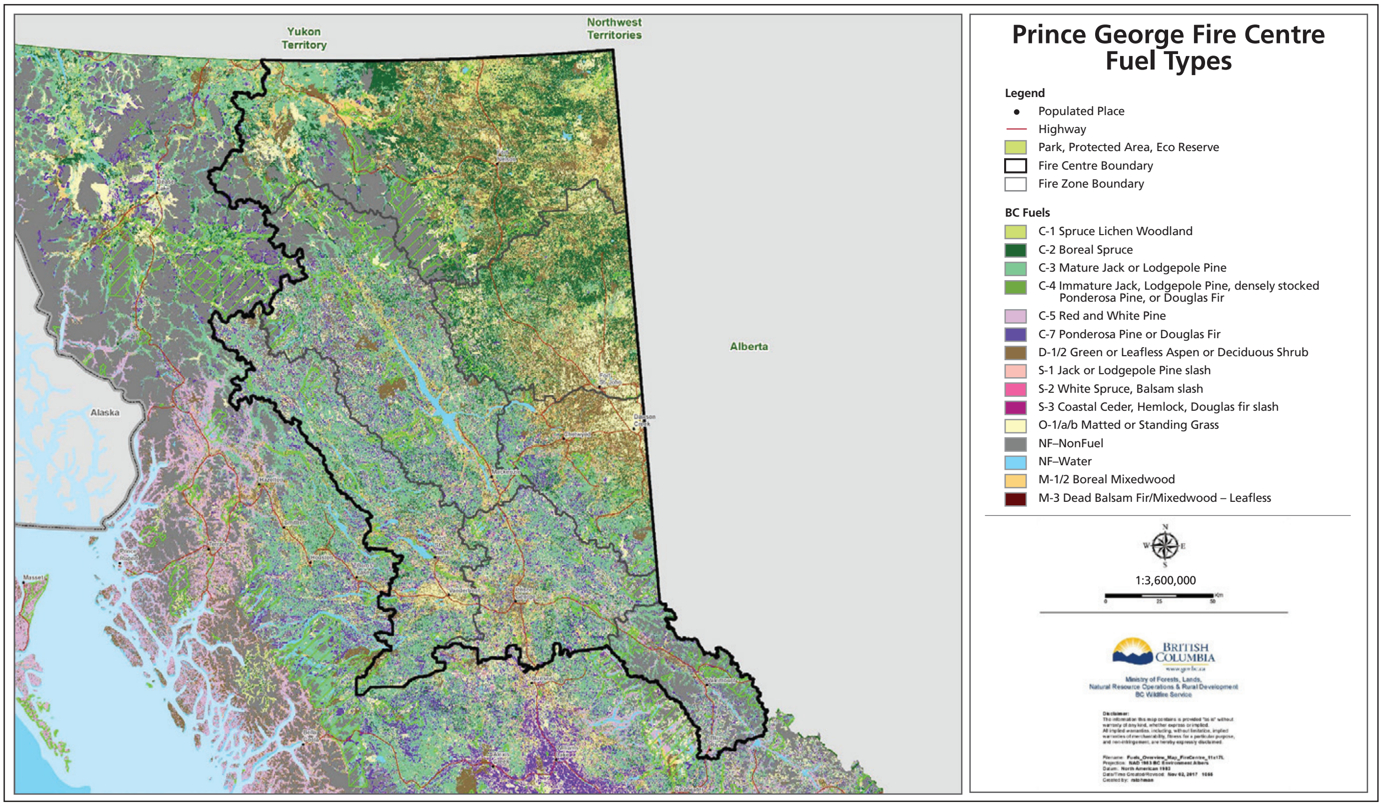

Figure 15. Prince George Fire Centre overview.

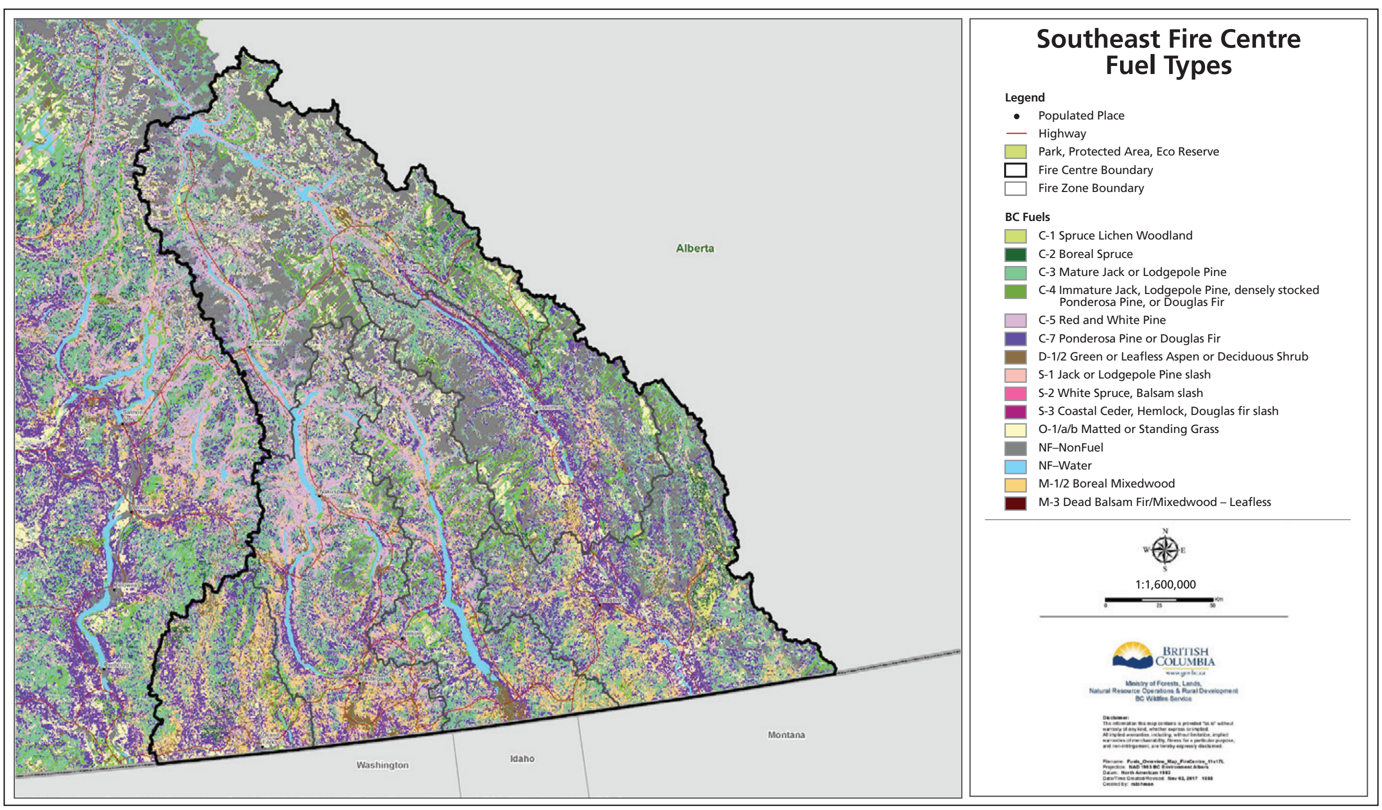

Figure 16. Southeast Fire Centre overview.

8.2 FBP Fuel Type Frequencies

8.2.1 Provincial distribution and noted changes

The relative importance of various fuel and cover types across the province is shown in Table 2, below. Excluding ocean, the total land area of BC typed in VRI polygons is 94,778,568.6 ha. The raster dataset, which includes both ocean portions in the VRI as well as neighbouring administrative areas, has a total area of 176,781,717 hectares (Figure 10).

Across the BC provincial land surface, the most common cover type is C-3, representing mature lodgepole pine stands as well as mature, fully-stocked stands of several other conifer species (Section 5.4.1). The next most abundant cover type is N (non-fuel), reflecting primarily the extensive alpine areas of the various cordilleran ranges. The third most common is C-5, used primarily to represent the large areas of forests in the Coast Mountains and islands that have relatively lower potential fire behaviour (Figure 12, Figure 14). Other dominant fuel types (covering more than 5% of the provincial area) include O-1, C-2, D-1/2, C-7, and M-1/2.

Also notable is the small area of M-3 (65% dead fir). These polygons represent the most volatile MPB red-attack areas (see Section 5.4.2). From over 220,000 hectares province-wide in the 2014 inventory (Perrakis and Eade 2016), this fuel type has faded from the landscape (8,811 ha; Table 2), as beetle-killed trees shed their needles and the MPB outbreak continues to collapse (Westfall and Ebata 2016).

Table 2. Fuel type frequency table – all fuel and cover types, 2017.

Fuel Type	# of polygons	Hectares	%
C-1	69,344	1,565,779.8	1.65
C-2	400,053	6,726,715.6	7.10
C-3	1,267,578	21,472,247.4	22.65
C-4	1,823	52,999.4	0.06
C-5	679,735	9,754,929.1	10.29
C-7	464,745	7,127,601.2	7.52
D-1/2	530,119	7,962,283.2	8.40
M-1/2	519,198	7,477,029.9	7.89
M-3 65% DF	431	8,810.6	0.01
O-1a/b	475,133	8,690,166.4	9.17
S-1	56,269	775,166.1	0.82
S-2	22,901	187,278.2	0.20
S-3	17,730	100,209.2	0.11
N	175,124	19,923,187.1	21.02
W	103,368	2,964,165.3	3.13
Total	**4,783,551**	**94,788,568.6**	**100.0**

Over the years of testing the fuel typing process (see Section 1.1), we have learned that large ecosystem disturbances, such as MPB impacts or big wildfire years (Sections 5.4.2 and 5.4.6, respectively) cause significant challenges for forest inventory accounting and can sometimes lead to confusion or inconsistencies. This year (2017), we noted that large areas of the older MPB-affected stands (5+ years since attack) that were formerly closed-canopy pine- and spruce dominated forests (Process #13, 246, 248; see full details in Appendix 4) had typed out as 'Sparse' cover, due to mortality and toppling of significant portions of the overstory. Due to the importance of dead pine fuel for fire behaviour (see Section 5.4.2), these stands do not match the typical 'Sparse' overstory fuel structure. Consequently, these stands were manually changed to C-3 (see Appendix 4, Row numbers 68, 383, 387), which was deemed a better fit for the observed fire behaviour in old MPB. Revisions will be made to the next update to correct these issues.

