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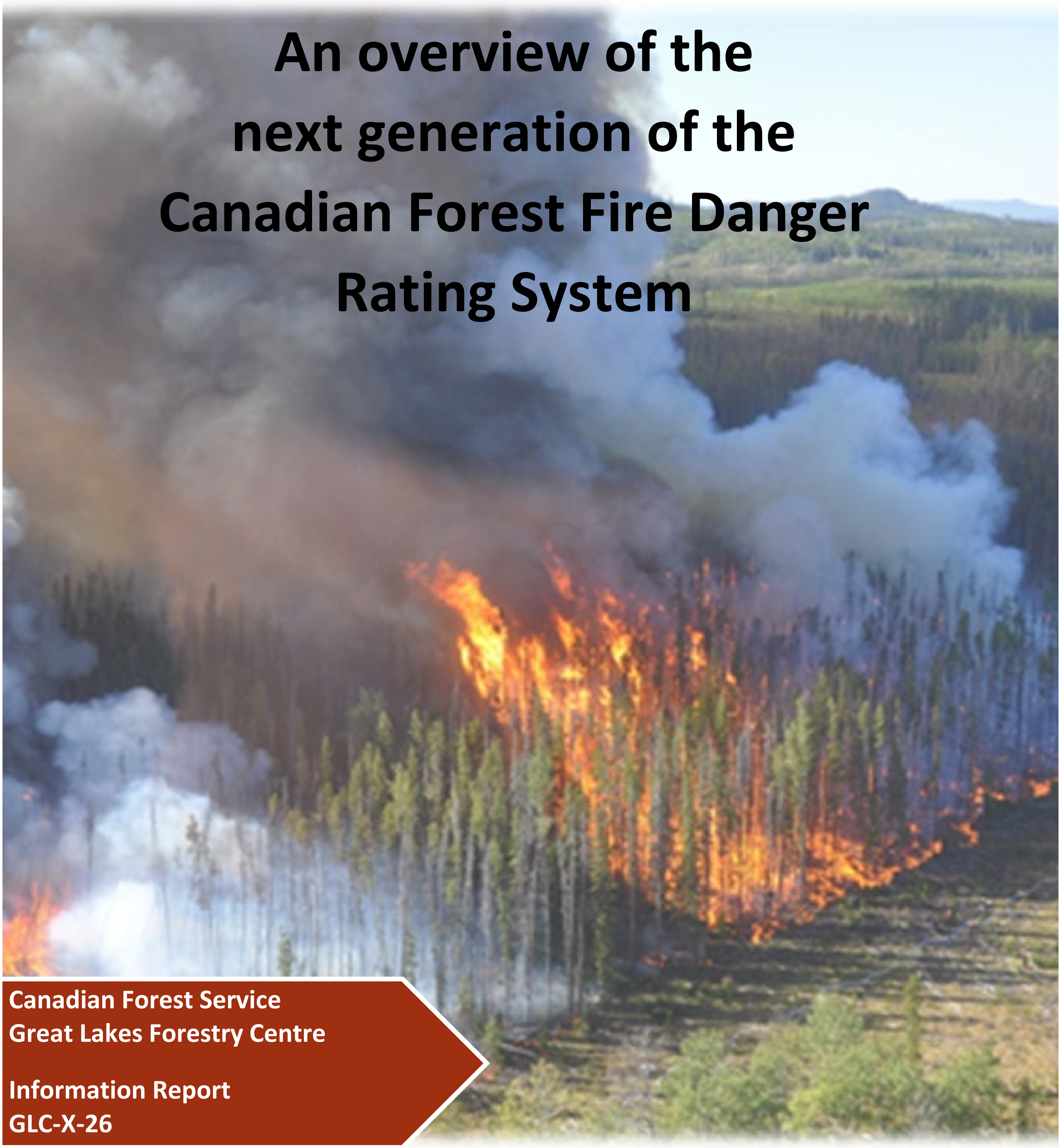

An overview of the next generation of the Canadian Forest Fire Danger Rating System

Canadian Forest Service
Great Lakes Forestry Centre

Information Report
GLC-X-26

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The Great Lakes Forestry Centre, Sault Ste. Marie, Ontario

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Preface

Citation: Canadian Forest Service Fire Danger Group. 2021. An overview of the next generation of the Canadian Forest Fire Danger Rating System (Information Report GLC-X-26). Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre.

The current core members of the Canadian Forest Service Fire Danger Group are Jonathan Boucher, Chelene Hanes, Natasha Jurko, Daniel Perrakis, Steve Taylor, Dan K. Thompson, and Mike Wotton. Every member of this core group has contributed to the authorship of this report documenting the vision for the next generation of the Canadian Forest Fire Danger Rating System (CFFDRS).

The CFFDRS has been evolving for a considerable time. There are numerous others who have contributed, over the span of more than a decade, to the development of this vision for this next generation of the CFFDRS. Important among these are the previous members of the Fire Danger Group who led the development of the last major enhancement to the CFFDRS in 1992: Marty Alexander, Bruce Lawson, Tim Lynham, Rob McAlpine, Brian Stocks, and Charles Van Wagner. Furthermore, over the last decade, regular contributions to the ongoing discussions about improvements to the CFFDRS involved Bill de Groot, Mike Flannigan, Brad Hawkes, and Brian Simpson. Important also are the many members of the Canadian and international fire management community who have provided their ongoing feedback and expertise to identify improvements and expanded flexibility needed to address the ongoing operational needs of wildland fire managers.

Executive Summary

Fire managers make decisions at the incident, regional, provincial, and national levels in a highly dynamic environment. The Canadian Forest Fire Danger Rating System (CFFDRS) is a family of linked subsystems and models that allows for a nationally consistent means of characterizing fire danger (a broad indicator of fire potential), fire behaviour, and fire occurrence across different scales of space and time to support decision making. The two most developed and widely used of these subsystems are the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behaviour Prediction (FBP) System. The CFFDRS provides a scientific backbone to assess wildland fire potential in Canada; the FWI System has also been adopted in many other countries and is a key component of a global wildfire early warning system. The current CFFDRS is the fifth generation of fire danger rating schemes in Canada and first with national scope; however, the CFFDRS has not been substantially updated since 1992. This document outlines a plan to modernize the CFFDRS to better support fire management requirements backed by a tradition of observation-based science and modelling.

The modernized CFFDRS (CFFDRS-2025) will incorporate new data sources and a more modular, process-based approach. Expanded subsystems will address fuel moisture, fire danger, fire behaviour, and fire occurrence prediction. The new features will include:

1. prediction of deciduous forest leaf-out and grassland green-up and curing timing, accounting for variable snowmelt dates and spring weather conditions;
2. a new system of fuel moisture models for key fuel layers;
3. new fire danger indices specific to grasslands and peatlands; modification of fire danger calculations to better reflect the peaks in daily fire weather;
4. re-engineering of fire behaviour models to represent processes of sustained ignition, surface fire behaviour, transition to crowning, crown fire behaviour, and fuel break breaching; and
5. completion of a national framework of statistical models to forecast the expected number and location of new fire starts and large fires.

This next generation CFFDRS will provide fire managers with better provincial and national forecasts of:

- the onset of elevated spring fire danger and fire behaviour in deciduous and mixedwood stands;
- fire danger beyond forests, including grassland and peatlands; and
- the potential for large fire occurrence.

It will also provide the means to better evaluate fire behaviour potential at the forest stand and incident level through improvements in modelling of:

- fire behaviour in a broader range of forest fuel types as well as during overnight and early morning periods;
- the effects of fuel treatments such as mechanical thinning and pruning on fire behaviour; and
- potential for fire brands to breach fuel breaks or to be transported moderate to longer distances.

The planned improvements and modernizations to the CFFDRS will be documented in more detail in a series of forthcoming technical documents. The vision laid out here represents a number of substantial improvements to be adopted with the goal of a phased implementation of this System starting in 2025. Key tools and concepts like the Fire Weather Index System and fuel types will remain and be compatible with new features. Outreach with fire management agencies is an integral and ongoing process.

1.0 Fire Danger Rating in Canada, Past, Present and Future

> *Early forest fire control practice in Canada was simple – one tried to keep wildfires out of the settlements and in the woods where they belonged. There was no planning – fire was fought wherever it could not be avoided. Later, as forest fire control became organized, specific plans for fire control action became an obvious necessity. To form a basis for such plans, a reliable measure of the day-by-day state of forest flammability was needed … (Williams 1963).*

Fire managers have the challenging job of making a wide range of decisions regarding the type and timing of operations that are required to prevent, prepare for and respond to wildfires or carry out prescribed fires. These activities are influenced by factors such as the number of fire ignitions and subsequent fire growth at immediate, hourly, daily, weekly, seasonal, annual and multi-decadal time scales, from the individual fire ignition level to countrywide considerations of factors such fire load and resource availability (Taylor 2020).

Historically, fire danger rating has been defined as the assessment of both fixed and variable factors of the fire environment (i.e., fuels, weather, and topography) that determine the ease of ignition, rate of spread, difficulty of control, and impact of wildland fires. The original purpose of fire danger rating systems was to provide fire managers with a daily means of judging the level of preparedness needed to keep wildfire losses or adverse impacts to a minimum and particularly to isolate those days with high potential fire activity. However, the temporal and spatial scale of information about the wildland fire environment that is available to fire managers has increased over the past century. The following section briefly summarizes the development of the current CFFDRS, some of the new fire danger rating challenges, and the new features that are needed.

1.1 Development of the CFFDRS

In its current form the CFFDRS includes several subsystems that have their analogue in other major sets of national systems around the world. The most well-known component of the CFFDRS is the FWI System (Van Wagner 1974, Van Wagner 1987), which provides indicators of moisture in key forest floor fuels as well as relative indicators of spread potential, and is used typically for activities such as daily planning for fire activity. By itself the FWI System is a complete system for fire danger rating assessment based on weather observations and has been used in its present state in Canada for nearly 50 years. The Fire Behaviour Prediction (FBP) System provides site and fuel type specific estimates of rate of spread, fuel consumption, fire intensity and other quantities for important benchmark fuel types in Canada and is used in many aspects of fire management activity. Two additional subsystems, the Accessory Fuel Moisture System and Fire Occurrence Prediction (FOP) System, which were identified in the 1980s as desired elements of CFFDRS, are incomplete. Further details on the structure, development, and application of the CFFDRS can be found in several papers and reports (Lawson et al. 1985, Stocks et al. 1989, Taylor and Alexander 2006, Wotton 2009b).

Information from the CFFDRS is used in most aspects of the forest fire management planning process throughout the day across Canada. Taylor and Alexander (2006) provide a comprehensive list of such applications, which range from prevention and preparedness planning to escape fire analysis and fire behaviour training. A core application of the CFFDRS has always been decision support for fire response: identifying potential ignition locations and the potential spread rate and intensity of active fires to inform tactics for safe and effective response. The CFFDRS, and particularly the FWI System, has also been adopted or adapted to aid fire managers in a number of other countries around the world (e.g., New Zealand, Mexico, Indonesia, Malaysia, Argentina, Costa Rica, France, and several boreal forest states in the US) (de Groot et al. 2005, de Groot et al. 2006, de Groot et al. 2007); a multi-decade global FWI System dataset has been created and is kept up to date for research purposes (Field et al. 2015). The application of the CFFDRS in regions with differing climates and vegetation to Canada can be explained, at least partially, by: the relative simplicity of the System's input data requirements, its ease of calculation and implementation, the significance of the discrete fuel layers represented by three standard moisture models, the numerous interpretive aids developed for its core subsystems, and the approach of modelling using data from an extensive program of field experimentation and wildfire observation.

The CFFDRS evolved from a continuous program of research that began in 1925 (Box 1), with the current CFFDRS being the fifth generation of Canadian fire danger rating methods (Stocks et al. 1989). The scope of danger rating has expanded over this period from simple regional fire danger indicators to a common national set of indicators that are interpreted regionally, and from qualitative indicators of fire potential to quantitative estimates of fire behavior. Collaboration between researchers and fire managers was key to development of the system, particularly in carrying out experimental burns. The CFFDRS must continue to evolve as research and operational experience progress, as fire management challenges change, and as technology advances and data on the fire environment expands.