The details of provincial fuel typing frequencies by process decision, including number of polygons and hectares assigned at each step, are contained in the FTL algorithm table (Appendix 5).

8.2.2 Fuel type distribution by BCWS Fire Centre

The fuel type breakdown by BCWS Fire Centre is shown in Table 3[22]. Wide variability in fuel type abundance across the province is readily apparent. For example, C-7 is a dominant fuel type (>18% of total) in the Cariboo and Kamloops Fire Centres (FC's), still very important in the Southeast FC (>10%) but of smaller importance (<5%) in other areas. It is important to note that C-7 is also used to represent **Sparse** tree density of various conifer species in northern areas (Prince George and Northwest FC's) despite the lack of Ponderosa pine or Douglas-fir trees in these areas (see Section 5.4.1). Similarly, C-5 is a dominant component of Coastal FC (>40% of total), moderately important in Kamloops, Southeast, and Northwest FC's (≈10%), but relatively rare in Cariboo FC (<3 %) and a very small player in Prince George FC (<1%). These variations generally reflect well-understood ecological differences between regions, summarized in documents such as the BC Biogeoclimatic Ecosystem Classification System[23], or provincial forest ecology guides (e.g. Klinka et al. 2000).

Table 4 shows the provincial frequency distribution of the mixedwood stands (M-1/2) by proportion of conifer species. Note that this scheme treats larch species as deciduous (see Section 5.4.2). Stands with 10–30% conifer cover comprise about 26% of M-1/2 stands; those with 35–55% conifer comprise 50% of mixedwood stands, and those with 60–80% conifer form the remaining 24%.Table 4 shows the provincial frequency distribution of the mixedwood stands (M-1/2) by proportion of conifer species. Note that this scheme treats

22 For an overview and map of the 6 BC Wildfire Service Fire Centres across BC, see http://bcwildfire.ca/hprScripts/WildfireNews/FireCentrePage.asp.

23 See the BC BECWEB site for more information: https://www.for.gov.bc.ca/hre/becweb/.

Table 3. Fuel type frequency by Fire Centre – all cover types, 2017

	Cariboo Fire Centre			Coastal Fire Centre			Kamloops Fire Centre		
Fuel Type	**# of polygons**	**Ha**	**%**	**# of polygons**	**Ha**	**%**	**# of polygons**	**Ha**	**%**
C-1	59	538.5	0.01	3,294	51,030.8	0.39	67	269.3777497	0.00
C-2	18,499	248,910.3	3.02	10,282	180,101.1	1.37	8,920	117,519.8599	1.64
C-3	164,867	2,833,569.6	34.35	43,808	743,808.6	5.67	133,094	1,876,508.64	26.22
C-4	377	9,610.3	0.12	19	267.4	0.00	514	6,351.821892	0.09
C-5	9,518	204,728.2	2.48	423,394	5,566,921.0	42.45	32,357	534,236.5428	7.46
C-7	87,033	1,515,645.0	18.38	13,648	193,403.7	1.47	109,957	1,637,283.028	22.87
D-1/2	21,537	356,885.8	4.33	154,288	1,926,226.5	14.69	20,525	269,487.2445	3.76
M-1/2	41,788	563,514.7	6.83	86,943	1,065,503.6	8.12	24,811	337,395.9847	4.71
M-3 65% DF	337	6,602.7	0.08	0	0.0	0.00	9	305.8447812	0.00
N	6,867	765,826.8	9.28	47,453	2,756,559.0	21.02	11,520	777,892.0505	10.87
O-1a/b	73,936	1,210,886.4	14.68	10,351	157,931.0	1.20	59,301	11,96149.413	16.71
S-1	15,134	202,766.9	2.46	3,933	29,751.7	0.23	11,785	14,9518.7009	2.09
S-2	5,126	35,533.9	0.43	858	3,781.3	0.03	3,222	20,464.76156	0.29
S-3	139	1,168.5	0.01	14,087	74,538.1	0.57	1,155	8,672.266118	0.12
W	14,954	291,937.5	3.54	14,818	365,613.8	2.79	6,683	225,853.0261	3.16
Total	**460,171**	**8,248,124.9**	**100.00**	**827,176**	**13,115,437.5**	**100.00**	**423,920**	**7,157,908.6**	**100.00**

	Northwest Fire Centre			Prince George Fire Centre			Southeast Fire Centre		
Fuel Type	**# of polygons**	**Ha**	**%**	**# of polygons**	**Ha**	**%**	**# of polygons**	**Ha**	**%**
C-1	7,883	417,505.2	1.71	56,850	1,073,326.9	3.19	1,427	23,017.1	0.28
C-2	25,159	761,437.0	3.13	331,483	5,284,170.9	15.69	6,626	134,145.1	1.63
C-3	181,606	5,019,342.1	20.60	610,844	9,058,311.5	26.90	139,704	1,940,584.0	23.57
C-4	114	4,933.4	0.02	652	29,814.0	0.09	167	2,022.6	0.02
C-5	143,563	2,400,621.9	9.85	12,425	185,487.4	0.55	60,082	861,802.8	10.47
C-7	46,782	981,214.7	4.03	133,133	1,675,726.0	4.98	76,541	1,124,324.1	13.66
D-1/2	80,213	1,485,482.0	6.10	220,089	3,429,707.8	10.19	35,125	494,054.6	6.00
M-1/2	49,003	885,169.2	3.63	265,402	3,852,751.2	11.44	52,619	772,506.8	9.38
M-3 65% DF	38	933.2	0.00	49	968.9	0.00	0	0.0	0.00
N	23,105	10,008,045.3	41.08	62,375	3,995,139.8	11.87	26,146	1,619,689.7	19.67
O-1a/b	45,088	1,328,439.9	5.45	238,639	3,876,228.5	11.51	50,245	920,130.8	11.18
S-1	3,775	55,415.5	0.23	15,963	256,414.3	0.76	6,432	81,299.1	0.99
S-2	2,968	31,706.9	0.13	9,860	85,127.0	0.25	1,124	10,664.3	0.13
S-3	954	4,906.4	0.02	200	1,877.0	0.01	1,390	9,044.7	0.11
W	31,550	976,433.4	4.01	30,212	863,965.5	2.57	5,636	240,299.6	2.92
Total	**641,801**	**24,361,586.1**	**100.00**	**1,988,176**	**33,669,016.7**	**100.00**	**463,264**	**8,233,585.4**	**100.00**

larch species as deciduous (see Section 5.4.2). Stands with 10–30% conifer cover comprise about 26% of M-1/2 stands; those with 35–55% conifer comprise 50% of mixedwood stands, and those with 60–80% conifer form the remaining 24%.

Table 4. Mixedwood (M-1/2) percent conifer frequency table, 2017.

% Conifer	# of grid cells	Ha	%
10	8,271	2,068	0.03
15	337,636	84,409	1.13
20	890,484	222,621	2.98
25	2,642,570	660,643	8.83
30	4,009,401	1,002,350	13.40
35	1,897,811	474,453	6.34
40	7,717,430	1,929,358	25.80
45	1,637,025	409,256	5.47
50	2,669,604	667,401	8.92
55	982,252	245,563	3.28
60	2,820,796	705,199	9.43
65	1,202,812	300,703	4.02
70	1,315,072	328,768	4.40
75	718,365	179,591	2.40
80	1,063,537	265,884	3.56
Total	**29,913,066**	**7,478,267**	**100.00**

Conclusions and next steps

9. Conclusions

9.1 Decision frequencies within the FTL

This project is considered successful, in that a province-wide fuel type layer has been created, implemented, used effectively with a suite of fire behaviour models and finally documented. Due to the constant gathering of new knowledge and information, and the dynamic nature of vegetation communities, the FTL is not considered complete but is rather in a state of continuous monitoring and updating. The current FTL algorithm has a few notable inefficiencies – where the resulting number of polygons is either too low or too high. Most of these will be targeted during the next revision.

As the FTL algorithm table (see Appendix 5) shows, the polygon frequencies are highly uneven. There are several instances where logical queries resulted in zero polygons; these lines are clearly superfluous in the algorithm and could be removed in the next iteration (although there is always a chance that such vegetation attributes could exist in the future). For example, there are currently zero polygons that result from a query of stands of pure (single species or nearly so) ponderosa pine (Py) between 4 and 12 m in height with more than 8000 stems/ha. Other decisions currently result in too many results and highlight the need for further discrimination, particularly when it is obvious that the resulting fuel structure could vary considerably. An example of the latter is stands of pure (single species) true fir ('Balsam') that are neither Grand fir nor Amabilis fir, and are not **Sparse** (i.e., they are **Open** or **Dense**; see Section 5.2). These are mostly subalpine fir ('Bl'), and there are more than 260,000 such polygons in the VRI (all typed as C-3). Subsequent revisions will aim to further differentiate these stands using additional attributes and ideally, more fire behaviour monitoring information.

9.2 Ground-truthing and fuel types

While designing this project, we have attempted to produce a comprehensive fuel type layer for fire behaviour prediction using the best and most current data available. However, there are significant limitations to the provincial scale approach when it comes to examining fine-scale variations in fuel structure on the landscape and modeling the behaviour of individual fires. It is apparent that this process could be significantly improved by ground-truthing, or field validation, of vegetation and fuel structure. As with any modeling, both the VRI inventory process and the separate fuel typing process described in this document involve human interpretations that are often uneven or prone to error. Both processes could clearly benefit from some quality control. There are several important considerations to note related to field verification of fuel types:

- Ground-truthing of forest inventory data (general vegetation and forest stand attributes) is important, and should be done as part of continuous improvement and building confidence with the base inventory data
  - The BC Forest Analysis and Inventory Branch is tasked with this, and undertakes a certain amount of provincial-level validation annually
  - It would also be advisable for the BCWS staff to ground-truth the VRI data, as much to breed familiarity with the variety of forest types as to verify that the data meets desired accuracy standards – a polygon mapped as a 140-year old stand of Douglas-fir and lodgepole pine with 1200 stems per hectare should indeed match that description, more or less
  - Ground truthing of specific VRI attributes used in the fuel typing (section 5.2, above) could be accomplished using straightforward forest survey techniques, and is highly recommended
    - Examples of VRI attributes that could be readily verified in the field (by properly trained technicians) include tree species composition, stand height, stand density, tree ages, and canopy cover; stand attributes can be deduced from individual tree attributes with proper sampling.
- Ground-truthing of fuel structure characteristics specific to fire behaviour prediction can also be undertaken – this involves assessing attributes that have been found to be

particularly significant in affecting fire behaviour, and may or may not be part of general forest stand characteristics: fuel loading (fine and coarse woody debris, litter and duff depth, crown fuel load), crown base height, canopy bulk density (difficult to measure directly), tree height, etc.

- Crown attributes (especially crown base height and canopy bulk density) can also be assessed by combining measured stand attributes with modeled crown fuel characteristics;
- Various tables and calculators can be used for such purposes (e.g., Cruz et al. 2003a, Reinhardt et al. 2006, Alexander and Cruz 2014); predictions based on these studies would also benefit from field validation, although these efforts often consist of significant research projects (e.g. destructive sampling and measurement of entire tree crowns) rather than simple field measurements
- These characteristics can be used to inform the selection of the best fit FBP fuel type; however, it is not always obvious how to do so. For example, surface fuel loading or canopy bulk density are not described quantitatively for FBP fuel types in the technical system description (Forestry Canada Fire Danger Group 1992).

Direct ground-truthing of FBP fuel types, however, is more problematic. As previously discussed, assigning an FBP fuel type to a particular stand or vegetation polygon is a complex, somewhat subjective process, often described as a blend of 'art' and science, and often implemented with regional idiosyncrasies (see Section 5.3). Evaluating FBP fuel types in the field requires specialized training and experience in a particular vegetation type, and is not readily done by most field technicians or contractors[24]. Through the present effort, we are seeking to make the fuel typing process more objective by typing stands with similar attributes identically. Improving the fuel typing process, then, becomes a matter of improving forest inventory data as well as the collection of fire behaviour case studies in documented vegetation types. This would, in theory, negate the need for actual FBP fuel type field validation – if the attributes of the vegetation community are correctly represented in a vegetation inventory polygon, and a reasonably robust fuel type model exists for that vegetation type, there would be no separate fuel type validation required.

Despite this intention, however, there are certain characteristics that are important to fire behaviour which are not (and are unlikely to ever be) captured by the VRI process. Attributes such as litter and duff depth and loading, the presence or abundance of dead conifer branches on standing trees, density of arboreal lichens, and the presence of particular understory species known to be particularly flammable (due to volatile oils or resins; e.g. common juniper), for example, are all potentially important for fire behaviour at the site level but are beyond the scope of VRI stand attribute mapping. These are also stand characteristics that are unlikely to be within the detection capabilities of remote sensing technologies, at least in the next few years (we would be glad to be proven wrong on that point). Some of these attributes are easily measured in the field and could potentially be used to aid in fire behaviour prediction.

Due to the large number of potentially important attributes, such field-based evaluations of fuel type are likely to remain subjective in nature; at the least, measurement effort is expected to remain very uneven. Therefore, we recommend that some fuel type validation be undertaken, if performed by personnel who have locally relevant fire behaviour skills and experience. Ultimately, fire behaviour observations and case studies are the best evidence – the fire is never wrong – but in the absence of such observations, careful field assessment of fuel type can also provide value.

9.3 Alternatives to the CFFDRS and FBP fuel types

Since the publication of the FBP System in its 'final' form (Forestry Canada Fire Danger Group 1992), there has been growing interest in modeling fire behaviour using models based on physical attributes; that is, dispensing with the somewhat artificial fuel type categories in favour of quantifiable fuel parameters. While the majority of this document has focused on fuel typing using the standard FBP System fuel types, some of these alternative modeling systems are worth discussing as viable alternatives in certain cases.

9.3.1 Crown Fire Initiation and Spread (CFIS) software model

One of the significant weaknesses of the FBP System approach is the lack of flexibility of the fuel types. For instance, the system offers almost no ability to represent the various chronological or successional stages that a vegetation community undergoes; fuel treatments or partial harvesting that reduce overstory fuel loading are also not captured. For example, a Douglas-fir/Ponderosa pine stand (typed as C-7) might undergo a 'low thinning' mechanical fuel treatment that removes 30–50% of basal area and most tree stems, focused primarily on the smaller diameter ladder fuels. This treatment would certainly reduce canopy bulk density and likely increase canopy base height; however, this stand has no obvious post-treatment FBPS fuel type match (under the present algorithm, it would likely still be typed as C-7).

A software-based modeling system that was addressed specifically to address this gap is the Crown Fire Initiation and Spread (CFIS) system, developed by Cruz, Alexander and others (Cruz et al. 2003b, Cruz et al. 2005, Alexander et al. 2006). The mathematical models driving the software are empirical models based on the CFFDRS dataset, using structural attributes (where significant) rather than fixed fuel types, and validated with several dozen additional wildfire observations. The CFIS software package[25] allows users to simply calculate the probability of crown fire initiation, and, if crown fire is predicted, the spread rate and type of crown fire behaviour (Figure 17). Notably, CFIS is sensitive to

24 The issue is not that these individuals cannot provide useful fuel type assessments (they sometimes can), but rather that the reasoning behind these subjective fuel type assessments is of greater interest.

25 For the CFIS software package and additional information, see www.frames.gov/cfis.

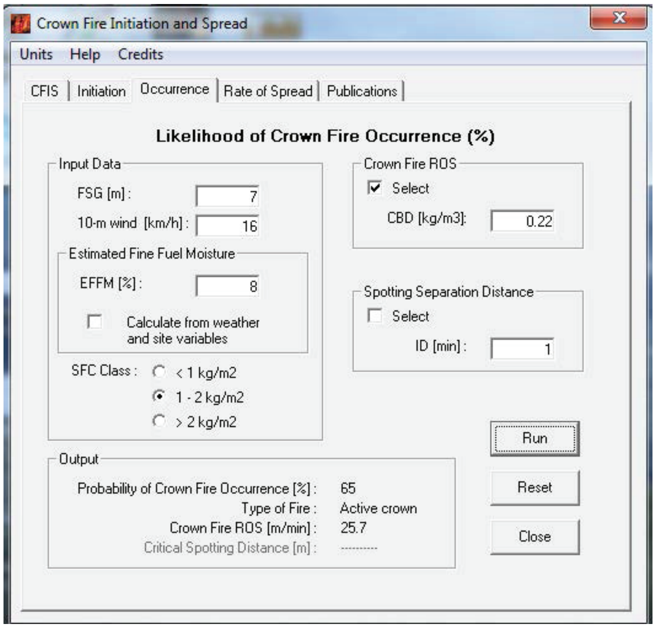

Figure 17. Screen shot of CFIS (Crown Fire Initiation and Spread) software model.

varying crown fuel parameters and somewhat sensitive to surface fuel loading as well, allowing for gaming with respect to fuel treatment parameters.

Limitations to more extensive use of CFIS include the lack of capacity for sloped terrain, the overly simplistic surface fuel consumption categories, and the lack of integration with other software tools. At the present time, it is a useful tool for limited scope applications but lacks an interface to be modular with other applications, such as spatial (GIS) data platforms or script-based analysis platforms. There are additional challenges using CFIS in Canadian fire operations because of its lack of common terminology and commonality of inputs compared with CFFDRS standards (FBP System fuel types, HFI and out outputs, etc.). Although CFIS is designed to stand alone (i.e. lack of integration can be considered a feature rather than a limitation), it is often unclear how users should communicate CFIS outputs compared with standard FBP System outputs.

Despite various limitations, CFIS (and the models developed by its authors) represents a valuable tool that is currently being explored by BCWS staff for developing and evaluating mechanical forest fuel treatments and fuel treatment objectives. At the present time, these analyses will be done in parallel with the standard FBP System approach for fire behaviour prediction, as there is no way to integrate CFIS inputs (or similar alternative fire behaviour models) into the fuel type layer.

9.3.2 Pure physical models

There is another class of models that dispenses entirely (or almost) with the empirical approach in favour of seeking mechanistic processes underlying fire behaviour. These models (physical and quasi-physical models, as per Sullivan 2009a) use complex 3- and 4-dimensional physics and chemistry processes, including heat transfer and fluid mechanics equations to seek a more fundamental and scalable understanding of fire dynamics (e.g. Linn et al. 2002, Mell et al. 2009, Hoffman et al. 2012). These examples show varying degrees of promise, but remain research (non-operational) tools for the time being. This is mostly due to the complexity of building datasets to use them, and the computing power and time required to run their software versions.

This may change in the future, but at the present time, these models are not being considered for operational purposes by the BCWS, and no effort is being made to prepare datasets for their use in BC. As discussed in the Introduction, the CFFDRS remains the primary tool for operational fire behaviour prediction, both on wildfires and in planning processes.

9.4 Final Conclusions

The present document describes the background, motivation, history, methodology, and results associated with a new provincial fuel type layer for fire behaviour prediction and calculations using the Canadian Fire Behaviour Prediction (FBP) System. The fuel type layer is currently being used by BC Wildfire Service for fire behaviour prediction and planning at multiple scales. The resultant data layer, and this document, are considered 'living' processes that are continuously being refined; at the time of writing the layer is re-processed annually when the new provincial Vegetation Resource Inventory data are published. The logic in the fuel typing algorithm is updated gradually as new information from wildfire observations and new studies emerge.

Although fire behaviour prediction using the FBP System remains a partly subjective endeavour, through this document we have attempted to make the process more transparent and accountable, and thereby encourage continued progress and innovation.