Box 1. Some milestones and eras in fire danger rating in Canada

1925	J.G. Wright outlines the need for fire danger research in a memo to the Director of Forestry, E.H. Finlayson.
1928	Studies into the moisture content and flammability of critical fuels begin at the Petawawa Forest Experiment Station (PFES).
1933	Wright and H.W. Beall produce the first set of fire danger tables, based on a "Tracer Index" that relate the moisture content of needle litter to expected fire behaviour.
1931 - 1961	Field studies of moisture content and flammability are extended to a variety of fuel types at 10 other field stations across Canada from Newfoundland to British Columbia to the Northwest Territories. Over 20,000 ignition tests are carried out.
1933 - 1960	Four generations of fire danger rating systems were developed with increasing universal applicability across Canada. By the mid 1960s, the fourth system – in nine different regional versions – was in widespread use across Canada.
1965	A group of federal fire researchers from across the country was formed to guide the development of a new national system of fire danger rating in Canada.
1967	S. J. Muraro proposed a modular approach to a new national fire danger rating system to replace the various regional systems.
1969 - 1970	A provisional version of the FWI System was released in 1969, followed by the first edition of the FWI System in the subsequent year.
1965 - 1995	CFS fire researchers renew the outdoor experimental burning program with increasingly larger field plots in several major “benchmark” fuel types. Quantitative estimates of rate of spread were also collected from a number of wildfires.
1982	The CFFDRS was formalized.
1984	Fourth, current version of the FWI System.
1984	Interim edition of the Fire Behaviour Prediction (FBP) System.
1987	Current structure of the CFFDRS proposed, including the FWI and FBP Systems, an Accessory Fuel Moisture System and a Fire Occurrence (FOP) Prediction System.
1992	First complete edition of the FBP System.
2009	Minor updates and revisions to the 1992 edition of the FBP System summarizes mathematical changes in the system over the intervening 15 years.

1.2 New Challenges

Renewal of the CFFDRS is not driven by any single issue or development. Rather, a number of today's fire management challenges and decisions require fire intelligence that is beyond what the models and subsystems of the current CFFDRS were designed to provide. Furthermore, some of these requirements can take advantage of new fire science and environment data that has yet to be incorporated in the CFFDRS.

Changing Fire Management Environment

The complexity of fire management in Canada has grown in recent decades, increasing the expectations placed on fire managers (Canadian Council of Forest Ministers 2005, Canadian Council of Forest Ministers 2016). Contemporary fire managers must plan for and respond to wildfires in a broader range of fuel complexes than were originally considered in the Canadian fire behaviour prediction models, while also continuing to balance a number of sometimes competing values and issues, including: biodiversity, smoke and carbon emissions, growing amount of wildland urban interface (WUI) and wildland industrial interface, changing public expectations and awareness, increased competition for the forest landbase, climate change and potentially declining forest ecosystem health as a result of fire exclusion policies (Canadian Council of Forest Ministers 2005, Hirsch and Fuglem 2006, Canadian Council of Forest Ministers 2016). For instance, the recent mountain pine beetle epidemic in western North America left millions of hectares of dying and dead lodgepole pine in the provinces of British Columbia and Alberta, creating widespread, and still-changing fuel types as trees die, snags decay and topple, and the residual vegetation community responds. While mountain pine beetle is native to many forests in central British Columbia, the spatial extent of the recent lengthy outbreak has changed the fuel complex over broad areas. Being able to predict fire behaviour in all naturally occurring or modified fuel complexes on the Canadian landscape is important not just for initial attack dispatch or escaped fire analysis, but also needed to support fire crew safety, aviation safety and effectiveness, evacuation planning and suppression effectiveness.

Several fire management strategies and practices are increasingly used to address these concerns. The sharing of fire management resources between provincial agencies in Canada during periods of high fire load has increased the scope of planning and decision-making. Pressures on resources and broader recognition of the ecological role of fire have also led to adaptation of past management policies into "appropriate response" strategies, which, in some jurisdictions, involve shifting from a zone-based approach to a case-by-case evaluation of the need for a response; such responses might range from aggressive suppression to basic monitoring. Fuels management techniques (e.g., stand thinning) are increasingly being applied to reduce fire potential in the WUI.

New Fire Environment Data

Increases in numerical processing and data communications speeds, computing capacity and the development of new sensors have dramatically altered the amount, types and speed that environmental data is available to fire managers (e.g., real-time weather observations, numerical weather forecasts, satellite fire monitoring and remote sensing of fuels information). While the original system was conceptually robust, this vastly increased information resolution (both spatial and temporal) available to fire management agencies today provides inputs that are beyond the designed capabilities of the CFFDRS. One objective of this next generation CFFDRS development program is to develop models that can use these new data sources in a consistent and scientifically sound fashion (Box 2).

Box 2. Some emerging fire environment information, monitoring tools and technologies (since 1992)

Hourly or sub-hourly weather observations, available in real-time.

Automated satellite green-up detection.

High resolution vegetation inventory systems providing updated forest structure and composition information; often combining remote detection with ground survey data sources.

LiDAR characterization of detailed forest structure and topographic attributes.

Direct, real-time moisture measurement capability.

Spatially-explicit (gridded) upper air forecast products for short- and medium-term prediction timelines.

Solar radiation observations (direct or remotely sensed).

Short-term lightning strike forecasting.

Daily (or more frequent) fire perimeter monitoring and mapping.

New Science and Applications

The last major update to the CFFDRS was the completion of the FBP System in 1992. Wildland fire science has continued to advance over the past several decades, spurred on by increasing wildfire problems in many jurisdictions and well-funded regional fire science programs (e.g., the US Joint Fire Sciences Program, the Bushfire and Natural Hazards CRC in Australia and numerous funded European Union consortium projects). Such programs have led to significant advances in methods for the day-to-day characterization of the wildfire environment. Similar levels of support for research have not occurred in Canada over the last decades, nonetheless there have been significant advances in wildfire-related research that have not yet been incorporated into the CFFDRS.

Many new fire management applications require fire behaviour and other inputs that are not available from the CFFDRS. As early as the late 1990s, work on a Canadian fire growth model (Tymstra et al. 2010) began to press the CFFDRS into use in situations for which it was not intended, for instance, growing fires during overnight hours. The focus on hourly (and sub-hourly) fire growth also highlighted important inconsistencies in different CFFDRS methodologies such as the hourly Fine Fuel Moisture Code (FFMC) calculation of Van Wagner (1977a) vs. diurnal adjustment of daily values from Van Wagner (1972) or Lawson et al. (1996). While stop-gap solutions to such problems were developed, the System continues to be pushed to assess fire potential across broader ranges of conditions and larger number of fire management decision support needs.

1.3 New Requirements

The depth of information on fire potential that will be needed to support more complex fire management decisions, along with new fire environment data and new fire science findings can't easily be provided for or accommodated within the present CFFDRS subsystems and models. Some of the key requirements include: 1) Changes to various subsystems to provide more flexible fire behaviour models that account for varying stand density and conditions in managed and disturbed stands; 2) Fire behaviour and growth models that are applicable in the full range of fuel types in Canada over the full daily burning cycle; 3) Enhancements to daily-scale regional fire danger indicators that are applicable to grasslands as well as forests are required to provide enhanced information for daily planning; and 4) Daily fire occurrence prediction models for all regions of Canada are needed to enhance early warning and inform resource sharing.

The CFS has begun a major research program to develop and document a next generation of the CFFDRS. While fire behaviour research at CFS has been ongoing over the last decade or more, this new program represents a significant investment focussed on finishing various models and documenting the structure of this next generation of the System. The objective of this report is to provide the fire research and management community with an overview of the next generation CFFDRS (NG-CFFDRS) research and development program which is planned to span 2020-2025. These new components will be formed into a new version of the System presently identified as "CFFDRS-2025". Throughout the remainder of this report, the use of the acronym CFFDRS refers generally to various iterations of the system since the 1970s. CFFDRS will remain the general label for the system as we move into the future; however, during the transition to this new generation of the system, several date-specific labels will be used. CFFDRS-1992 refers to the state of the System as of the completion of the FBP System in 1992 (but including the minor FBP System updates described in Wotton et al. 2009). CFFDRS-2025 refers to the expected state of the System in 2025, while the NG-CFFDRS is the R&D program that is focussed on creating the CFFDRS-2025.

2.0 Design of the next generation CFFDRS

Significant changes to a well-established and operationally critical system such as the CFFDRS must first of all consider the impact on users. CFFDRS-2025 should be regarded not as a significant reinvention of the System, but simply as a further evolutionary step; it is a major consolidation and implementation of ongoing science to enhance the flexibility of CFFDRS and allow it to use newer data and to characterize the fire environment in broader range of situations. The foundations of the System that characterize key aspects of the Canadian wildland fire environment remain sound and the System itself remains effective. This section reviews the scope of the next generation CFFDRS and outlines the new structure and features that will be described in the remainder of the document.

2.1 Scope and Design Principles

CFFDRS-2025 will not include every element that users might consider missing from the System, but will focus on what can be done to improve the core of the System, enhancing flexibility and addressing key information needs in modern fire management.

The core principles that underlie CFFDRS development shown in Box 3 will continue to guide the NG-CFFDRS program as new models are developed and integrated.

Box 3. Core Principles of CFFDRS Development

Modularity -- the system is comprised of components that can be retained or substituted as needed, allowing for continuous improvement and the adoption of new science.

Ease of use and interpretation, but with flexibility for advanced users and more granular data.

Physically realistic/logical model forms fitted to observed data from the field.

Internally consistent systems and subsystems.

Hourly and daily measures of ease of ignition, fire behaviour and occurrence from point to stand-level to the broader landscape level will remain the main focus of the CFFDRS. Landscape-level fire growth in heterogeneous landscapes, and longer-term (multi-year) fire frequency, are also considered out of the core CFFDRS scope; however, models of large, landscape-level fires will continue to rely on the spread models of the CFFDRS. Secondary fire characteristics and effects such as smoke emissions and tree mortality, as well as fire management considerations such as likelihood of containment, are recognized as important to applications (see Section 9) but are not considered within the scope of the CFFDRS. New CFFDRS features will improve these applications.

2.2 New features and structure

Many of the new features required to provide improved flexibility and functionality in the CFFDRS have been discussed for well over a decade and there has been considerable research and model development carried out prior to 2020. Some of these new fire danger, fire behavior and fire occurrence elements are outlined in Box 4, along with new moisture models and fire environment data that are needed in the new models.

Box 4. CFFDRS-2025 features proposed to enhance flexibility and functionality

Fire environment

- Categorical forest floor types
- Dynamic models of available crown biomass and crown bulk density
- Phenology of leaf flush and grass curing
- Timing of snowmelt initiating fire season
- In-stand wind speed

Fuel moisture

- Improved stand-specific adjustment and diurnal modelling of moisture content in litter, and forest floor organic matter
- Improved seasonal dynamics of foliar moisture

Fire weather and danger

- Incorporate peak burning period weather to inform peak burning period fire behaviour
- Indexes of spread, fuel availability and fire intensity for peatlands and grasslands

Fire behaviour

- Probability of sustained flaming
- Mixed modelling framework for:
  - Surface fire spread rate and consumption
  - Likelihood of crown fire initiation, conditional on a surface fire
  - Crown fire spread rate and consumption
- Combustion zone characteristics: flame dimensions/temperature, residence time, smoldering
- Medium range ember production and transport

Fire occurrence

- Number of human- and lightning-caused fire occurrences on a daily basis
- Number of large fires (>100 ha)

The new CFFDRS-2025 elements will continue to be implemented as a suite of integrated modules that differ only slightly in high level appearance and organization from CFFDRS-1992 (Figure 1). Well-known subsystems, the FWI System and the FBP System, are still present but will be modified internally with updated models in some cases. Users will continue to access the level of complexity appropriate to their needs. The Fuel Moisture, Fire Weather Index and Fire Behavior Prediction subsystems are applicable at point or stand-level scales but may be extrapolated to the landscape scale in fire management systems (e.g., Section 8). In contrast, the Fire Occurrence Prediction System is only applicable at the landscape scale, where the geographic area covered by the model is discretized into a grid.

A summary of some of the key changes to the subsystems is presented immediately below. These changes will be described in more detail in the remaining sections of this report (Sections 3 through 8). Specific differences between the different versions of each subsystem are contrasted in Table 1.

Fire Environment Inputs (Section 3)

Fuels, weather, topography and location factors will remain as the basic inputs to CFFDRS-2025 subsystems and models. However, some new weather observations and additional information on fuel characteristics will be required for new and more flexible fuel moisture and fire behaviour models (Sections 4 and 6).

Fuel Moisture Models (Section 4)

The standard daily moisture models tracking different key layers of a pine forest still exist in the FWI System. However, a larger suite of stand-specific surface fuel and organic layer moisture models will be available in the Fuel Moisture System (FMS) for more site-specific or fuel-specific applications. Moisture tracking models for faster drying exposed and elevated fuels as well as slower-drying deep organic layers in peatlands will be introduced.

Fire Weather Index (Section 5)

In order to permit compatibility between hourly and daily moisture calculations and to better represent fire danger in the peak afternoon burning period, the daily moisture codes and behaviour indexes will be calculated from weather observations during peak daily burning conditions rather than at 13:00 Local Daylight Time. In addition, new optional codes and indexes will be introduced for grassland and peatland fuels.

Fire Behaviour Prediction (Section 6)

Some more significant changes will be required to increase fire behaviour prediction functionality. New fire spread rate models will decouple from the reliance on ISI (Initial Spread Index) and rely, more directly, on estimates of actual fine fuel moisture content and actual wind speed similar to other semi-empirical fire behaviour models developed in recent years (Cheney et al. 1998, Fernandes 2001, Cheney et al. 2012, Anderson et al. 2015, Cruz et al. 2015). However, for the FBP System’s many general uses, the key FBP System inputs (e.g., FFMC and wind) will remain the same and the changes will be transparent.