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Appendices[1]

Appendix 1: FBP Fuel Types

- Fuel type is defined as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behaviour under defined burning conditions" (CIFFC 2003)
- The main list of FBP fuel types is copied from Forestry Canada Fire Danger Group (1992); the D-2 fuel type is described in Alexander (2010); detailed descriptions are provided below
- Reports describing additional new fuel types have been published but have not been finalized or formally adopted for use in the FBP System (e.g. Stocks et al. 2004, Pepin 2014, Perrakis et al. 2014b)

Group/Identifier	Descriptive Name
Coniferous	
C-1	Spruce-lichen woodland
C-2	Boreal spruce
C-3	Mature jack or lodgepole pine
C-4	Immature jack or lodgepole pine
C-5	Red and white pine
C-6	Conifer plantation
C-7	Ponderosa pine-Douglas-fir
Deciduous	
D-1	Leafless aspen
D-2	Green aspen
Mixedwood	
M-1	Boreal mixedwood-leafless
M-2	Boreal mixedwood-green
M-3	Dead balsam fir mixedwood-leafless
M-4	Dead balsam fir mixedwood-green
Slash	
S-1	Jack or lodgepole pine slash
S-2	White spruce-balsam slash
S-3	Coastal cedar-hemlock-Douglas-fir slash
Open	
0-1	Grass

1 Full references for citations in the Appendix have been added to the References section in the main document.

Appendix 2: FBP Fuel Type Descriptions[2]

Forest floor and organic layer	Surface and ladder fuels	Stand structure and composition
Fuel Type C-1 (Spruce-Lichen Woodland)		
Continuous reindeer lichen; organic layer absent or shallow, uncompacted.	Very sparse herb/shrub cover and down woody fuels; tree crowns extend to ground.	Open black spruce with dense clumps; assoc. sp. jack pine, white birch; well-drained upland sites.
Fuel Type C-2 (Boreal Spruce)		
Continuous feather moss and/or Cladonia; deep, compacted organic layer.	Continuous shrub (e.g., Labrador tea); low to moderate down woody fuels; tree crowns extend nearly to ground; arboreal lichens, flaky bark.	Moderately well-stocked black spruce stands on both upland and lowland sites; Sphagnum bogs excluded.
Fuel Type C-3 (Mature Jack or Lodgepole Pine)		
Continuous feather moss; moderately deep, compacted organic layer.	Sparse conifer understory may be present; sparse down woody fuels; tree crowns separated from ground.	Fully stocked jack or lodgepole pine stands; mature.
Fuel Type C-4 (Immature Jack or Lodgepole Pine)		
Continuous needle litter; moderately compacted organic layer.	Moderate shrub/herb cover; continuous vertical crown fuel continuity; heavy standing dead and down, dead woody fuel.	Dense jack or lodgepole pine stands; immature.
Fuel Type C-5 (Red and White Pine)		
Continuous needle litter; moderately shallow organic layer.	Moderate herb and shrub (e.g. hazel); moderate dense understory (e.g. red maple, balsam fir); tree crowns separated from ground.	Moderately well-stocked red and white pine stands; mature; assoc. sp. white spruce, white birch, and aspen.
Fuel Type C-6 (Conifer Plantation)		
Continuous needle litter; moderately shallow organic layer.	Absent herb/shrub cover; absent understory; tree crowns separated from ground.	Fully stocked conifer plantations; complete crown closure regardless of mean stand height; mean stand crown base height controls ROS and crowning.
Fuel Type C-7 (Ponderosa Pine-Douglas-fir)		
Continuous needle litter; absent to shallow organic layer.	Discontinuous grasses, herbs, except in conifer thickets, where absent; light woody fuels; tree crowns separated from ground except in thickets.	Open ponderosa pine and Douglas-fir stands; mature uneven-aged; assoc. sp. western larch, lodgepole pine; understory conifer thickets.
Fuel Types D-1 and D-2 (Aspen)		
Continuous leaf litter; shallow, uncompacted organic layer.	Moderate medium to tall shrubs and herb layers; absent conifer understory; sparse, dead, down woody fuels.	Moderately well-stocked trembling aspen stands; semimature. Fuel types are differentiated by season.
Fuel Types M-1 and M-2 (Boreal Mixedwood)		
Continuous leaf litter in deciduous portions of stands; discontinuous feather moss and needle litter in conifer portions of stands; organic layers shallow, uncompacted to moderately compacted.	Moderate shrub and continuous herb layers; low to moderate dead, down woody fuels; conifer crowns extend nearly to ground; scattered to moderate conifer understory.	Moderately well-stocked mixed stand of boreal conifers (e.g., black/white spruce, balsam/subalpine fir) and deciduous species (e.g., trembling aspen, white birch). Fuel types are differentiated by season and percent conifer/deciduous sp. composition.
Fuel Types M-3 and M-4 (Dead Balsam Fir Mixedwood)		
Continuous leaf litter in deciduous portions of stands; discontinuous feather moss, needle litter and hard- wood leaves in mixed portions of stands; organic layers moderately compacted, 8–10 cm.	Dense continuous herbaceous cover after greenup; down woody fuels low initially, but becoming heavy several years after balsam mortality; ladder fuels dominated by dead balsam understory.	Moderately well-stocked mixed stand of spruce, pine and birch with dead balsam fir, often as an understory. Fuel types differentiated by season and age since balsam mortality.
Fuel Type S-1 (Jack or Lodgepole Pine Slash)		
Continuous feather moss; discontinuous needle litter; moderately deep, compacted organic layer.	Continuous slash, moderate loading and depth; high foliage retention; absent to sparse shrub and herb cover.	Slash from clearcut logging; mature jack or lodgepole pine stands.

2 From Forestry Canada Fire Danger Group (1992), Table 3. Fuel type D-2 has been added (as per Alexander 2010), with minor changes to the text, following the format of the original table. Latin names are given in Table A3, below.

Fuel Type S-2 (White Spruce-Balsam Slash)		
Continuous feather moss and needle litter; moderately deep, compacted organic layer.	Continuous to discontinuous slash (due to skidder trails); moderate foliage retention; moderate loading and depth; moderate shrub and herb cover.	Slash from clearcut logging; mature or overmature white spruce, subalpine fir or balsam fir stands.
Fuel Type S-3 (Coastal Cedar-Hemlock-Douglas-fir Slash)		
Continuous feather moss or compacted old needle litter below fresh needle litter from slash; moderately deep to deep, compacted organic layer.	Continuous slash, high foliage retention (cedar), moderate for other species; heavy loading, deep slash; sparse to moderate shrub and herb cover.	Slash from clearcut logging; mature to overmature cedar, hemlock, or Douglas-fir stands.
Fuel Type 0-1 (Grass)		
Continuous dead grass litter; organic layer absent to shallow and moderately compacted.	Continuous standing grass (current year crop). Standard loading is 0.35 kg/m^2,[a] but other loading can be accommodated; percent cured or dead must be estimated. Sparse or scattered shrubs and down woody fuel. Subtypes for both early spring matted grass and late summer standing cured grass are included.	Scattered tress, if present, do not appreciably affect fire behavior.

[a] Standard loading was 0.3 kg/m^2 in the original document; now changed to 0.35 kg/m^2 (Wotton et al. 2009)