Overall, the spread rate models of the FBP System will rely more directly on the “dual-equilibrium” or “multi-phase” model described by Van Wagner (1993), but will explicitly incorporate more physical stand characteristics embedded within the fuel type standards (or estimated and input by users) to achieve a broader range of flexibility. This will be a significant change, though also transparent to those users who do not need or want to understand the fuel complex in explicit detail.

As in the present system, much of the added complexity will not require user input, unless it is required for specialized applications.

Fire Occurrence Prediction (Section 7)

Methods for predicting the number and location of new human- and lightning-caused fire starts in the short to medium term (1–10 days) will be developed for all fire management agencies across Canada. This information will be provided to fire management agencies, and also inform national-scale considerations such as resource sharing.

Sections 3 to 7 expand on the important changes in each subsystem, but are not a complete technical description. These sections present differing levels of detail, reflecting both the complexity of the CFFDRS subsystems and the changes being proposed. Although there are strong linkages and interdependencies between each of these sections some readers may wish to understand the proposed changes to the well-known CFFDRS subsystems (e.g., the FWI and FBP Systems) described in sections 5 and 6 prior to returning to the new data requirements and input models in section 3. Section 8 Fire Management Applications relates how the new features of CFFDRS-2025 will impact and improve fire management applications with strong linkages to the CFFDRS. The final section 9 Next Steps outlines some of the elements that will be needed to realize CFFDRS-2025.

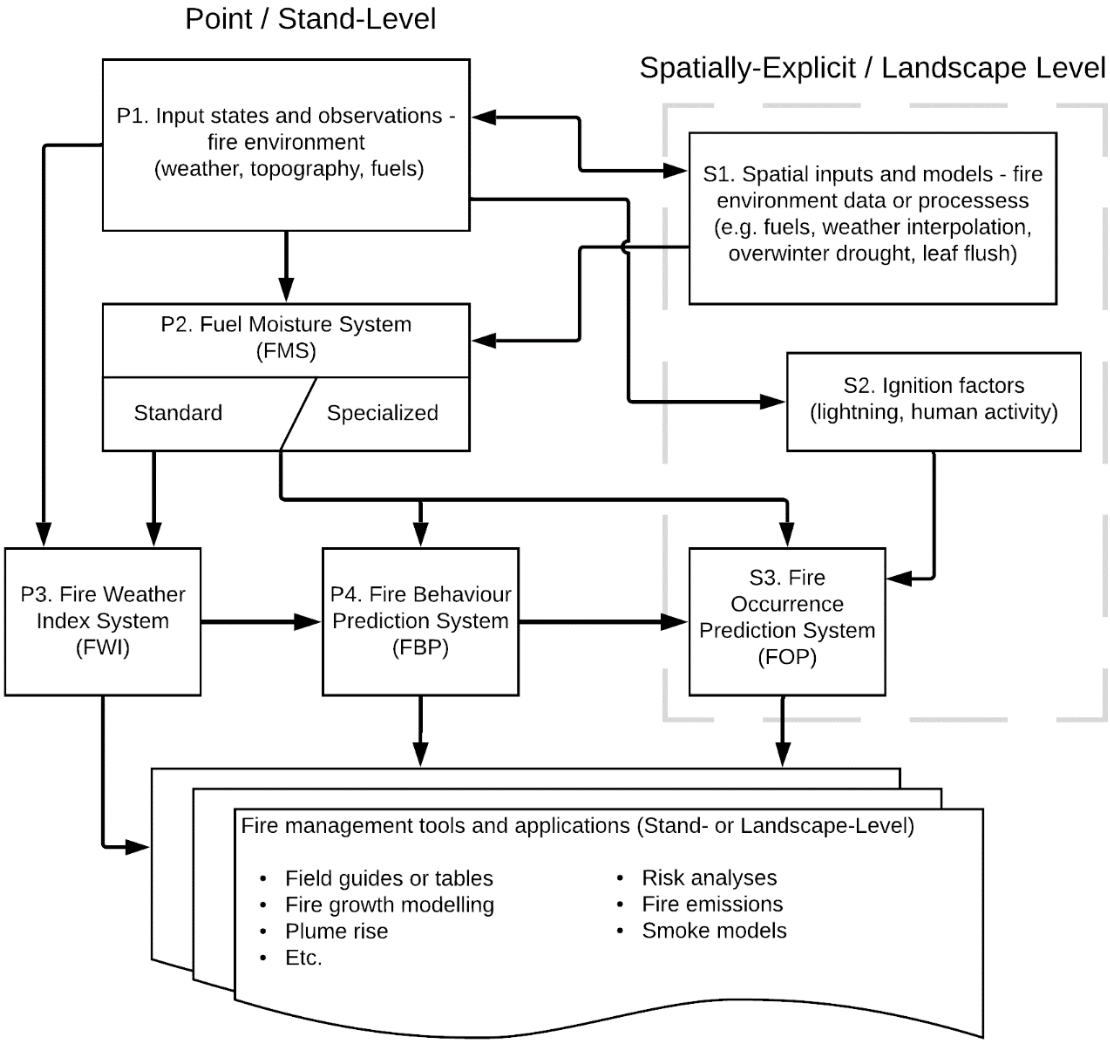

Figure 1. Proposed conceptual structure of CFFDRS-2025. From stand-level inputs and observations of the fire environment (P1), the Fuel Moisture System (FMS; P2) predicts fuel moisture content using either standard or specialized models for input into (P3) the Fire Weather Index System for broad-scale daily fire danger rating or as inputs into (P4) the Fire Behaviour Prediction (FBP) System. Outputs of the FWI and FBP Systems can be used in a variety of tools and applications related to fire management (e.g., one-dimensional tools such as the 'Red Book' (Taylor and Alexander 2018) or RedApp) or used in further analyses. The spatially-explicit modelling stream (S1) initiates from geographically-defined inputs and processes (such as layers representing phenological events, vegetation cover, etc.); these inputs or processes typically use the same FMS, FWI, and FBP System model calculations as the point data, but can include additional spatially-defined elements such as (S2) ignition factors (indices of lightning or human activity); these elements are key inputs to (S3) Fire Occurrence Prediction (FOP) models. Contemporary tools and applications using CFFDRS models are increasingly spatially explicit (e.g., fire growth, landscape risk analysis, smoke transport, etc.).

Table 1. Comparison of features of the CFFDRS and the proposed next generation CFFDRS

Component	Current and Historic State (CFFDRS-1992)	Next Generation State (CFFDRS-2025)
CFFDRS Scope	Designed primarily for preparedness and tactical planning.	Includes outputs that can support more complex fire management decision-making and prioritization planning in a risk management context, such as fuel treatment, smoke emissions, fire effects, and other management models.
Fire Environment Inputs	Uses daily station-based weather observations (often interpolated across the landscape), fuel type, and topography.	Includes methods for the use of spatial inputs of environmental conditions derived from model and/or satellite observations (e.g., green-up, curing, snow). Fuel characteristics are explicitly characterized. Guidance for using interpolation and spatial weather inputs (forecast, reanalysis, and ensembles) in fire weather, fuel moisture, and fire danger calculation.
Fuel Moisture System (FMS)	Unorganized set of models exist that were developed over time in individual studies for specific situations. Live fuel moisture uses static models.	Moisture estimation relies on a consistent structure across temporal scales (diurnal variability possible for all elements) and includes forest floor moisture models varying by vegetation community and solar radiation effects. Live fuel moisture (and vegetation state) vary seasonally with vegetation type and weather conditions.
Fire Weather Index (FWI) System	Designed around daily station-based surface weather observations. Mainly focused on larger regional scale and peak burning prediction (ISI, FWI).	Maintains the emphasis on prediction of regional peak fire potential but with linkage to FMS and FBP System for consistency. New weather observation timing requirements are introduced. Improved overwintering of drought and station start-up. Guidance is provided on burning day length and overnight fire activity.
	Uses a single reference fuel type for fuel moisture and fire behaviour indicators – closed canopy mature pine.	Maintains closed canopy conifer as the reference fuel type but adds new optional indices for very different fuel complexes (grassland, peatland).
Fire Behaviour Prediction (FBP) System	Uses fixed fuel types – mostly boreal. Structure cannot be changed within most fuel types. Fuel load is fixed.	Includes flexibility to change stand structure (e.g., crown base height, canopy bulk density, stand height, forest floor cover type) and fuel loading. Stand structure can be modified by natural disturbance or fuel treatment. Fuel load is an input; consumption is partially dependent on load as well as fuel moisture.

Component	Current and Historic State (CFFDRS-1992)	Next Generation State (CFFDRS-2025)
Fire Behaviour Prediction (FBP) System	Spread rate equations are linked to FWI System output for discrete fuel types. Deterministic.	Spread rate models are linked to the direct effect of wind and moisture to allow changing of stand structure to influence fire behaviour in a physically logical and consistent way.
	One simple spread rate model form (i.e., fitted curve) for all fire types (i.e., surface through to crowing).	Spread rate is predicted from mixed models of surface fire, probability of crowning, crown fire spread. Behaviour models integrate structural elements of the stand.
	Probability of sustained flaming ignition is undeveloped.	Forest floor cover type specific ignition probability dependent on forest floor moisture is now included and, like surface fire spread models, related to stand structure.
	Flame zone properties are not addressed.	Guidance is provided defining flame zone characteristics (geometry, residence time, temperature, flame length) varying with fuel load and type.
	Spotting is not addressed explicitly. Short range spotting is implicitly included in spread rate models.	Includes guidance on firebrand generation and medium-range transport is available.
Fire Occurrence Prediction (FOP) System	Incomplete regional fire occurrence models developed with multiple frameworks and methods.	A nationally complete suite of spatially detailed daily human- and lightning-caused fire occurrence models exists; models for daily prediction of the number and probability of larger fires (>100 ha) are also included.
Fire Management Tools and Applications	Numerous applications have been developed, based directly on CFFDRS subsystems (e.g., Prometheus), but sometimes adaptation of CFFDRS elements is done in an ad hoc way out of necessity.	Fire likelihood and risk applications support the full range of mitigation planning options at the stand and landscape scale. Fire growth models better represent sub-daily weather as well as variability in fuels structure and state.

3.0 Fire Environment Inputs

It is premature and beyond the scope of this document to provide a comprehensive list of the required inputs for every subsystem within CFFDRS-2025. To a large extent the basic inputs will remain the same as they are in CFFDRS-1992; providing basic continuity between the current and new subsystems is a goal of this overall NG-CFFDRS program. However, to improve consistency and achieve greater flexibility in the System as a whole, some changes to inputs as well as additional inputs will be required. This section is not a review of all the inputs required for the CFFDRS but focusses on describing the most relevant changes to inputs needed for the system; most of the new inputs described are required for accessing the more advanced features of the CFFDRS. Where possible, the rationale for these changes is provided or is further expanded upon in the subsequent sections that describe the planned changes to the core CFFDRS subsystems (Sections 4 to 7).

3.1 Weather and other physical environment inputs

Weather itself, both observed and forecasted, remains the most critical element of the fire environment for informing fire management decisions and weather inputs will remain a core element of the CFFDRS. Changes being introduced for CFFDRS-2025 will improve the consistent use of finer resolution weather information (i.e., hourly or sub-hourly weather) within the system. The core attributes of day-to-day (and diurnal) weather influencing the fire environment (e.g., temperature, humidity, wind, rainfall) will not change, although optional additional elements (such as solar radiation) will be introduced. Importantly, however, the timing of those core weather observations may change. For instance, a core change being developed for the daily FWI System is to shift from the use of the noon weather observation, to relying on maximum and minimums values observed (or forecasted) for the day. This change, described in more detail in Section 5, will reconcile artificial differences between hourly and daily fuel moisture calculations that presently exist in the current system and can affect fire behaviour predictions.

The timing and magnitude of snowmelt recharge into the forest floor are important for the resumption of forest floor fuel moisture calculation in the spring after ground thaw, as well as indicators of the initiation of potential spring wildfire activity. CFFDRS-2025 will include guidance on estimating initialization dates for fire weather observations (i.e., improved forecasting of the timing of complete snow loss at the forest floor) as well as improved weather-based schemes to estimate snowmelt inputs to spring forest floor moisture. Such schemes will incorporate stand structure variables as well as remotely sensed inputs.

New ignition and spread models in the FBP System will be driven by sub-canopy winds and solar radiation through its influence on litter moisture content. In-stand, both of these elements (surface wind and solar radiation) will be influenced by canopy structure, allowing for the impacts of thinning or stand mortality to be assessed; this is a key aspect of improved flexibility in the FBP System. Existing models from forest meteorology will be adapted to estimate forest canopy drag on wind penetrating into a canopy. In addition, forest canopy cover will be used to estimate the amount of solar radiation penetrating to the forest floor; while the ability to use direct measures of solar radiation will exist, basic models of idealized solar radiation for any location and day of year and time of day will be provided to users without access to solar radiation observations.