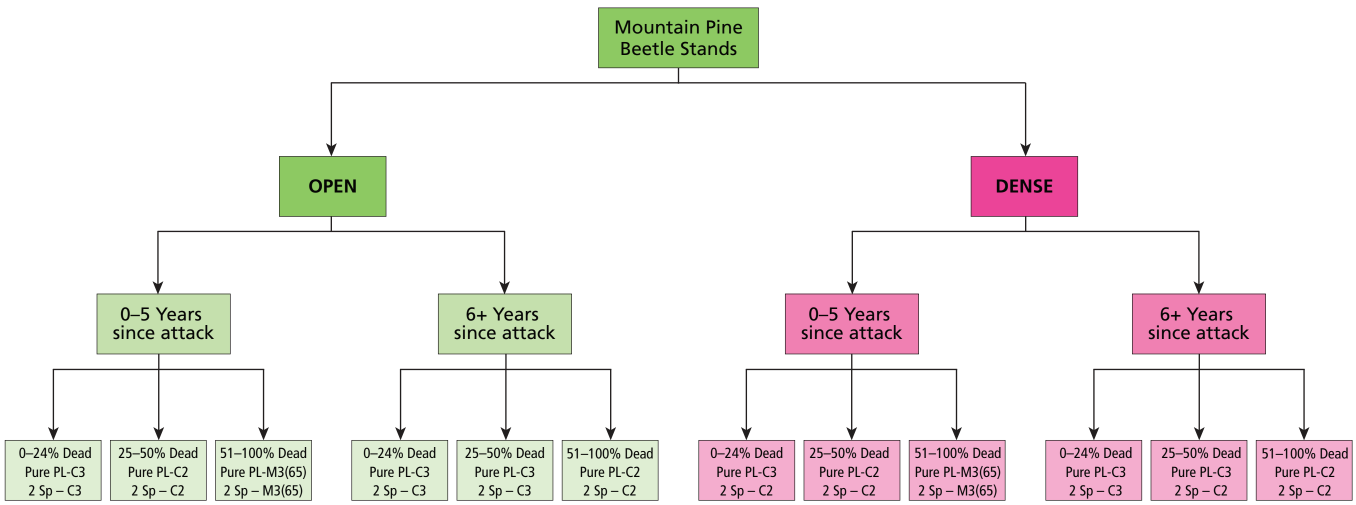
Appendix 3: BC conifer species codes

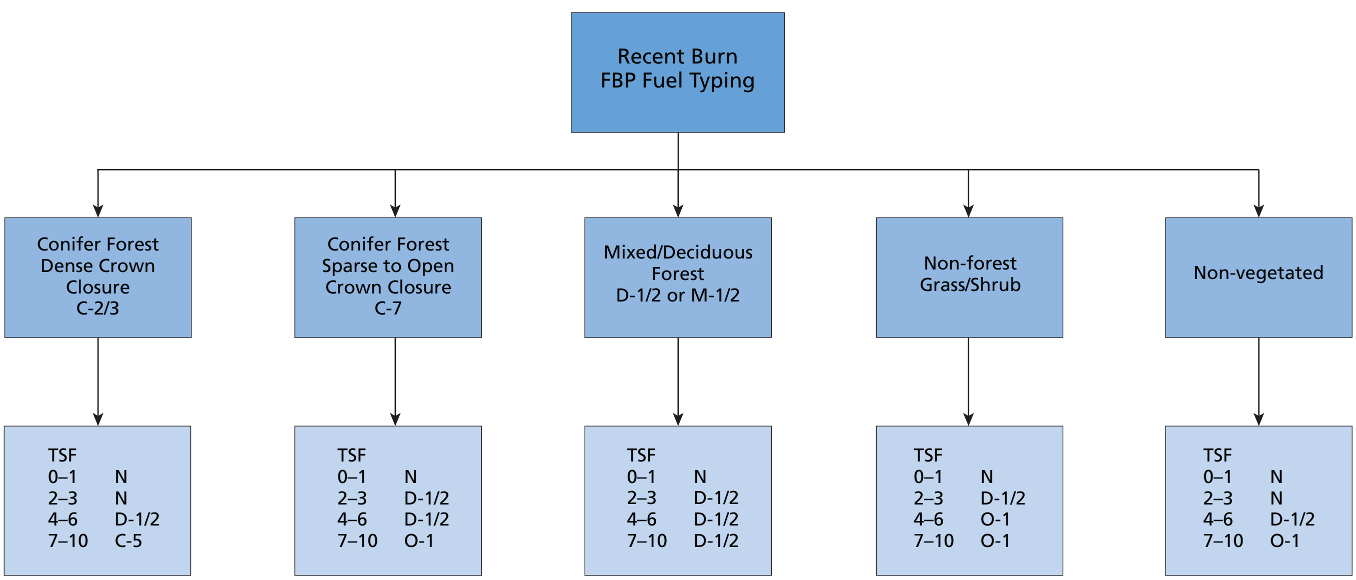
The following is a list of the common vegetation names used in the document. 'Code' values are excerpted from the BC VRI Data Dictionary. The second code letter is sometimes shown in lowercase (e.g. Fd for Douglas-fir).

Code	Common name	Latin name (excl. authority)
B	True fir	*Abies spp.*
BL	Alpine fir	*Abies lasiocarpa*
BA	Amabalis fir	*Abies amabalis*
BG	Grand fir	*Abies grandis*
CW	Western redcedar	*Thuja plicata*
FD	Douglas-fir	*Pseudotsuga menziesii*
H	Hemlocks	*Tsuga spp.*
HW	Western hemlock	*Tsuga heterophylla*
HM	Mountain hemlock	*Tsuga mertensiana*
L	Larch	*Larix spp.*
LA	Alpine larch	*Larix lyalli*
LT	Tamarack	*Larix laricina*
LW	Western larch	*Larix occidentalis*
P	Pine	*Pinus spp.*
PF	Limber pine	*Pinus flexilis*
PL	Lodgepole pine	*Pinus contorta*
PW	Western white pine	*Pinus monticola*
PA	Whitebark pine	*Pinus albicaulis*
PY	Yellow pine	*Pinus ponderosa*
PJ	Jack pine	*Pinus banksiana*
S	Spruce	*Picea spp.*
SB	Black spruce	*Picea mariana*
SE	Engelmann spruce	*Picea engelmannii*
SS	Sitka spruce	*Picea sitchensis*
SW	White spruce	*Picea glauca*
SX	Hybrid spruce	*Picea spp.*
YC	Yellow-cedar	*Chamaecyparis nootkatensis*
	White birch	*Betula papyrifera*
	Trembling aspen	*Populus tremuloides*
	Feathermoss	*Pleurozium spp.*
	Reindeer lichen	*Cladonia spp.*

Appendix 4: Process charts for MPB-affected stands and recent burns[3]

These flowcharts show the processing logic for mountain pine beetle-affected stands (top) and recent burns (bottom). 'Open' and 'Dense' refer to canopy cover 26–60% and >60%, respectively (Section 5.2); Pure Pl (lodgepole pine) are >80% lodgepole pine by percent of total canopy cover; '2 sp' stands are a mix of Pl and white/hybrid spruce or subalpine fir; TSF means time since fire (years). Fuel types N, D-1/2, C-5, and O-1 refer to Canadian Fire Behaviour Prediction System fuel types (Section 4.2).





3 See also Sections 5.4.2, 5.4.6 in text.

Appendix 5: Fuel Typing Algorithm

The full fuel typing algorithm is including in the following pages, as implemented in 2017.

Some references to VRI attributes are informal, for ease of description (e.g. 'Pure pine' signifies overstory composition of 81% pine species, or greater). As described in Section 4, following a number of pre-processing steps implemented on the BC vegetation inventory layer, the polygons were classified as described in the table below via Python script (over 2000 lines long as of summer 2017). The technical rationale for fuel typing assignments are found in Section 5.

Totals at the bottom of table differ somewhat from those in Table 2 due to the inclusion of some ocean areas (the VRI layer contains approximately 5 million hectares of ocean polygons; Table 2 only includes land and inland waters).

Right-hand column headings are as follows:

- FBP FT: FBP fuel type; also includes N (non-fuel) and W (water; identical to non-fuel for modeling purposes)
- Modifier: FBP FT modifier; at this time mostly associated with mixedwood (M-1/2) stands
  - Percent conifer (%C), percentage of overstory composed of conifer species
  - For some stands, this is fixed (e.g. 50%), simulating an M-1/2 stand of 50% spruce and 50% deciduous trees
  - For other stands, this varies, depending on the percent conifer and dominant tree species in the stand (see Section 5.4.3)
  - As noted in the text (Section 5.4.2, Appendix 4), certain newly attacked (red-attack) MPB-killed stands are typed as M-3 (65% dead fir); in this case, the modifier is the % dead fir (fixed at 65)
- Process #: nominal (categorical) unique value designated to each fuel type assignment to keep track of logic and decisions
  - Process numbers are not available for polygons typed using the National fuel type grid (#9000); see section 7.2).
- Freq.: frequency (number of polygons) associated with each fuel type assignment, colour-coded as follows:

Rare	**0 – 100**
Moderate	**101 – 10,000**
Abundant	**10,001 – 75,000**
Over subscribed	**75,001 +**

- Some logical combinations exist in the algorithm but have zero (or very few) polygons with those attributes (gray colour, as noted in table above); others are overly abundant (pink in table above), and may be further subdivided in the next update of the algorithm. See discussion in text (section 9.1).
- Process numbers marked with an asterisk (*) were identified as misclassified, and have been manually changed to C-3; see Section 8.2.1. This applies to Process numbers 13, 246, 248 (Rows 68, 383, 387).

FT Key 2017	FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Non-vegetated (BCLCCS Lv1 = N)						1
Logged (Harvest date NOT null)						2
Harvest date 0–6 years ago						3
Coast	S-3		500	1,900	11,008	4
Interior	S-1		502	705	15,955	5
Harvest date 7–24 years ago						6
BEC = CWH, MH, ICH	D-1/2		508	1,475	7,339	7
Else (dry)	O-1a/b		510	1,199	24,861	8
Harvest date 25+ years ago						9
BEC = CMA, IMA	N		512	0		10
BAFA	D-1/2		514	0		11
CWH – dry	M-1/2	40	516	37	266	12
CWH – wet	C-5		518	82	875	13
BWBS	C-2		520	18	221	14
SWB	M-1/2	50	522	0		15
SBS	C-3		524	33	389	16
SBPS	C-7		526	12	230	17
MS	C-7		528	31	531	18
IDF – dry	C-7		530	30	561	19
IDF – wet	C-3		532	1	7	20
PP	O-1a/b		534	1	1	21
BG	O-1a/b		536	0		22
MH	D-1/2		538	1	1	23
ESSF	C-7		540	355	4,759	24
CDF – dry	C-7		542	0		25
CDF – wet	C-5		544	1	2	26
ICH – dry	C-3		546	31	240	27
ICH – wet	C-5		548	460	5,410	28
Else (not logged)						29
Recently burned ((Earliest_nonlogging_dist_type = B, BE, BG, BW, BR, or NB) AND Fire year <11 years before present)						30
Time since fire (TSF) 0–3 years before present	N		1611	82	1,245	31
TSF 4–6 years	D-1/2		1612	118	1,183	32
Else (TSF 7–10 years)	O-1a/b		1613	0		33
Else (not recently burned)						34
BCLCCSC Lv 2 = L (bare land), or Null						35
If Alpine (BCLCS_Lv3 = A)	N		504	46,328	16,947,315	36
Else						37
If trees present (Sp.1 not Null)						38
BEC = CWH, MH, ICH	D-1/2		1537	5,435	48,391	39
Else (dry)	O-1a/b		1539	3,518	51,476	40
Else (Sp1 Null)	N		1541	61,009	1,036,858	41
BCLCCSC Lv 2 = W (water; includes most VRI ocean polygons)	W		506	75,987	7,305,211	42
Else	N		1543	6,379	59,402	43
Vegetated (BCLCCS Lv1 = 'V')						44
Forested/treed (BCLCCS Lv2 = 'T'; 10% or more tree cover)						45
Recently burned ((Earliest_nonlogging_dist_type = B, BE, BG, BW, BR, or NB) AND Fire year <11 years before present)						46
Conifer forest (Percent conifer >= 60, excluding larch (treat as decid.))						47
Crown closure > 40						48
Time since fire 0–3 years	N		1614	1,439	30,471	49
TSF 4–6 years	D-1/2		1615	2,545	56,590	50
TSF 7–10 years	C-5		1616	0		51