3.2 Plant phenology

Plant phenology (i.e., grass greenness and curing, deciduous leaf-out, and conifer bud flush) inputs in the CFFDRS are integral modifiers to fire behaviour and the transition between the spring and summer fire seasons that need to be determined by fire management agency staff. In the last decade, operational monitoring of grass and deciduous phenology has become easier and widespread with strong linkages to fire activity (Pickell et al., 2017). CFFDRS-2025 will provide a framework for simple operational now-casting and medium-term (4 to 14 days) projections of grassland greenup and curing and deciduous phenology using only weather forecast data or a blend of remote sensing observations and weather forecasts. Conifer bud flush (spring dip) is not easily observed by satellite, but statistical relationships using more easily observed variables like weather and deciduous green-up will be explored to provide a more robust bud flush model that is sensitive to annual variations in temperature and moisture conditions.

3.3 Fuel structure attributes

A key strength and limitation of the current FBP System is the use of a fixed set fuel types that are primarily defined by fixed compositional and structural attributes (see Appendix A, Table A-1 for details). Selection of the best-fit fuel type determines the relevant equations and parameters for all subsequent models (e.g., spread rate, fuel consumption, crown involvement, slope effects). Because this approach is sufficient and simple to implement for many fire behaviour prediction applications, standard fuel types will remain available to users in CFFDRS-2025.

For more advanced fire behaviour applications, the capability is being created to modify the fuel complex in a systematic and physically logical fashion to achieve predictions in more specific stands or situations. The goal of this increased flexibility is not to see a proliferation of fuel types, but simply to allow physically logical and internally consistent modification of key fuel complex attributes where these are critically needed (e.g., fuel management treatments, risk modelling near communities, etc.). These new fuel complex attributes can be categorized in three vertical strata: ground and surface fuels, elevated or ladder fuels, and canopy fuels (Figure 2). The full list of these anticipated structural attributes, accompanied with a short description and units, can be found in Appendix A (Table A-2). Fuel structure variables of crown fuels can be described at the individual tree scale (i.e., diameter or height), or as stand/plot level averages, as represented in Figure 3.

In the surface strata, attributes will be described for a set of discrete ground cover types. The present list is the following:

- Dry conifer (conifer needles only)
- Wet conifer (conifer needles on feathermoss or Sphagnum)
- Deciduous leaf litter
- Mixedwood (mixed leaf and conifer needles)
- Lichen (reindeer lichen and other similar lichen cover types)
- Grass

These cover types reflect a wide range of surface cover material found throughout the Canadian environment and also, importantly, represent cover types for which fire behaviour observations exist and for which models can therefore be developed. As new fire behaviour observations become available and models are developed, this list of cover types can be expanded.

Suggested methods and techniques for estimating structure attributes in the field or using remote sensing techniques will be described in future technical documents. In some situations, users could estimate structural attributes directly in the field or define them for different types of simulation scenarios. However, mapping products based on the FBP System or fire growth model outputs require spatial information about the fuel. A goal of the NG-CFFDRS program is to have spatially detailed information (e.g., maps) for each structural attribute needed for new CFFDRS-2025 subsystems (see Appendix A, Table A-2). Many of the structural attributes of interest are found in conventional forest inventory information (e.g., tree species, diameter, height), or could be acquired via remote sensing (e.g., proportion coniferous vs. deciduous); these data are easily obtained at appropriate spatial resolution. However, other structural attributes are unconventional (e.g., litter and duff load, downed woody debris load, stand effective crown base height) and require investment in field sampling or estimation using alternate models (e.g., McAlpine and Hobbs 1994, Cruz et al. 2003). Thus, a significant field-based research effort in the coming years will include evaluating, refining and documenting methods for measuring and mapping these attributes for a range of forest types. Guidelines for ground sampling and mapping methods of these fuel structural attributes will be provided for locally informed fuel mapping by land managers.

Damaged or disturbed forests

Predicting fire behaviour in forest stands damaged or affected by biotic (e.g., insect infestation) or abiotic (e.g., wind storms) disturbances is important in many parts of Canada; these forests can exhibit extreme fire behavior in some cases (e.g., M-3 100%). The new structure-based description of fuels in CFFDRS-2025 will allow some aspects of these dynamically changing stands to be accounted for. For instance, changes related to overstory mortality affect the availability of downed and dead woody material on the forest floor as well as canopy closure, canopy bulk density, and effective canopy base height. These changes will be optional fuel type characteristics inputs in CFFDRS-2025, used in new models of in-stand wind and surface-to-crown fire transition (Section 6.3). Understanding post-disturbance fuel succession patterns will be essential, requiring a detailed understanding of the nature of various forests disturbances (e.g., insect biology and ecology), as well as techniques for effective field measurements in damaged forests.

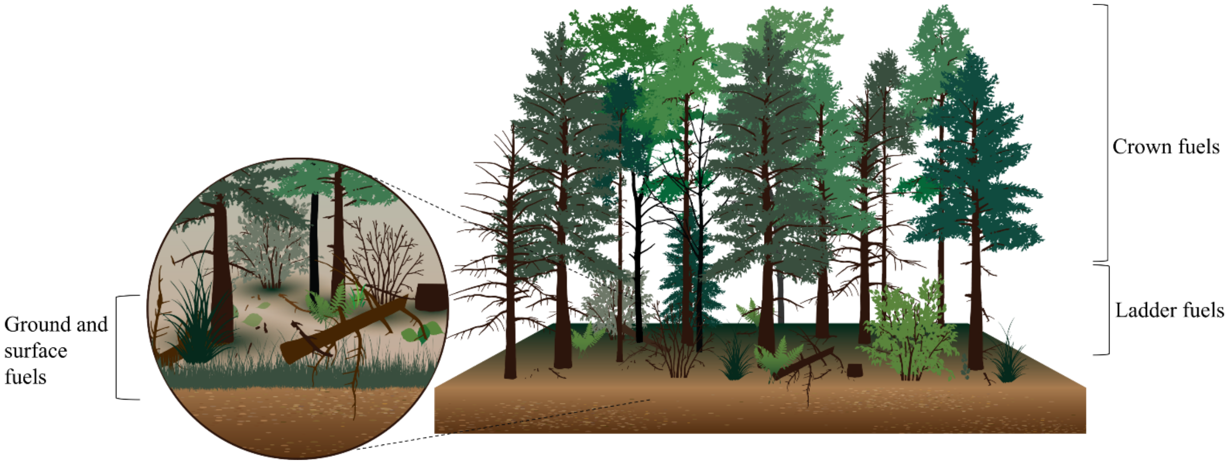

Figure 2. The basic vertical strata used to describe the fuel complex in CFFDRS-2025.

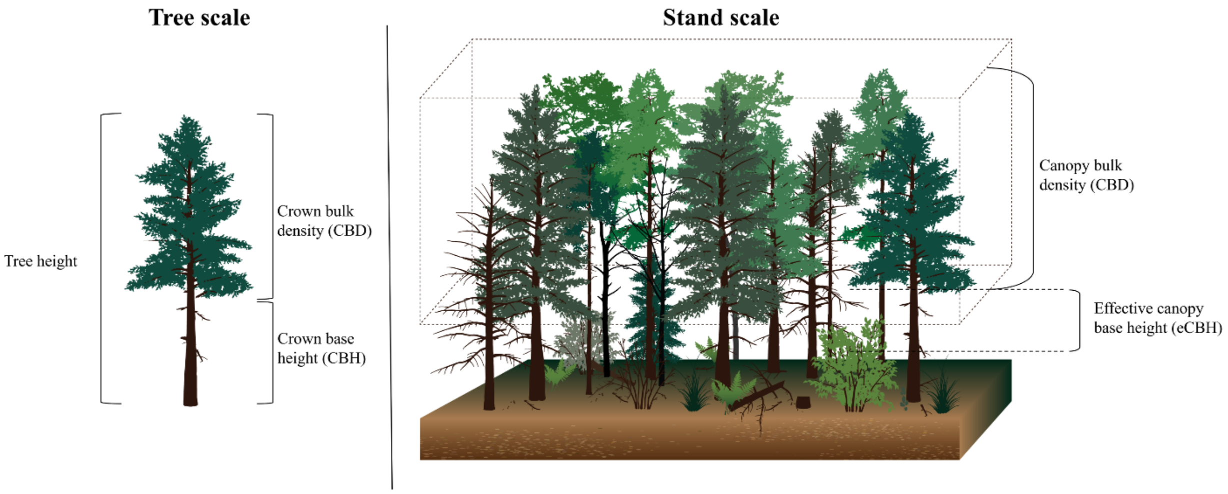

Figure 3. Structural attributes of fuels needed in CFFDRS-2025 at the tree scale and the stand scale.

4.0 The Fuel Moisture System

The moisture content of fuel particles strongly affects the initiation of the combustion reaction and the rate of heat transfer within a fuelbed. The FFMC, Duff Moisture Code (DMC) and Drought Code (DC) of the FWI System have been the primary indicators of the moisture content of surface litter, the upper portion of the forest floor (0-7 cm thick), and deep organic layers, respectively, for decades. These single fuel layer "standard" moisture codes will be retained in CFFDRS-2025, and in particular in the FWI System (Section 5). However, a new Fuel Moisture System (FMS) will provide a means to directly estimate the moisture content of important fuel layers in a range of different stand types at different times throughout the day (Figure 4). Some of the existing methods (i.e., hourly FFMC (Van Wagner 1977a) or the diurnal FFMC adjustment (Lawson et al. 1996)) are considered components of the Accessory Fuel Moisture System (AFMS) in the current CFFDRS (Stocks et al. 1989); however, the elements of the AFMS were never assembled and documented. Models developed for the NG-CFFDRS program will expand on and update these methods and provide clear linkages to the standard daily estimates of moisture that are used within the FWI System. The new FMS will house the collection of fuel moisture models and indicators that are used throughout CFFDRS-2025 (Figure 4).

Site-specific moisture content

While the FFMC and its "generalized pine forest" (Van Wagner 1974) has been a very robust moisture index, there are situations where quantifying the actual litter moisture content more accurately is desirable. Studies from a broad range of conifer forest types have shown that stand conditions can affect the moisture content of the forest floor. Methods for calculating moisture content for a range of ground surface cover types, stand types and stand closure levels will be introduced for applications where accurate estimates are required for specific forest stand conditions, such as the probability of flaming ignition and surface fire spread, to provide enhanced flexibility and accuracy. Methods for estimating moisture content of fast drying grasslands and other elevated fine fuels will be included along with methods of estimating the moisture content in the deeper, water-table influenced organic layers of peatlands. New models will incorporate (where appropriate) solar radiation and thus be able to account for differences in surface heating due to slope and aspect or locally specific topographic shading, the effects of canopy openness, as well as the effects of latitude and time of year more explicitly.

Hourly scale

Increased availability of frequent (i.e., hourly) weather observations allows for estimation of moisture in different fuels at different times of day. Methods for using hourly weather data to estimate hourly FFMC have been available to users for some time (Van Wagner 1977a); new methods will be developed to provide diurnal estimation of fuel moisture for a range of surface fuel types. Furthermore, new methods will create consistency between diurnally estimated fuel moisture and the standard daily moisture codes used in the FWI System (see Section 5.1). Vertical linkages between fuel layers in and on the forest floor will be included to reduce inconsistencies.

Foliar moisture content

Improved models of foliar moisture content changes driven by plant phenology will be developed. These methods will account for seasonal differences in weather.

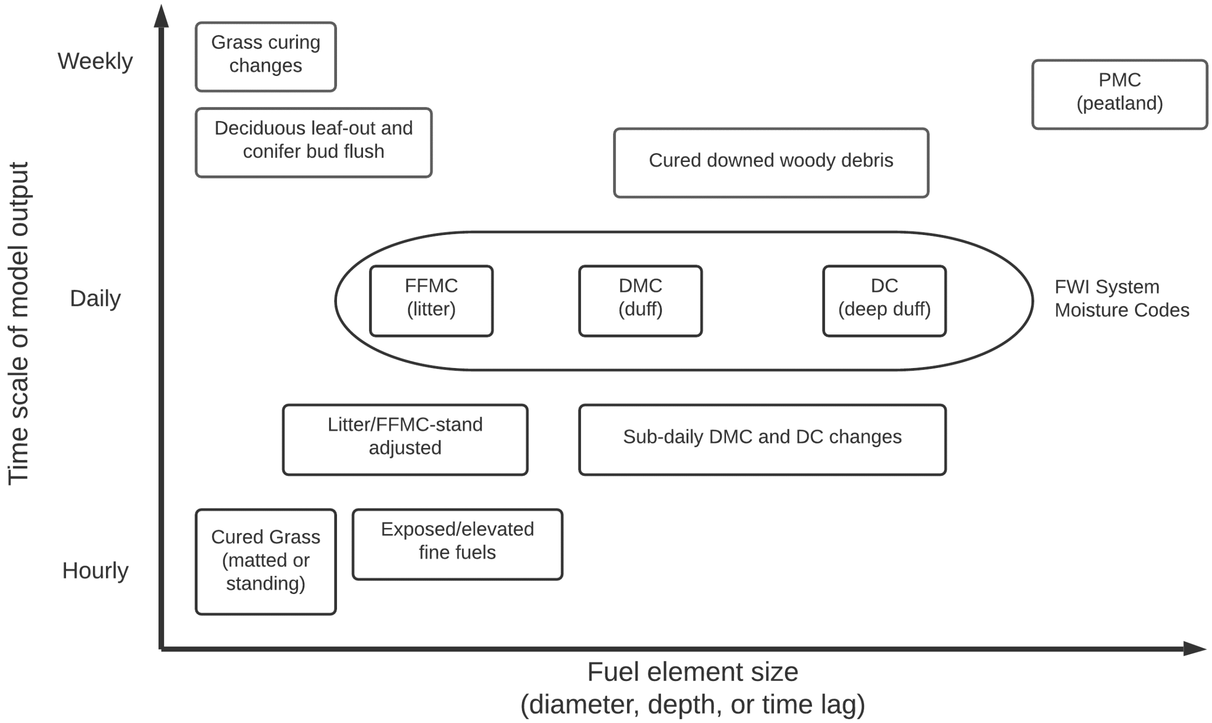

Figure 4. General elements of Fuel Moisture System arranged (approximately) by fuel time lag (along the x-axis) and the temporal scale of how often the output might be needed operationally (along the y-axis). The enclosed boxes in the centre are the core fuel moisture codes that are a key part of the FWI System.

5.0 The Fire Weather Index System

The current FWI System aims to be as simple as possible while still accounting for the critical elements influencing forest fire danger. For many daily planning requirements there is still much value in a nationally consistent system of unitless indicators representing wildfire potential in a single, common forest fuel type. For the last 50 years the regional interpretation of these outputs to provide information about the local fire environment has been a successful part of operational fire management planning. Therefore, in the CFFDRS-2025, the core structure and interpretation of the FWI System will remain unchanged (Figure 5). However, the daily moisture codes and behaviour indexes will be calculated from weather observations during peak daily burning conditions rather than at 13:00 Local Daylight Time (LDT). In addition, new optional codes and indexes will be introduced for grassland and peatland fuels. A set of optional outputs will also provide regional planners with indicators about burning day duration and atmospheric conditions (Figure 5).

5.1 Weather inputs for peak burning conditions

The convention of using noon standard time weather observations as an early indicator (i.e., a forecast) of the weather during the peak burning period later in the day in the FWI System is a legacy of a practice introduced in the 1930s (Beall 1939). In the absence of other observations or forecasts, it was a way to inform the afternoon's fire suppression planning using the principle of persistence. However, this practice can under or overestimate fire danger considerably at the peak burning period in unstable weather conditions (e.g., the passage of a cold front in the afternoon bringing strong winds or rain). It is also less relevant now that multi-day weather forecasts (including numerical weather prediction model outputs) are ubiquitous in wildfire management; daily preparedness planning at the district or regional level typically takes place in the morning of a day and/or on the previous afternoon with forecasted weather. Thus, the fuel moisture content calculation methods within the new FWI System will be modified to rely on the forecast or observed daily maximum temperature, minimum humidity, and the wind speed at the time of maximum temperature to better represent the peak burning conditions. Accumulated precipitation will remain an input, and the optional use of the timing of that precipitation will allow increased accuracy in the new FWI System's moisture content bookkeeping methods. The change from noon (standard time) weather observations to the use of daily maximum and minimums will also provide a clearer linkage between typical weather forecast quantities and the new FWI System calculations; this change to the calculations will also allow hourly data, where it is available, to be used consistently the FWI System calculation. This change in the time of daily weather inputs also provides a much-needed means of reconciling differences between the daily FFMC (Van Wagner 1987) and hourly FFMC calculation methods (Van Wagner 1977a) as well as the diurnal FFMC adjustment procedure (Lawson et al. 1996). The discrepancy in predictions from these three different methods has long been a concern raised by users of the CFFDRS.

While the final bookkeeping estimate of moisture content will be shifted to the end of the drying period (i.e., late in a typical day or early the subsequent morning), this will not affect the timing of the operational planning activity, which is usually based on forecast information and should be transparent to fire management agencies that use automated calculation methods. However, maximum temperature (and other quantities) will have to be forecasted or measured (or both) instead of relying solely on the traditional noon (standard time) observation as a forecast of late afternoon peak conditions. Methods will be provided for adjusting the noon observations to the maximum and minimums needed in the new calculations for those who cannot access forecast maximums, and to adjust historical daily records.

Latitude and longitude of the location of the weather observation and calendar date will replace the month of year input to the FWI System. This will allow for the explicit calculation of daylength (and consequent potential solar radiation exposure), which can influence the drying expected in a day, and better adjustment of the moisture codes for latitude.

5.2 Additional fire danger indicators

The codes and indices of the FWI System are designed to be indicators of forest floor fuel layers' moisture and potential fire behavior in a typical jack pine stand. Fire ignition and spread potential in cured grasslands can be quite different from closed canopy forest stands. Grass fuels can dry very rapidly and sustain high-intensity fire within hours after rain. A set of three optional moisture and relative behaviour indicators will be added to the FWI System to better represent fire danger in grasslands. A new Grassland Moisture Code (GMC) will rely on an estimate of expected solar radiation (or even general cloudiness) if such an observation (or forecast) is available; latitude/longitude-based estimates of potential solar radiation can be used in the absence of observations. Two additional unitless fire behaviour indicators, a Grassland Spread Index (GSI) and a Grassland Fire Weather Index (GFWI) will be provided that parallel the FWI System's ISI and FWI (Figure 5). These new grassland indices will also rely on an estimate of the degree of curing of the grassland (similar to grassland fuels in the FBP System), which can be: an observation, a default value (i.e., 90% cured), or can be estimated from remote sensing or weather-based observations from the inputs (Sec 4.2) or the FMS (Sec 5). Early versions of these indices in cured grasslands (Wotton 2009a) have been found to provide significant improvement in moisture and fire behaviour prediction in springtime fully cured grasslands (Kidnie and Wotton 2015).

A Peatland Moisture Code (PMC) will be developed to represent ecosystems where fire potential and drying of fuels is controlled by slower processes than captured in the current FWI System. The PMC is envisioned as an indicator of the water table depth relative to surface in forested peatlands. With sufficiently dry conditions, the PMC will indicate the absence of surface water in these systems, a state that can allow moisture in surface fuels to vary similar to models of upland forest floors present in the FMS.

Several other indicators of fire danger (e.g., overnight recovery, atmospheric stability) that have been used to inform operational planning will be also evaluated in the development and testing of the updates to the FWI System. These appear as optional outputs in Figure 5, though are still under consideration.

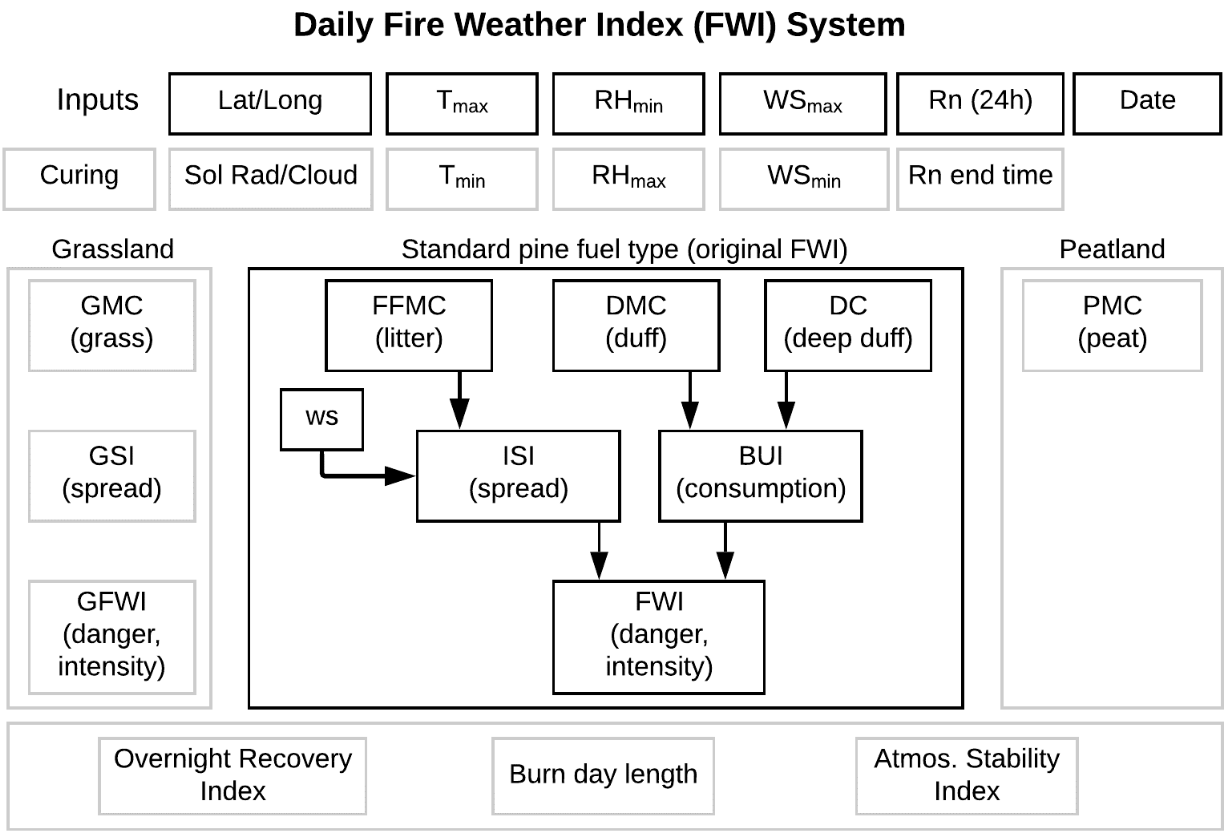

Figure 5. The FWI System including core and proposed optional components. The core of the FWI System is inside the central box outlined with a thick black line and does not change in structure from the current FWI System structure. Optional elements (which are in grey boxes) include inputs, specific fuel-type dependent indices, and additional burning day characterization and atmospheric factors. T_{max} and T_{min} are the daily maximum and minimum surface air temperature. RH_{max} and RH_{min} are the corresponding maximum and minimum daily relative humidity. WS_{max} is the peak (or maximum) average wind speed, while WS_{min} is the minimum average wind speed. Rn(24h) is the 24-hour accumulated rainfall and Rn(endtime) is the time that measured rainfall ends. Sol Rad is the 24-hour total solar radiation or a fractional cloudiness value. Curing is the state of grassland greenness as defined in the FBP System.

6.0 The Fire Behaviour Prediction System

Fire spread modelling in the CFFDRS has relied on an approach where model forms that describe the basic physical processes driving flame front propagation are calibrated with observations of fire spread from the field (i.e., large-plot experimental fires, prescribed fires, and wildfire observations). This not a purely data driven statistical modelling approach however. Rather than using data to find the best fit to a range of possible functional forms, a specific model form was chosen that was consistent with physical arguments, captured the most important processes, and agreed with the experience of fire behaviour experts. Observed data is used to calibrate these pre-determined model forms; ultimately, good spread rate observations from the field constitute a very sparse dataset. Where observations have been lacking, expert science-based opinion has been used to fill gaps (e.g., mixedwood spread rate change as conifer content changes in the current M-1/M-2 fuel type). The reliance on empirical observations of fire behaviour has been key to gaining confidence in the outputs of the FBP System in operational fire behaviour prediction.

While it remains the cornerstone of successful operational planning, the FBP System needs enhanced flexibility to allow users to predict fire behaviour in a wider range of increasingly common situations. Some users also want to see a broader range of physically meaningful quantitative outputs (e.g., fuel load specific consumption, spot fire probability, fuel-break breaching probability, probability of sustainable smouldering and flaming ignition). To achieve these goals, many of the models within the FBP System will be redeveloped. However, in keeping with the longstanding fundamental design principles of the CFFDRS, this redevelopment will continue to rely primarily upon the approach of calibrating physically logical models of fire behaviour processes using field observations.

While increased flexibility will be achieved, for many of the most common uses in day-to-day operations, the new FBP System will be no more complicated than the current FBP System; maintaining this ease of use is a core CFFDRS design principle (see Box 3). Improved flexibility for specific fuel complex modifications will be available to those users who want to use this enhanced capability.

Conditional fire spread rate

It is important to understand that the FBP System models are developed from observations of established spreading fires; data from the experimental program on days when an ignited plot failed to obtain sustained spread are not included in the models. Therefore, both in the original FBP System and in the new FBP System, the basic spread rate models should be considered to be "conditional" models of spread; if a fire is spreading with a coherent fire line, then the spread rate model should provide a reasonable estimate of average spread rate for the conditions. While the conditional nature of the FBP System's spread rate models is not new, the inclusion of the probability of sustained flaming models directly in the System structure should help users understand this subtlety. These sustained flaming probability models will use the same basic predictor variables as the new surface fire spread rate models in the new FBP System and will help to link ignition sustainability to the equilibrium spread rate models.