FT Key 2017	FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg Forested Else (Crown closure <= 40)						52
Time since fire 0–1 year	N		1617	0		53
Time since fire 2–6 years	D-1/2		1618	24,610	563,797	54
TSF 7–10 years	O-1a/b		1619	0		55
Else (Mixedwood or deciduous forest (Percent conifer < 60))						56
TSF 0–1 years	N		1620	0		57
TSF 2–10 years	D-1/2		1621	2,268	41,826	58
Else (not recently burned)						59
						60
Single species (Sp.1 >= 80%)						61
Conifer stand (Sp. 1 conifer, except Larch (L))						62
Pure lodgepole or jack or undefined pine (Sp. 1 = Pl, Pli, Plc, Pj, or P)						63
Recently Logged (Harvest_date <= 7 years ago)	S-1		15	2,121	61,026	64
Else (older Harvest date or Harvest date null)						65
Sparse (BCLCCSC Lv5 = SP)						66
BEC = CWH, CDF, MH or ICH (wet)	D-1/2		12	2,631	45,282	67
Else (other BEC zone)	C-7		13*	102,852	2,020,886	68
Else (dense or open)						69
< 4 m height (Sp. 1 height < 4 m)	O-1a/b		14	2,196	74,444	70
4–12 m height (Sp. 1 height 4–12m)						71
Overstocked (Live stems/ha + Dead stems/ha > 8000)	C-4		18	1,430	46,694	72
Else (fully stocked, not overstocked, or LiveS/Ha and Dead S/Ha both null)	C-3		16	42,328	1,058,189	73
Else (> 12 m height)						74
Crown closure < 40 (very open stand type)						75
BEC = BG, PP, IDF, or MS	C-7		20	8,742	141,859	76
BEC = CWH, MH, ICH	C-5		21	839	11,897	77
Else (other BEC zone)	C-3		19	25,050	499,074	78
Else (closed forest or cc null)						79
If MPB attack (Earliest_nonlogging_dist_type = IBM)						80
If red-attack (Year of attack <= 5 years ago)						81
Stand_percent_dead > 50%	M-3	65	1510	325	6,982	82
Stand_percent_dead 25–50%	C-2		1512	2,987	52,292	83
Else (percent dead < 25%)	C-3		1514	262	4,565	84
Else (Gray attack: Year of attack > 5 years ago)						85
Stand_percent_dead > 50%	C-2		1516	647	10,063	86
Stand_percent_dead 25–50%	C-3		1518	8,784	141,765	87
Else (percent dead < 25%)	C-3		1520	18,940	340,776	88
Else (non-MPB closed mature pine stand)	C-3		1522	80,676	1,402,026	89
Py (ponderosa pine)						90
Dense or Open (BCLCCSC Lv5 = DE or OP)						91
Recently logged (Harvest_date <= 10 years ago)	S-1		1526	1	52	92
Else (older logging or Harvest date null)						93
< 4 m height	O-1a/b		1528	2	66	94
4–12 m height (Sp. 1 height 5–12 m)						95
Overstocked (Live stems/ha + Dead stems/ha > 8000)	C-4		1530	0		96
Fully stocked (Live stems/ha + Dead stems/ha 3000–8000)	C-3		1532	0		97
Else – Moderately stocked (< 3000 /ha or null)	C-7		1534	24	202	98
12–17 m height						99
Dense	C-3		1536	9	119	100
Else (Open)	C-7		1538	128	2,195	101
Else (> 17 m height)	C-7		1540	1,469	20,762	102

FT Key 2017					FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Forested	Sing. Sp	Conif.	Else (Sparse)						103
				Stand_percent_dead >= 40%	O-1a/b		1542	83	2,588	104
				Else (percent dead < 40%)						105
				Logged (Harvest_date) <= 10 years ago	S-1		1544	14	562	106
				Else (older logging or Harvest date null)	C-7		1546	1,852	35,139	107
				Pa, Pf, Pw (whitebark, limber, or western white pine)				2064		108
				Dense	C-3		1601	21	540	109
				Else (sparse or open)						110
				Live stems/ha + dead stems/ha >= 900	C-3		1602	157	2,244	111
				Live stems/ha + dead stems/ha 600–900	C-7		1603	367	5,947	112
				Else	C-5		10	1,462	25,831	113
				Pure Douglas-fir (Sp. 1 = Fd, or any F)						114
				Recently logged (Harvest_date <= 6 years ago)						115
				BEC = CWH, MH, ICH (wet), CDF	S-3		1548	319	3,244	116
				Else (dry BEC zone or ICH (dry))	S-1		1550	162	2,306	117
				Else (older logging or Harvest date null)						118
				< 4 m height						119
				BEC = CWH, MH, ICH (wet), CDF	D-1/2		22	893	9,124	120
				Else	O-1/ab		23	516	5,880	121
				>= 4 m height						122
				Crown closure > 55 (quite dense)						123
				4–12 m height						124
				BEC = CWH, MH, ICH (wet), CDF	C-3		24	401	4,905	125
				Else (dry BEC zone or ICH (dry))						126
				Stand Percent dead > 34	C-4		25	0		127
				Else	C-3		29	401	6,292	128
				Else (> 12 m height)						129
				BEC = CWH, MH, ICH (wet), CDF	C-5		26	17,606	230,562	130
				Else (dry BEC zone or ICH (dry))	C-7		27	21,411	323,358	131
				Crown closure 26–55 (or Null)						132
				BEC = CWH, CDF, MH or ICH (wet)	C-5		28	16,026	180,043	133
				Else (interior, drier BEC zones)	C-7		31	73,954	1,184,294	134
				Crown closure < 26						135
				BEC = CWH, CDF, MH or ICH (wet)	D-1/2		95	6,379	65,563	136
				Else (other BEC zone)	O-1a/b		96	33,872	519,607	137
				Pure spruce						138
				Se						139
				Recently logged (Harvest_date <= 10 years ago)	S-2		1552	43	748	140
				Else (older logging or Harvest date null)						141
				Sparse	D-1/2		32	6,359	70,994	142
				Dense	C-2		33	1,317	19,450	143
				Else (open)	C-3		34	17,807	234,141	144
				Ss						145
				Recently logged (Harvest_date <= 6 years ago)	S-3		1554	2	57	146
				Else (older logging or Harvest date null)						147
				Sparse	D-1/2		1556	269	2,087	148
				Dense or Open	C-5		36	2,357	25,800	149
				Sb or Sw						150
				Recently logged (Harvest_date <= 10 years ago)	S-2		1558	11	152	151
				Else (older logging or Harvest date null)						152
				Dense or Open	C-2		38	195,039	3,027,424	153

FT Key 2017	FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg / Forested / Sing. Sp / Conif / Else (Sparse)						154
BEC = BWBS or SWB	C-1		42	41,266	892,752	155
Else	M-1/2	30	44	12,423	101,949	156
S(other – Sx or S)						157
Recently logged (Harvest_date <= 7 years ago)	S-2		1560	721	16,703	158
Else (older logging or Harvest date null)						159
BEC = BWBS or SWB						160
Dense or Open	C-2		46	35,525	1,202,115	161
Else (Sparse)	C-1		50	10,398	284,779	162
Else (not BWBS or SWB)						163
Sparse	C-7		51	43,033	494,640	164
Else (open or dense)						165
BEC = CWH or CDF	C-5		52	406	6,993	166
Else (interior spruce, not sitka)						167
< 4 m height	O-1a/b		53	993	11,572	168
Else (> 4 m height)						169
Open	C-3		54	63,638	840,234	170
Else (Dense)	C-2		55	3,846	48,787	171
						172
Pure Hemlock, Redcedar or Yellow-cedar (Sp. 1 = H (any), C (any) or Y (any))						173
Recently logged (Harvest_date <= 6 years ago)	S-3		1562	378	3,665	174
Else (older logging or Harvest date null)						175
Dense						176
< 4 m height	D-1/2		58	96	1,070	177
4–15 m height	C-3		60	1,618	19,149	178
Else (taller, dense stands)						179
Age < 60	C-3		62	2,073	29,441	180
Age 60–99	M-1/2	40	64	3,813	48,979	181
Else (old, dense or unknown stands)	C-5		66	14,382	241,789	182
Open	C-5		1564	66,104	886,837	183
Else (Sparse)	D-1/2		68	20,509	298,117	184
True fir (Balsam; Sp. 1 = B (any))						185
Bg	C-7		82	23	212	186
Ba	M-1/2	40	84	10,913	107,969	187
B(other – mainly Bl)						188
Sparse	C-7		86	97,563	1,456,500	189
Else	C-3		88	273,760	4,546,737	190
Yew (Sp. 1 = T(any))	C-5		90	4	186	191
Juniper (Sp. 1 = J(any))	O-1a/b		93	1	3	192
Deciduous/broadleaf or larch stand (Sp. 1 deciduous or L(any))	D-1/2		94	180,488	2,602,979	193
Mixed species stand (2 or more primary species; Sp. 1 < 80%)						194
Mixed species deciduous stand (% C (except Larch) <= 20%)	D-1/2		100	65,880	994,729	195
Mixed species conifer or mixedwood stand (% C (except Larch) > 20)						196
%C 21–40 (decid.-dominated mixedwood stands)						197
Logged (Harvest_date) <= 6 years ago	S-1		1529	228	4,936	198
Else (older logging or Harvest date null)						199
Dominant conifer species (DCSp): Sb, Sw, Sx, Se	M-1/2	= %C	102	67,053	880,438	200
DCSp S						201
Coast	M-1/2	= %C * 0.5	1545	262	3,865	202
Else (interior)	M-1/2	= %C	1547	5,599	127,142	203
Else						204
Sparse	M-1/2	= %C * 0.5	104	10,326	185,154	205
Else	M-1/2	= %C * 0.7	106	42,472	602,479	206