Figure 6 shows a simple schematic of the new FBP System and its core components. This figure is not intended to show the calculation flow in the System in a specific way, but merely highlight some of the core elements in the System. There are significant dependencies between the new FBP System and other CFFDRS subsystems. The new FBP System will have five modules that represent interrelated processes of: (1) flaming ignition sustainability; (2) surface fire spread and fuel consumption; (3) surface to crown fire transition; (4) crown fire spread and fuel consumption; and (5) spotting of firebrands. These will be discussed in the following sub-sections, as well as combustion zone characterization, acceleration, and elliptical fire growth.

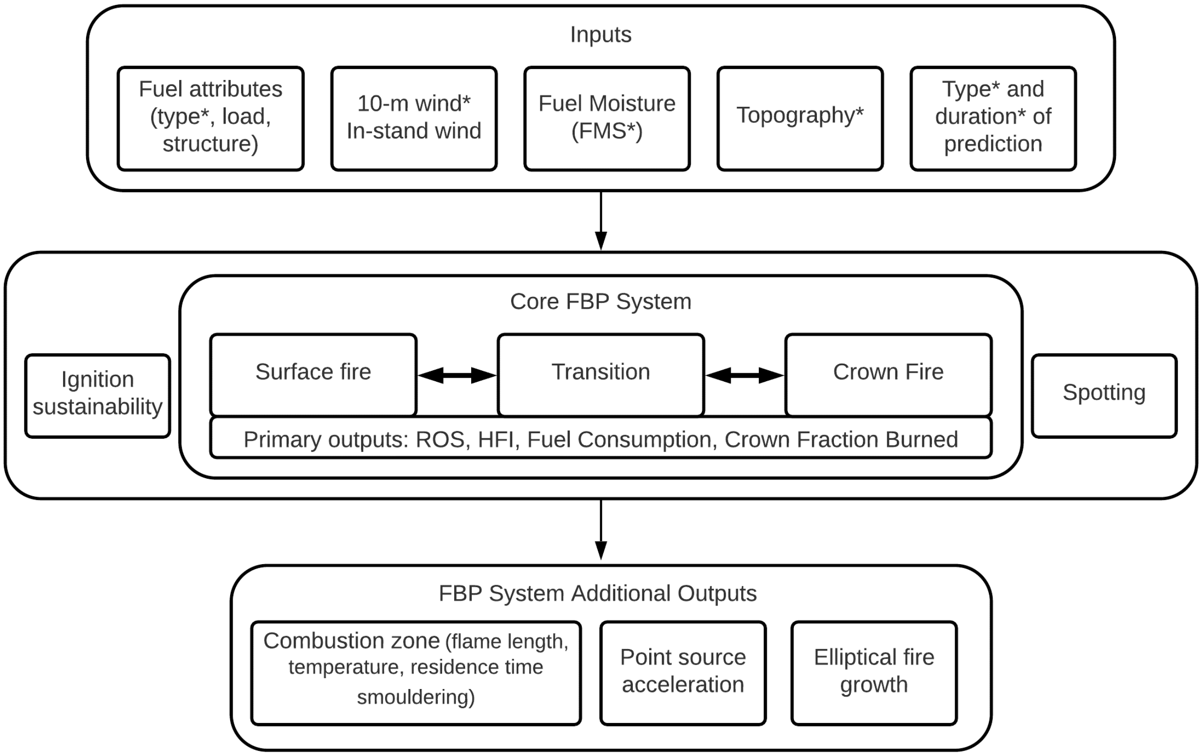

Figure 6. Overall high-level structure of the new FBP System.
*Indicates basic inputs with optional inputs for advanced users.

6.1 Ignition probability

A method of assessing the probability of sustained flaming is the first step in determining fire behaviour. Field studies in a dozen forest types throughout Canada during the 1930s-60s provided a dataset of over 20,000 test fire ignitions that formed the basis of the first regional hazard rating systems in Canada. Some of the data were subsequently used to develop statistical models of flaming ignition for different forest types in Canada (e.g., Lawson et al. 1994; Lawson and Armitage 1997). Initial re-analysis of the broader Canada-wide dataset carried out as part of the NG-CFFDRS program developed models of the probability of a sustained flaming ignition for six forest floor cover types: dry conifer (conifer needles only), wet conifer (conifer needles on feathermoss or sphagnum), deciduous leaf litter, mixed leaf and conifer needles, reindeer lichen (*Cladonia* spp.), and, grass. These models estimate the probability of sustained flaming ignition as a function of surface fuel moisture and in-stand wind near the surface. The surface fuel moisture input will be estimated from the most appropriate method; that is, it may be derived from the FFMC itself, the new GMC, the in-stand specific adjustment to the FFMC (which is part of the new FMS), or even from a direct measure of moisture from the field. In-stand wind will be estimated from the standard 10-m open wind observation and stand structure characteristics of the fuel complex (see Sec 3.1 for details). The use of in-stand wind direct observations will be possible for site-specific and specialized applications.

This ongoing analysis is occurring in parallel with the development of new models of surface fire spread rate specific to each forest floor cover type; similar model forms are being used, because the physical logic underlying what primarily influences these two processes is the same. This provides strong linkages between probability of ignition sustainability and the rate of spread of a spreading surface fire.

6.2 Fire spread modelling

In the original FBP System, most fuel types use a single spread rate equation with a sigmoidal ("s-shaped") form across the entire range of expected fire behaviour in conifer and mixedwood stands. The notable exception is the C-6 "conifer plantation" type, where separate models of surface and crown fire spread rates were coupled or "mixed" together through the crown fraction burned formulation. This mixed model approach has often been referred to as the "dual equilibrium spread model". After publication of the FBP System (Forestry Canada Fire Danger Group 1992), Van Wagner (1993) also demonstrated how such dual spread rate models could be developed from the experimental observations collected in mature and immature jack pine fuel types. The new FBP spread rate modelling framework will be based on this dual or mixed model concept, which, when coupled with more explicit quantification of fuel complex attributes and other elements like in-stand wind, will allow greater flexibility in modelling the impact of modified fuel structure on fire behaviour.

Surface fire behaviour

Forests

Surface fire spread rate will be modelled for a set of forest floor cover types that are distinct from the fuel types of the current FBP System. These forest floor cover types will be the same as those used for estimating the probability of sustainable flaming (Section 6.1): dry conifer (conifer needles only), wet conifer (conifer needles on feathermoss or sphagnum), deciduous leaf litter, mixed leaf and conifer needles, reindeer lichen (*Cladonia* spp.), and grass. Models will rely on estimated in-stand wind and surface moisture explicitly and therefore are similar to the model forms used in many existing surface spread rate models (e.g., Cheney et al. 1998, Anderson et al. 2015) and also very similar to the original ISI.

Methods of estimating litter moisture for specific stand types and fuel arrangements are being developed in the new FMS. There has been considerable research and modelling focussed on the impact of stand biomass on the reduction of winds at the surface of a forest; these existing research findings will inform the wind reduction methods embedded within the new (CFFDRS-2025) FBP System. These models will allow users to incorporate the impact on fire behaviour from changes in stand density (e.g., due to fuel management such as thinning) and also allow for spread rate prediction in locally modified environments such as the edges of newly cut forests or along linear features such as powerline or energy infrastructure rights of way.

Data from the FBP System fire database have been expanded by going back to documentation on fires and adding in observations of surface fuel moisture, in-stand wind, stand density, etc. where they were found to exist. Estimates were made where this data did not exist. This reanalysis work is ongoing and newly observed fire behaviour data will be incorporated whenever it is available.

Grass

The grassland spread rate models in the original FBP System were developed from data that came from Australian experimental burning observations. New grass spread rate models will be adapted from newer Australian experimental results that have been conducted since 1992. The most recent model for grass curing effect on spread rate, found through experimental burning in Australia (Cruz et al. 2015), will also be adapted into the current FBP System formulation; it is very similar to the model that was implemented in FBP System during its minor revisions in 2009.

Slash

Experimental observations of spread rate in slash types will be reanalyzed. New models will be developed based on models of faster drying exposed and elevated fine fuels in the new FMS (Section 4). The existing FBP System slash fuel models use fixed fuel load values (Appendix A, Table A-1); in contrast, CFFDRS-2025 users will be able to modify the size class distribution of the woody debris to represent different forest harvesting practices as well as heavy fuel loads resulting from blowdown. Slash models will also include fire behaviour predictions for newer types of mulch (masticated) fuels composed primarily of finely chipped stemwood, which feature significantly lower spread rates and intensities compared to existing slash fuel types.

Shrubs

Though shrublands are a relatively minor constituent of the Canadian boreal forest landscape compared to other regions, guidance on shrubland fire behaviour is still absent from the current FBP System. Insights from the Anderson et al. (2015) shrub model and similar studies will be merged with the limited experimental fire data available across Canada (e.g., Pepin and Wotton, 2020). Similar to other shrub models, the ability to adjust deciduous foliar moisture content and fuel load will be incorporated in order to adjust for seasonal trends.

Fuel Load and Consumption

The fixed fuel types in the current FBP System, except for grass (O-1), use empirical fuel consumption equations with constant fuel load values (see Appendix A, Table A-1); surface fuel consumption is primarily predicted by the BUI and other fixed values associated with each fuel type. New fuel consumption models of the forest floor and downed and dead woody surface material currently under development will allow the users to modify the fuel load and predict consumption based on initial fuel load and fuel moisture conditions. Similarly, fuel load in canopy fuels will also be variable and canopy consumption will be calculated using fuel load specific models. Consumption functions will be more sensitive to fuel size classes and partition consumption between flaming and smouldering combustion; this will reduce the problem of over-predicting fire intensity due to large woody debris loading and consumption. This more explicit characterization will allow partitioning of consumption into the proportions associated with the passing of the main flame front (and thus directly contributing to fireline intensity) and that associated with burn-out after the passage of the main fire front. For instance, slash fuel consumption models will be modified to include a smouldering or residual flaming phase of combustion for the larger diameter classes that contribute to smoke emissions and suppression load, but not to head fire intensity. For users who do not want, or need, to consider adjusting fuel loads, standard values will be associated with each fuel type defined.

6.3 Surface to Crown transition and Canopy Fraction Burned.

The transition from surface fire to crown fire represents a very critical development in a fire's behaviour and can lead to rapid intensity and spread rate increases. Van Wagner (1977b, 1989, 1993) provided the original surface to crown mechanism used in the current FBP System. The initiation of crowning was related to the intensity of a surface fire (and hence the vertical temperature profile above the fire), the live canopy base height (LCBH; see Box 5), and the foliar moisture content in the tree crown. In Van Wagner's conceptual model (Van Wagner 1977b), how much surface fire intensity exceeded the minimum threshold for crown initiation influenced the extent of crowning throughout a stand.

This basic conceptual approach to the surface to crown transition will be maintained in the new FBP System; however, because of the importance of this transition, this is an ongoing area of active research and new crown initiation models are being developed and tested. Ideally, new observational evidence from experimental burning will also supplement existing understanding of this process. New models will incorporate both the natural temporal variability of in-stand wind speed and spatial variability in the surface fuel to crown base height distance (effective Crown Base Height: eCBH, see Sec 3.3 and Figure 3).

Models of overstory fuel consumption will be based on estimates of the canopy fraction burned, crown fuel load (as in the present FBP System), and fire intensity, but the crown fuel load will be dynamic (replacing the fixed canopy fuel loads of the current FBP System) as previously noted (Section 3.3).

6.4 Crown fire behaviour

Conifer stands

The re-analysis of the CFS experimental fire database for crown fires by Cruz et al. (2005) demonstrated that a sound general model of active crown fire spread rate could be developed for a range of coniferous forests in Canada. Wind is the primary factor influencing variation in spread rate for active crown fires in Canadian conifer stands. This ability to model fire behaviour over a range of conifer forests with a single spread model allows considerable consistency across a range of forest types throughout Canada. Canopy bulk density will be used to estimate rate of spread of active crowning threshold (Van Wagner 1977b). By allowing modification of canopy bulk density within the FBP System fuel types, users will be able to assess fire behaviour potential across various stand thinning prescriptions in fuel management applications.

Mixedwood stands

Fire behaviour in mixedwood stands is currently represented as a simple linear blend of aspen (leafless or green condition) and boreal spruce(C-2); this linear blend of two fuel types was created due to the lack of a large datasets of fire behaviour observations in this fuel type. Conceptually, a blended or mixing model approach will continue to be used in this fuel type; however non-linear mixing model forms will be explored that will rely on basic physical logic of the process and are consistent with any observations available for this forest type. This is a fuel type for which few experimental burning observations exist. Ideally, over time, new observations will be documented in this forest type and these will be

Box 5. Fixed fuel type attributes: Live Canopy Base Height (LCBH)

One of the clearest examples of the limitations caused by fixed fuel type attributes is the use of live canopy base height (LCBH) in the current FBP System. The LCBH in conifer stands is understood to exert a strong influence on the ease of crown fire initiation. Van Wagner's (1977) model characterizes crown fire potential, in the form of the critical surface fire intensity, as a function of LCBH and foliar moisture content on the basis of observed and physical evidence. The Van Wagner model is used in the current FBP System to predict crown fire initiation and involvement, and thereby type of fire (surface, intermittent crown, continuous crown). However, each of the current FBP System conifer fuel types (with the exception of C-6) has a fixed LCBH value assigned to it (Appendix, Table A-2). Because the spread rate models in the FBP System were designed separately using a single empirical model formulation, a fixed LCBH was chosen for each fuel type to produce model output that approximately matched the observed thresholds where fires began to partially engage the crowns. Assigned LCBH values were therefore "the result of some trial" (FCFDG 1992, p. 35) and do not necessarily represent the measured LCBH value in the experimental stands. The LCBH values in the existing FBP System are therefore neither changeable within a specific fuel type, because of the purely empirical nature of spread rate functions, nor verifiable in the field. This has led to frequent challenges related to fuel typing and properly representing the full range of forest vegetation conditions in a given landscape.

The next generation FBP System (CFFDRS-2025) will more clearly define the LCBH, provide guidance for field verification, and permit users to modify the LCBH as needed. The system will properly account for the impact of these changes on in-stand weather, spread rate, and fire intensity.

used with findings from other modelling studies to improve spread rate prediction capability in this fuel type.

6.5 Spotting

Ember production and medium-range transport (tens to hundreds of metres) downwind is an important process in conifer crown fires. The present FBP System implicitly includes the influence of shorter-range spotting in its fire spread model estimates derived partially from wildfire observation data. With embers increasingly recognized as a key ignition vector in structure losses (e.g., Syphard and Keeley 2019) and as a source of fire breaching across containment lines and other non-fuel features, ember production and their short-range transport will be addressed in the new FBP System. Firebrand research has advanced considerably in the past decade, with numerous observational (Storey et al. 2020) and physics-based approaches (Koo et al. 2012) becoming available to predict ember transport. However, the first, and most challenging, part of the firebrand problem lies in the production rate of firebrands, which depends on the amount and arrangement of fuels (e.g., Figure 2, 3). Ember lofting height and transport distance is related to the fire intensity, wind speed, and ember mass and shape (Koo et al. 2012); this aspect of the spotting process has received the most attention in previous research. Much further research can, and should, be done on all elements of the spotting process; the understanding of this process would also be greatly improved by documenting observations of spotting by fire management personnel in the field. The new FBP System will include methods for estimating expected spot fire occurrence and ember transport distances. These methods will be sensitive to changes in stand structure (i.e., thinning or mortality) as well as fire weather and fireline intensity and will be developed from existing observational datasets and informed by previous mathematical and physical modelling.

The initiation of spot fires from firebrands landing will be a function of surface fuel moisture (from FMS, Figure 4) as well as flaming ignition sustainability (from new FBP, Figure 6). The breaching of fires by spotting across fuel breaks (e.g., roadways, mechanical guards, waterbodies) will also be sensitive to the potential for lower fuel moisture contents at the edge of forests due to enhanced wind and solar radiation inputs to the forest floor. The reliance of sustainable ignition and surface fire spread rate models on direct estimates of surface fuel moisture and wind at the surface will allow consistent estimation of the impact of edge effects on fire behaviour within the new FBP System.

6.6 Combustion zone characterization

Numerous direct applications of the FBP System, such as plume rise, smoke and emissions models, tree mortality and soil heating models require more information about a spreading fire than has been provided in the FBP System in the past. As these related applications have been developed, ad hoc methods and models have been used to provide these quantities; however, this has led to inconsistent application and linkage of FBP System outputs into various applications. While standardization can lead to inflexibility, the new FBP System will provide standards for these parameters based on field observations during experimental and prescribed fires. The goal is not to provide definitive values that must be used by those developing wildland fire management applications, but to provide general guidance to users of the System.

These outputs will remain secondary outputs not affecting or even considered by most casual operational users of the System.

Flame length and height

Flame length is an easily observable quantity on wildfires and has strong association with overall energy release from the combustion zone (during flaming combustion). Numerous fireline intensity–flame length (or height) relationships exist in the literature (e.g., Alexander and Cruz 2012) because the relationship can be very strongly influenced by the fuel complex that is burning and therefore no single relationship will perfectly predict flame length. In the new FBP System, to provide a reference for users of the System, flame length relationships will be explicitly identified for key fuel complexes that produce significantly different flame lengths under similar intensities (i.e., grassland, surface fire in a forest, or logging slash).

Flame height is a critical metric for fire effects models of lower branch mortality where vegetation is heat killed but not ignited. Crown fire initiation models also rely on estimates of flame height for ignition of conifer branches at the effective Crown Base Height. Flame height and flame length are strongly linked through the angle at which free burning flames bend in the wind (or under the influence of slope). Basic models of expected average flame angle (angle from vertical) will be provided that balance the horizontal force of the wind with vertical buoyancy due to energy release from the burning fuel (i.e., fireline intensity). These will focus only on providing an indication of the long term expected average of flame angle (in the order of several minutes of spread) of a fire burning through a fuel complex and will allow linkage between flame length and flame height estimates.

Residence time of flaming and temperature

Flaming residence time, both on the surface and in the crown, has been measured during experimental fires; standard values for flame front residence time will be provided (based on field measurement) for a range of fuel complexes. Flame temperature has also been observed over a considerable range of fireline intensities. The transition to residual or sparse flaming and smouldering follows after the passage of the fire front (and its associated residence time) in all but grassland fuels; the fraction of surface fuel consumption occurring after the passage of the flaming front will be provided.

Smouldering sustainability

The likelihood of sustained smoldering combustion is important to modelling lightning ignition holdovers and the growth and extinguishment of free burning fires over periods of days to weeks. Smoldering combustion is dependent on the bulk density and ash content of forest floor organic matter and moisture content (Frandsen, 1987, 1997); therefore smouldering combustion prediction will be improved through the explicit characterization of forest floor bulk density in new fuel models (Section 3) and the site specific moisture model available in the FMS (Section 4).

6.7 Additional fire spread related elements of the FBP System

The current FBP System distinguishes outputs as primary and secondary. Primary outputs were those that captured key elements of the behaviour of a well-established headfire spreading in equilibrium with its environment: spread rate, fuel consumption, fire intensity and type of fire. The secondary outputs captured such elements as the growth of a fire from a point source (termed its "acceleration") and the spatial growth and shape of a free burning fire in homogenous fuels and weather conditions. These elements will remain in the new FBP system and be enhanced where new science and observations allow.

Slope

Predicting the influence of topography on local fire behaviour is critical. Elements of the new FMS will allow slope adjustment of fuel moisture content to account for exposure aspect. The upslope enhancement of spread rate in the FBP System will be maintained. The functional form and relative strength of the slope model will be re-examined along with existing research observations of slope fire spread both from wildfires and from well-established fire physics models. The balancing of the slope and wind effects will be reformulated given the new modelling framework for the spread rate models overall. More complex interactions between variable slope direction and winds and their influence on the development of fires are not considered explicitly in the new FBP System. These are considered the domain of spatially explicit wind and terrain modelling systems coupled with spatial fire growth models.

Acceleration

The time required for the growth of a fire from a point to a spreading line fire that has achieved some long-term state of equilibrium with its environment is an important piece of information for wildland fire management planning. This is particularly important if the expected eventual equilibrium reached is a high intensity fire spreading beyond a certain threshold of suppression resource effectiveness. The acceleration function originally developed in the FBP System will be enhanced with more recent observations of fireline acceleration and growth and coupling with the new models of probability of sustained flaming, and the variability of in-stand wind and surface spread rate. This will provide enhanced understanding of the uncertainty around the time required for acceleration to equilibrium spread condition.

Elliptical growth, back and flank fire spread

The current FBP System included a basic elliptical fire growth model for a free burning point ignition spreading in constant weather conditions, through uniform fuels, and across uniformly flat terrain. This basic conceptual model of elliptical growth will be maintained in the new FBP System. In the reanalysis of basic spread models, the back fire spread model will also be redeveloped to maintain consistency with the new surface fire model forms. Little further field-based experimentation or documentation of back and flank fire spread has been carried out since the FBP System was originally designed and thus the model formulations will likely remain based on physically consistent logic more than empirically derived equations. The empirically developed models of fire shape (i.e., the length-to-breadth ratio) for forest and open grasslands will be maintained, and refined with new observations or from any consistent insights found by fire physics modelling. Flank (or lateral) fire growth rate will continue to be determined from the combination of head and back fire spread rates and fire shape as in the current FBP System.

7.0 Fire Occurrence Prediction

The Ignition Probability in Section 6.1 is the conditional probability of an ignition at a point exposed to a heat source, which has been modelled from thousands of small test fires. In contrast, fire occurrence is a spatial measure and is defined as the unconditional probability of a fire occurring in a grid cell on any day, and in aggregate, the number of fires that are expected to occur in a particular geographic region. Fire occurrence models are developed from purely statistical relationships between historical fire occurrences in fire report data and environmental factors. The input data may be spatial or imputed to the grid, as with point-based weather observations.

7.1 Development of FOP

Research to develop statistical relationships between the number of fire starts in a region on any day and environmental variables such as relative humidity began almost 100 years ago. In early fire occurrence models, forest districts were the base geographic unit; district-wide fire occurrence was related to weather and danger measures from a representative weather station. In Canada, Beall (1934) estimated the expected number of fires by danger class in the Algonquin District of Ontario as an empirical frequency, based on 14 years of historical fire data, and weather and fire danger observations at Petawawa. Stochastic modelling frameworks were introduced in the 1970s (Cunningham and Martell 1973).

Contemporary FOP frameworks are cell based; the region of interest is discretized into grid cells, where a cell by day observation, or voxel, is the primary sampling unit; historical fire occurrence (yes, no or 0, 1) and explanatory data are compiled by voxel. The probability of a lightning or human caused fire is modeled in relation to a set of explanatory fire weather, fuel, topography, lightning and human presence variables representing the fire environment. The modelling process involves selection of explanatory variables, data compilation and model fitting. This approach allows representation of explanatory data in a more granular, spatially explicit manner, and greater spatial resolution in predicting probable fire locations.

A national Fire Occurrence Prediction System was conceived as part of the CFFDRS in the 1980s (Stocks et al. 1989), and issues facing the development of a FOP System were outlined in a national workshop (Lynham 1991). Subsequently, provincial models were developed for Ontario (Wotton and Martell 2005) and British Columbia (Todd and Kourtz 1991, Kourtz and Todd 1991; Magnussen and Taylor 2012, Nadeem et al. 2020); however, a national system was not realized.

Fire occurrence prediction is data driven, and a challenge of FOP using this approach is that even at a moderately coarse resolution of 20 km, fire occurrences are rare at a daily time step; statistical methods are needed to detect rare events. Furthermore, at the scale of Canada the cell x day data frame is enormous. Several conditions have changed that make the completion of a national FOP system framework feasible. The availability of digital records has increased, including fire weather, lightning detections, fuels, topographic and demographic data at a national scale. Computing capacity is greatly expanded and statistical methods have also improved considerably; see reviews in Taylor et al. (2013) and Xi et al. (2019). The required data (e.g., lightning, weather) for daily prediction is also increasingly available in real-time for the implementation of fire occurrence models into spatial fire management systems.

7.2 Progress towards a national FOP Systems

Work is in progress to implement a series of models of lightning and human-caused fire, and large fire models for six regions of Canada: British Columbia, Territories, Prairies, Ontario, Quebec, and Atlantic at a 20x20 km grid scale. Data on approximately 70 environmental explanatory variables were compiled for each day in 30 fire seasons for each of approximately 10,000 grid cells. The explanatory variables include weather and FWI System variables that were derived from all of the historic fire weather data available from Canadian fire management agencies, as well as from MSC and from adjacent stations in the US. Twenty-four statistical models (4 model types x 6 regions) are being fit following methods in Nadeem et al. (2020); the models are tuned for each geographic region and are not transferable. In addition to a lightning-caused FOP model that includes observed lighting strikes among the explanatory variables, a separate lightning caused FOP model is fitted that includes atmospheric stability indices as a proxy for lightning for medium term prediction applications. Conditional large fire occurrence models (>100 ha) are also being developed (e.g., if a lighting or human caused fire occurs, what is the likelihood of it becoming a large fire?). The outcome of the modelling process is a set of exponents for each explanatory variable for each model type by region in a logistic model framework. The series of 24 models has a common functional form, but the explanatory variables have different weights in different regions. This scheme can be readily implemented in spatial fire management systems. It should be noted that these or other national series of FOP models will not necessarily supplant existing provincial models, but provide additional guidance, as well as national level intelligence.