FT Key 2017					FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Forested	Sp>=2	%C>20	**%C 41–65 (mixedwood stands, close to 50/50 conifer-decid.)**						207
				Logged (Harvest_date) <= 6 years ago	S-1		1531	492	9,110	208
				Else (older logging or Harvest date null)						209
				DCSp: Pl, Pli, Plc, Pj, P						210
				Sparse	M-1/2	= %C *0.6	112	10,880	217,946	211
				Open	M-1/2	= %C *0.7	114	18,251	388,002	212
				Dense	M-1/2	= %C *0.8	116	4,714	68,277	213
				Py	M-1/2	= %C *0.6	1533	0		214
				Pa, Pf, Pw	M-1/2	= %C *0.5	118	442	5,979	215
				Fd (any F)						216
				BEC = CWH, CDF or ICH	M-1/2	= %C *0.5	120	11,225	172,353	217
				Else	M-1/2	= %C *0.6	122	10,050	131,719	218
				Se						219
				Sparse	M-1/2	= %C *0.6	124	423	5,582	220
				Else (dense or open)	M-1/2	= %C *0.9	126	1,630	21,604	221
				Ss	M-1/2	= %C *0.4	128	671	7,259	222
				Sb or Sw	M-1/2	= %C	130	41,288	566,272	223
				S(other - Sx, S)						224
				BEC = BWBS or SWB						225
				Dense or Open	M-1/2	= %C	132	7,256	151,803	226
				Else (Sparse)	M-1/2	= %C *0.6	136	1,528	25,706	227
				Else (not BWBS or SWB)						228
				Sparse	M-1/2	= %C *0.6	138	6,296	79,253	229
				Else (open or dense)						230
				Interior	M-1/2	= %C *0.8	140	16,298	205,432	231
				Else (Coast)	M-1/2	= %C *0.5	142	192	3,079	232
				H(any), C(any) or Y(any)	M-1/2	= %C *0.4	144	6,905	82,891	233
				B(any)	M-1/2	= %C *0.6	146	3,947	61,778	234
				T(any)	C-5		148	8	91	235
				J(any)	O-1a/b		149	0		236
				%C 65–80 (conifer-dominated mixedwood stands)						237
				Logged (Harvest_date) <= 6 years ago	S-1		1535	926	18,697	238
				Else (older logging or Harvest date null)						239
				DCSp: Pl, Pli, Plc, Pj, P						240
				Sparse	M-1/2	= %C *0.5	154	16,843	293,828	241
				Open	M-1/2	= %C *0.7	156	26,994	454,296	242
				Dense	M-1/2	= %C *0.8	158	7,122	102,518	243
				Py	C-7		160	269	3,501	244
				Pa, Pf, Pw	C-5		162	435	6,628	245
				Fd (any F)						246
				BEC = CWH, CDF or ICH (wet)	C-5		164	14,369	202,781	247
				Else						248
				Dense	M-1/2	= %C *0.7	166	2,785	42,323	249
				Else	C-7		168	21,095	298,400	250
				Se						251
				Sparse	M-1/2	= %C *0.6	170	751	9,854	252
				Else (dense or open)	M-1/2	= %C *0.7	172	3,086	38,396	253
				Ss	C-5		174	743	8,407	254
				Sb or Sw	M-1/2	= %C	176	49,026	672,536	255
				S(other - Sx, S)						256
				BEC = BWBS or SWB						257

FT Key 2017					FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Forested	Sp>=2	%C>20	Dense or Open	M-1/2	= %C	178	6,273	101,636	258
				Else (Sparse)	M-1/2	= %C *0.6	182	1,598	23,257	259
				Else (not BWBS or SWB)						260
				Sparse	M-1/2	= %C *0.6	184	9,558	119,972	261
				Else (open or dense)						262
				Interior	M-1/2	= %C *0.8	186	23,770	315,977	263
				Else (Coast)	C-5		188	201	2,874	264
				H(any), C(any) or Y(any)	C-5		190	12,128	154,712	265
				B(any)	C-7		192	7,426	113,693	266
				T(any)	C-5		194	0		267
				J(any)	C-7		195	0		268
				%C 81–100 (pure conifer, mixed-species stands)						269
				Sp.1 Pl, Pli, Plc, Pj, P						270
				Logged (Harvest_date) <= 7 years ago	S-1		1570	3,484	102,474	271
				Else (older Harvest date or Harvest date null)						272
				Sparse (BCLCCSC Lv5 = SP)						273
				BEC = CWH, CDF, MH or ICH (wet)	D-1/2		290	6,939	128,551	274
				Else (other BEC zone)	C-7		292	73,945	1,252,805	275
				Else (dense or open)						276
				< 4 m height (Sp. 1 height < 4 m)	O-1a/b		208	1,343	21,221	277
				Else (>= 4 m height)						278
				Sp.2 S(any) or B(any)						279
				4–12 m height (Sp. 1 height 4–12m)						280
				Overstocked (Live stems/ha + Dead stems/ha > 8000)	C-4		210	380	6,254	281
				Else not overstocked, or LiveS/Ha and Dead S/Ha both null)	C-3		211	18,296	359,215	282
				Else (> 12 m height)						283
				Crown closure < 40 (very open stand type)						284
				BEC = BG, PP, IDF, or MS	C-7		209	2,554	40,225	285
				BEC = CWH, MH, ICH	C-5		1572	396	5,499	286
				Else (other BEC zone)	C-3		1574	28,381	495,856	287
				Else (closed forest or cc null)						288
				If MPB (Earliest nonlogging dist_type = IBM)						289
				If Year of attack <=5 years ago						290
				If Dense						291
				Stand_percent_dead > 50%	M-3	65	1576	0		292
				Stand_percent_dead 25–50%	C-2		212	6	70	293
				Else (percent dead < 25%)	C-2		1578	3	48	294
				Else (Open)						295
				Stand_percent_dead > 50%	M-3	65	1580	106	1,828	296
				Stand_percent_dead 25–50%	C-2		1582	1,327	19,807	297
				Else (percent dead < 25%)	C-3		214	89	1,268	298
				Else (Year of attack > 5 years ago)						299
				If Dense						300
				Stand_percent_dead > 50%	C-2		1584	5	52	301
				Stand_percent_dead 25–50%	C-2		1586	66	1,002	302
				Else (percent dead < 25%)	C-3		1588	2,616	39,827	303
				Else (Open)						304
				Stand_percent_dead > 50%	C-2		215	276	4,012	305
				Stand_percent_dead 25–50%	C-3		1590	8,686	135,798	306
				Else (percent dead < 25%)	C-3		293	15,098	218,016	307
				Else (non-MPB closed mature pine stand)	C-3		294	42,360	701,389	308

FT Key 2017					FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Forested	Sp >=2	%C>20	Else (Sp2 other)						309
				Crown closure < 40						310
				BEC = IDF, PP, BG, SBPS, MS	C-7		296	2,981	52,714	311
				BEC = CWH, CDF, ICH	C-5		297	2,306	31,842	312
				Else	C-3		298	1,320	18,097	313
				Else (Crown closure >= 40 or null)	C-3		299	18,540	246,789	314
				Sp. 1 Py						315
				Logged (Harvest_date) <= 7 years ago	S-1		1566	12	449	316
				Else (older Harvest date or Harvest date null)						317
				< 4 m height (Sp. 1 height < 4)	O-1a/b		1568	169	2,084	318
				Else (taller)						319
				Dense (BCLCCSC Lv5 = DE)	C-3		200	42	794	320
				Else (open or sparse)	C-7		202	3,401	66,834	321
				Sp. 1 Pa, Pf, or Pw				6041		322
				Dense	C-3		1604	75	1,277	323
				Else (sparse or open)						324
				Live stems/ha + dead stems/ha >= 900	C-3		1605	1,423	22,642	325
				Live stems/ha + dead stems/ha 600–900	C-7		1606	1,130	20,480	326
				Else	C-5		204	3,404	59,302	327
				Sp. 1 Fd (any F)						328
				Logged (Harvest_date) <= 6 years ago						329
				BEC=CWH, MH, ICH (wet), CDF	S-3		1592	653	9,116	330
				Else (dry BEC zone or ICH (dry))	S-1		1594	284	3,952	331
				Else (older Harvest date or Harvest date null)						332
				< 4 m height						333
				BEC = CWH, MH, ICH (wet), CDF	D-1/2		1596	2,261	26,495	334
				Else	O-1a/b		1598	1,203	13,516	335
				>= 4 m height						336
				Crown closure > 55 (quite dense)						337
				4-–12 m height						338
				BEC=CWH, MH, ICH (wet), CDF	C-3		216	1,222	14,816	339
				Else (dry BEC zone or ICH (dry))						340
				Stand Percent dead > 34	C-4		217	1	7	341
				Else						342
				Sp.2 = PY	C-7		218	12	189	343
				Else (other Sp. 2)	C-3		1549	312	4,979	344
				Else (> 12 m height)						345
				BEC = CWH, MH, ICH (wet), CDF	C-5		220	31,659	470,062	346
				Else (dry BEC zone or ICH (dry))	C-7		221	12,508	183,842	347
				Crown closure 26–55 (or Null)						348
				BEC = CWH, CDF, MH or ICH (wet)	C-5		222	30,051	379,547	349
				Else (interior, drier BEC zones)	C-7		223	38,536	567,413	350
				Crown closure < 26						351
				BEC = CWH, CDF, MH or ICH (wet)	D-1/2		225	7,050	84,688	352
				Else (other BEC zone)	O-1a/b		219	12,144	186,668	353
				Sp. 1 S(any)						354
				Logged (Harvest_date) <= 6 years ago				1121		355
				BEC=CWH, CDF, MH or ICH (wet)	S-3		1607	154	2,447	356
				Else (interior or dry BEC zone)	S-2		1511	1,476	36,260	357
				Else (older logging or Harvest date null)						358
				Sp. 1 Se						359

FT Key 2017					FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Forested	Sp >=2	%C>20	Sparse	C-7		224	16,199	210,295	360
				Dense or Open						361
				Sp. 2 = Bl, B, Pl, P, Pli						362
				Dense	C-2		1513	4,133	65,351	363
				Else	C-3		1515	59,964	873,179	364
				Sp. 2 = Hw, Hm, Cw, Yc						365
				Dense	C-3		1517	443	7,171	366
				Else	C-5		1519	3,528	46,075	367
				Else (other Sp. 2)	C-3		1521	6,408	80,159	368
				Sp. 1 Ss	C-5		228	8,928	112,870	369
				Sp. 1 Sb						370
				Dense or Open	C-2		230	43,724	667,988	371
				Else (Sparse)						372
				BEC = BWBS	C-1		234	3,856	91,834	373
				Else	C-3		236	3,929	58,422	374
				S(other – Sx, Sw, S)						375
				BEC = BWBS						376
				Dense	C-2		238	5,890	66,205	377
				Open	C-3		240	29,135	654,307	378
				Else (Sparse)	C-1		244	5,801	147,637	379
				Else (not BWBS)						380
				BEC = CWH, MH or CDF						381
				Sp. 2 = P(any), Bl, B						382
				Sparse	C-7		246*	75	1,225	383
				Else	C-3		1608	215	9,412	384
				Else	C-5		1609	1,618	23,435	385
				Else (interior, non-boreal)						386
				Sparse	C-7		248*	67,302	1,011,393	387
				Else						388
				Dense	C-2		1523	17,496	238,373	389
				Else (Open)						390
				Stand percent_dead > 34	C-2		1525	19,026	255,908	391
				Else (percent_dead <= 34 or Null)						392
				Sp. 2 = Pl, Pli, P	C-2		1610	38,568	512,276	393
				Else (Sp2 other)	C-3		250	127,955	2,125,494	394
				H(any), C(any), Y(any)						395
				Logged (Harvest_date) <= 6 years ago	S-3		1527	625	7,401	396
				Else (older logging or Harvest date null)						397
				Dense						398
				< 4 m height	D-1/2		252	263	3,074	399
				4–15 m height	C-3		253	7,698	100,254	400
				Else (taller, dense stands)						401
				Age < 60	C-3		254	8,153	123,594	402
				Age 60–99	M-1/2	40	256	10,804	134,710	403
				Else (old, dense or unknown stands)	C-5		255	82,202	1,250,540	404
				Open	C-5		257	353,681	4,509,133	405
				Else (Sparse)	D-1/2		258	62,985	907,753	406
										407
				Bg	C-7		274	140	1,737	408
				Ba						409
				Sp. 2 = Se, Sw, S	C-3		276	2,137	27,685	410

FT Key 2017					FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Forested	Sp >=2	%C>20	Else	M-1/2	40	277	42,292	490,882	411
				B(other - mainly Bl)						412
				Coast	M-1/2	40	1622	11,024	202,829	413
				Else (Interior)						414
				Sparse	C-7		278	41,732	694,001	415
				Dense						416
				Sp. 2 = Se, Sw, S	C-2		279	14,362	214,127	417
				Else	C-3		280	2,131	30,764	418
				Else (Open)	C-3		281	152,496	2,621,059	419
				T(any)	C-5		282	2	15	420
				J(any)	C-7		286	0		421
	Non-forested (BCLCCS Lv2 = N)									422
		Recently burned ((Earliest_nonlogging_dist_type = B, BE, BG, BW, BR, or NB) AND Fire year < 11 years before present)								423
		Time since fire (TSF) 0–1 years before present			N		1623	0		424
		TSF 2–3 years			D-1/2		1624	8,814	145,138	425
		Else (TSF 4–10 years)			O-1a/b		1625	0		426
		Else (not recently burned)								427
		Logged (harvest date NOT null)								428
		Sp. 1 NOT <null> (trees present)								429
		Harvest date 0–7 years ago								430
		Sp. 1 P(any)			S-1		300	24,508	207,245	431
		Sp. 1 S(any), B(any)			S-2		302	20,650	133,415	432
		Sp. 1 Cw, Yc, H(any)			S-3		304	9,583	41,819	433
		Sp. 1 Fd								434
		BEC = CWH, ICH			S-3		306	4,116	21,452	435
		Else			S-1		308	3,067	23,822	436
		Else			S-1		310	4,368	30,229	437
		Harv. date 8–24 years ago								438
		BEC = CWH, MH, ICH (wet)			D-1/2		600	17,570	138,949	439
		Else (dry)			O-1a/b		602	29,996	465,991	440
		Harv. date >= 25 years ago - BEC								441
		BEC = CMA, IMA			N		604	6	112	442
		BAFA			D-1/2		606	0		443
		CWH – dry			M-1/2	40	608	705	8,207	444
		CWH – wet			C-5		610	2,316	38,976	445
		BWBS			C-2		612	772	12,524	446
		SWB			M-1/2	50	614	0		447
		SBS			C-3		616	2,302	33,486	448
		SBPS			C-7		618	828	22,200	449
		MS			C-3		620	2,827	41,645	450
		IDF – dry			C-7		622	1,581	28,182	451
		IDF – wet			C-3		624	234	2,747	452
		PP			O-1a/b		626	80	1,081	453
		BG			O-1a/b		628	1	45	454
		MH			D-1/2		630	236	3,817	455
		ESSF			C-3		632	2,935	54,219	456
		CDF – dry			C-7		634	0		457
		CDF – wet			C-5		636	19	136	458
		ICH – dry			C-3		638	245	3,355	459
		ICH – wet			C-5		640	3,096	54,683	460
		Sp. 1 null (no trees)								461

FT Key 2017			FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
Veg	Non-treed	Harvest date 0–5 years ago	S-1		312	15,897	294,354	462
		Harv. date 6–24 years ago						463
		BEC = CWH, MH, ICH	D-1/2		642	4,153	37,346	464
		Else (dry)	O-1a/b		644	11,575	206,579	465
		Harv. date >= 25 years ago - BEC						466
		BEC = CMA, IMA	N		646	1	16	467
		BAFA	D-1/2		648	0		468
		CWH – dry	M-1/2	40	650	169	1,887	469
		CWH – wet	C-5		652	518	7,142	470
		BWBS	C-2		654	171	3,604	471
		SWB	M-1/2	25	656	0		472
		SBS	C-3		658	529	9,418	473
		SBPS	C-7		660	212	7,842	474
		MS	C-7		662	300	6,682	475
		IDF – dry	C-7		664	584	11,564	476
		IDF – wet	M-1/2	50	666	94	1,348	477
		PP	O-1a/b		668	55	2,560	478
		BG	O-1a/b		670	6	40	479
		MH	D-1/2		672	42	2,074	480
		ESSF	C-7		674	344	8,343	481
		CDF – dry	C-7		676	0		482
		CDF – wet	C-5		678	4	15	483
		ICH – dry	M-1/2	40	680	32	418	484
		ICH – wet	C-5		682	535	11,141	485
		Unlogged (harvest date null)						486
		Sp1 = Not Null (trees present)						487
		BEC = CMA, IMA	N		400	6,589	190,651	488
		BEC = CWH, MH, ICH, BAFA	D-1/2		402	52,179	945,232	489
		Else (dry)	O-1a/b		404	220,319	3,260,999	490
		Sp1 = Null (no trees)						491
		If FIP (Inventory_Standard_CD = F)						492
		If Non-productive Code = 11, 12, 13 (brush, old burn, etc.)						493
		BEC = CWH, MH, ICH	D-1/2		406	15,545	247,366	494
		Else (dry)	O-1a/b		408	25,086	1,162,812	495
		If Non-productive Code = 35 (swamp)	W		410	24,600	300,120	496
		If Non-productive Code = 42 (clearing – usually agricultural field)	N		412	5,451	226,066	497
		If Non-productive Code = 60, 62, 63 (meadow, hayfield, open range)	O-1a/b		414	10,634	418,363	498
		If Non-productive Code = Null						499
		BEC = CMA, IMA	N		416	11	607	500
		BEC = CWH, MH, ICH, BAFA	D-1/2		418	6,070	108,219	501
		Else (dry)	O-1a/b		420	8,171	396,023	502
		Else (other non productive)	N		422	0		503
		Else (I_S_CD =VRI or I)						504
		If Land_cover_class_CD = LA, RE, RI, OC	W		424	2,145	16,482	505
		If Land_cover_class_CD = HG	O-1a/b		426	15,033	377,186	506
		If Land_cover_class_CD = BY, BM, BL	D-1/2		428	8,941	146,180	507
		If Land_cover_class_CD = SL, ST, HE, HF or Null						508
		BEC = CMA, IMA	N		430	4,887	174,412	509
		BEC = CWH, MH, ICH	D-1/2		432	16,204	218,186	510
		Else (dry)	O-1a/b		434	90,416	1,342,419	511
		Else (L_c_c_CD = rock, ice or other bare or unburnable land)	N		436	40,820	791,881	512

FT Key 2017	FBP FT	Modifier	Process #	Frequency	Area (ha)	Row #
BCLCS Level 1 Unknown or null and BCLCS Level 4 contains National Fuel Type Code (missing VRI, Nat. Fuel Type used)						513
National FT = 101	C-1		9000	8,023	148,778	514
102	C-2		9000	14,841	304,738.5	515
103	C-3		9000	506	5,506.4	516
104	C-4		9000	12	44.6	517
105	C-5		9000	7,512	751,101.8	518
106	C-6		9000	0		519
107	C-7		9000	2,394	47,938.7	520
108	D-1/2		9000	398	4,310.4	521
109	M-1/2	50	9000	2,465	84,968.3	522
110	M-1/2	50	9000	0		523
111	C-2		9000	0		524
112	C-2		9000	0		525
113	S-1		9000	0		526
114	S-2		9000	0		527
115	S-3		9000	0		528
116	O-1a/b		9000	7,110	149,009.0	529
117	O-1a/b		9000	0		530
118	W		9000	2,093	29,808.5	531
119	N		9000	1,992	441,858.8	532
120	D-1/2		9000	0		533
121	N		9000	128	21,897.1	534
122	O-1a/b		9000	7	33.2	535
123	M-1/2	50	9000	8,833	121,267.6	536
Else (Errors or missing VRI + slivers/holes in Nat. Fuel Grid – mostly Gulf Islands; also Can/US border, AB/BC border) – calculate from BEC zone alone						537
Non_veg_cover_type = 'OC'	W		9996	0		538
Else						539
BEC = CMA, IMA	N		9810/ 9826	2	393	540
BAFA	D-1/2		9800	0		541
CWH – dry	M-1/2	40	9812	78	2,661	542
CWH – wet	C-5		9814	156	3,662	543
BWBS	C-2		9804	8	276	544
SWB	M-1/2	25	9838	2	83	545
SBS	C-3		9836	117	1,133	546
SBPS	C-7		9834	0		547
MS	C-3		9830	3	63	548
IDF – dry	C-7		9822	7	285	549
IDF – wet	M-1/2	50	9824	0		550
PP	C-7		9832	1	10	551
BG	O-1a/b		9802	0		552
MH	C-5		9828	2	205	553
ESSF	C-3		9816	29	232	554
CDF – dry	C-7		9806	0		555
CDF – wet	C-5		9808	188	7,828	556
ICH – dry	M-1/2	40	9818	0		557
ICH – wet	C-5		9820	1	2	558
Totals:				**4,785,011**	**99,476,072**	**559**

For more information about the Canadian Forest Service, visit our website at **nrcan.gc.ca/forests** or contact any of the following Canadian Forest Service establishments

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