While physical understanding guides variable selection in FOP models, as in other components of the CFFDRS, the models are purely data-driven and should be updated and refitted as new environmental data accrues: each fire season potentially provides more information on the relationship between fire occurrence and the fire environment. Thus, a national FOP System does not have a fixed end state, but is a framework for an ongoing modelling process. The FOP System, more than any other component of CFFDRS-2025 is dependent on high quality fire, weather and other environmental data, much of which comes from fire management agencies. Agency efforts on data standardization and integration are extremely helpful. The relatively low fire weather station density in much of Canada is a limitation on model accuracy.

Once national FOP models have been implemented in spatial fire management information systems, modelling will shift to focus on methods for predicting sharp peaks in lightning fire occurrence (e.g. > 50 lightning fires per day) that remain challenging.

8.0 Fire management tools and applications

In Section 2, the overall design vision of the NG-CFFDRS was presented (Figure 1). From basic fire environment observations at the stand or landscape level, data elements flow through one or more sub-components: the FMS, FWI System, FBP System and FOP System. Specialized components can also include various spatially-defined data layers or modelling processes. Inputs and outputs, as well as the final terminus of the flowchart, will vary depending on a user's desired objectives and outcomes.

While the technical details of the various CFFDRS-2025 components consist of numerous empirical and physical equations, most end-users will not interact with the mathematics of the system. Rather, they will make use of tools and applications tailored to specific fire management purposes. Current tools using the original CFFDRS include field guides, spreadsheet calculators, fire growth modelling software, risk management frameworks, and corporate fire management systems. For users satisfied with the level of complexity of the present CFFDRS, the increased modelling complexity proposed for CFFDRS-2025 will remain mostly hidden; the appearance and use of field guides and software calculators will remain. The use of more complex versions of CFFDRS sub-models should result in outputs that more closely match observed field values, although testing and validation will continue to be required.

The fire management decision-making environment is now tied more closely than ever to information systems synthesizing large amounts of spatial and temporal information on the fire environment and fire potential, and projecting it into the future. Systems like medium range spatial fire weather forecasts, fire growth, and smoke modelling systems will be important tools for wildland fire management decision making in the 21st century in Canada. The CFFDRS has significant links to many such systems (Table 2) and those systems where these links are strongest merit some discussion here, even though they are considered outside the scope of the core of the CFFDRS.

Table 2. Examples of links between fire management applications and CFFDRS outputs (*new CFFDRS-2025 outputs are in italics*)

Fire management applications	**CFFDRS outputs used**
Spatial fire management information systems	FWI, head fire intensity, *grassland and forest FWI, probability of fire occurrence.*
Preparedness and resource planning models	FWI, head fire intensity, fire size at 30 min. *Grassland and forest FWI, expected number of human and lightning caused fires, expected number of large fires.*
Fire growth models	Front, flank, and backfire ROS, fire intensity in *varying stand structures over the diurnal cycle. Ember transport, probability of sustained smoldering.*
Smoke models	Surface and crown fuel consumption, fire intensity *in a broader range of fuel complexes. Probability of sustained smoldering, flaming and smoldering consumption.*
Carbon models	Total fuel consumption *in varying stand structures with varying surface fuel load. Partitioning of flaming vs. smouldering combustion.*
Fuel management prescriptions	Fire behavior potential *in stands with a broader range of stand characteristics.*
Prescribed fire prediction and ecological effects models	Surface fuel consumption, crown fraction burned, *fire intensity and flame height in varying stand structures.*
Wildfire risk assessment	Front, flank, and backfire ROS and intensity in *varying stand structures over the diurnal cycle. Ember transport, probability of sustained smoldering, probability of human and lightning caused fires, probability of large fires.*

Spatial fire management information systems

The FWI and FBP Systems were designed to use a relatively small number of easily available surface weather, fuel and topographic data inputs. When these systems were initially applied in field operations, input data came primarily from weather stations and observations. With the advent of commercial Geographic Information Systems in the 1980s fire management systems such as the Spatial Fire Management System (Englefield et al. 2000, Lee et al. 2002) were developed to manage interpolation of fire weather data from large number of stations and the calculation and display of FWI and FBP outputs over large geographic areas. This spatially explicit CFFDRS output has been an important means of informing planning and decision making at regional, provincial and national scales (e.g., the Canadian Wildland Fire Information System) and globally. Spatial fire management systems will be important to incorporating the new spatial data sources (outlined Section 3) in CFFDRS-2025. This strong interdependence will require close collaboration between fire danger researchers and developers.

Fire growth

While mainly a research application when the current FBP System was developed, fire growth modelling has become very common in both short (hours to multiple days) and long-term (beyond 10 days) fire management planning. There have been numerous “engines” for driving landscape scale fire growth modelling developed (e.g., cellular automata, raster-based propagation, minimum travel time implementations, Huygens’ wavelet model of propagation). Several of these fire growth engines have been implemented in different operational applications throughout Canada (e.g., Prometheus, the CFS model PFAS, or the Ontario model FireSTAR). The NG-CFFDRS updates will require these fire growth “engines” be driven by new, multi-attribute fuel layers, and that the core fire behaviour models within the growth models themselves change. The NG-CFFDRS development team will assist the developers of these operationally relevant fire growth applications with the core model adaptations needed.

Fuel breaks, both natural and man-made, are a major means of reducing fire spread (e.g., O’Connor et al., 2017). In fire growth models, these typically linear features (roads, waterways, and mechanically cleared vegetation) occur at scales often smaller than the grid resolution of the fire growth model. Systematic field observations, physics-based modelling, and expert knowledge techniques will be considered as data sources for fuel break breaching guidance in CFFDRS-2025. Ultimately, relationships between fire intensity, heat transfer (both by flames and firebrand transport) as well as forest structure will be integrated into general guidance that describes the likelihood of a fuel break being compromised under a set of fire behaviour conditions.

Smoke emissions and plume rise

CFFDRS outputs are integral for wildfire smoke transport models such as Bluesky (Larkin et al. 2010) and FireWork (Chen et al. 2019) that utilize satellite-based active fire detections alongside calculated fuel consumption and intensity. Enhanced spatial representation of variations in fuel consumption (and therefore intensity) will improve continental smoke dispersion models. Smoke plume rise is a function of both fire intensity (the fraction of fire intensity allocated to convective heating) and temperature gradients in the atmosphere. The NG-CFFDRS will provide improved guidance on the allocation of fire intensity to convective smoke plume rise. For fires of high intensity, smoke models that incorporate recent scientific advances (e.g., Josephson et al. 2019) on intensity-dependent particulate (PM2.5) emission rates will benefit from an improved representation of head fire intensity with variable fuel loading. This interaction between intensity, emissions, and plume rise is also critical for residual flaming and smouldering in low-intensity fires, which persist overnight and fail to penetrate through nocturnal inversions, leading to localized pockets of high overnight surface PM2.5. Though the CFFDRS itself does not resolve smoke dispersion, the hourly timing of the transition from flaming to residual smouldering is critical for modelling that guides public health warnings around wildfire smoke.

As an extension of the flaming zone properties what will be characterized in CFFDRS-2025, smouldering combustion will be defined separately from flaming. Surface fuel combustion will be partitioned into flaming and smouldering phases, each with an associated residence time, combustion rate, and associated emission factors. This simple parameterization of the transition from crown fire to residual flaming to smouldering is important for properly capturing low-energy smoke plumes from smouldering during periods of low atmospheric ventilation, when ground-level particulate levels reach their maximum (Landis et al. 2018).

Prescribed fire prescriptions and fire effects

Fire intensity metrics related to heat input and critical temperature-mortality thresholds of plant tissue such as height of lethal crown scorch are often utilized for predicting the ecological effects of mixed-severity fire (Hood and Lutes, 2017), while crown fraction burned is important to interpreting the extent of canopy impact in high intensity fire. Predicting the ecological outcomes of both low and high intensity fire is an important component of prescribed burn planning, as tree mortality may be a desired or undesired outcome depending on management objectives. Specific heat transfer (dose) models for plant tissue and the resulting response or tree mortality models (e.g., Ryan and Reinhardt, 1988) are not in scope for the CFFDRS-2025. The improved representation of surface fire, flaming temperature and residence time, as well as smouldering, and of crown fraction burned in variable stand structures will provide enriched inputs for physics-based fire effects models.

Although the applications mentioned are above and beyond the scope of the CFFDRS, they are strongly dependent on it, much like software applications are linked to a computer operating system. In as much as the CFFDRS is not a system unto itself but part of a larger fire modelling ecosystem, the NG-CFFDRS research program will include cooperating in the development of such systems with Canadian fire agencies to provide ongoing consistent guidance on the use of CFFDRS elements in fire management applications, as well as to be responsive to the need to develop additional CFFDRS elements that may be required for particular applications.

9.0 Next Steps

An effective national danger rating system includes four key elements (Taylor and Alexander 2006): a modular system of fire danger models appropriate to the fire environment, a technical infrastructure to gather data and display outputs, training and interpretive guidance, and ongoing collaboration among researchers and fire managers (Box 6). This document outlines the components needed for CFFDRS-2025, the foundational element of fire danger rating in Canada. The goal of the NG-CFFDRS research program is to complete development and integration of the new components of each sub-system by 2024 and to complete documentation of the state of the System as a whole by 2025. Several steps will be needed to complete and implement CFFDRS-2025, with scientific, technical and human dimensions (Box 6).

Reanalysis and Adaptation

Some new prospective models required to increase the CFFDRS functionality have been developed and are being tested (e.g., Cruz et al. 2005, Wotton 2009a, de Groot et al. 2009) while others are currently under development and nearing completion, in part based on reanalysis of existing data. Existing fire science from other jurisdictions will be evaluated and included in cases where it is compatible and fills key gaps in the System (e.g., Cheney et al. 1998; Anderson et al. 2015).

Box 6. Four key elements of a national Fire Danger Rating System

A modular system of fire danger indicators or models of fire occurrence and behaviour in important fire environments developed through a sustained program of scientific research and based on relationships between fire weather, fuels, topography, and ignition sources.

A reliable technical infrastructure to gather, process, disseminate, and archive fire weather data and forecasts (weather instruments/stations, standards, communication) and fire danger predictions (text and map displays) within operational agencies.

Guidelines, decision aids, and training for fire managers in the application of fire danger indicators appropriate to the needs and capabilities of operational agencies based on research and operational experience.

Cooperation between fire management agencies and with research agencies to foster communication, to share resources, and to set common standards for information, resources, and training (policies, cost-sharing agreements, national training courses, working groups).

Field Experiments and Data Acquisition

Reanalysis of existing data is insufficient for the new models under development. Some critical components will require extensive field and analytical research programs. Examples of ongoing data collection needs include: testing the effect of varying stand structure on the fire environment and fire behaviour, observing firebrand generation rates across a variety of forest ecosystems, characterizing the physical attributes of non-traditional stand types, and developing and validating new fuel moisture estimation methods for non-traditional fuel types. An ongoing commitment to wildfire and experimental data collection alongside innovations in measurement techniques is critical to gather information on the full range of the fire environment in Canada.

Model Validation

The CFFDRS is a large and complicated set of models developed at different times by a large research group. Considerable effort will be spent testing the System overall; specifically, how output from models interact with other parts of the System. Early adopters will be engaged in this testing phase to ensure that the whole System forms an integrated, physically logical and rational framework. This job of testing (and improving) models is never complete however and will continue to rely heavily on the users of the System to provide feedback on what needs improvement or clarification in the System overall. Quality documentation of real-world fire behaviour by experienced personnel can provide observations of unusual or extreme fire behaviour, can help provide validation data, or can enhance understanding to produce more realistic and reliable outputs.

Knowledge Exchange

The operational implementation and use of the CFFDRS involves more than just incorporating science into information applications; an understanding of the System and its limitations by users is critical. We also recognize the need to develop effective knowledge exchange and technology transfer to update existing fire management training material. Significant changes to the CFFDRS have far reaching impacts within organizations and that practical knowledge transfer and user uptake is a critical element of the successful implementation of CFFDRS-2025.

Collaboration

Ongoing and sustained collaboration with fire management agencies is crucial to NG-CFFDRS development and implementation in a number of areas. (1) Design: While this overview outlines a vision of the elements and structure for a NG-CFFDRS, knowledge exchange goes both ways and agencies will be engaged to provide feedback and refine system design. (2) Field data collection: Field experiments such as experimental burning projects can only be carried out with the support and close collaboration of management agencies. (3) Validation: Wildfire observations and model validation. 4) Implementation: Fire management agencies in Canada have a key role in developing the infrastructure to gather weather and fuels data, and in implementing CFFDRS in management. The success of the CFFDRS in the past hinged on the close collaboration between fire science and management; the success of CFFDRS-2025 will require that this collaborative relationship continues.

The development of methods to assess broadly defined elements of fire danger has been ongoing in Canada for 90 years. The NG-CFFDRS development program described here represents the next evolution of that system but it is not an end point. Furthermore, what is described here is a vision for what we hope to complete, document and be ready to begin implementing with fire management agencies by 2025. It is a large program of modifications with some risky field-based elements. We anticipate having to prioritize what gets done in this period and what ultimately constitutes this next generation of the CFFDRS. Research, in particular the collection of observations of fire behaviour in the field (be it in experimental fires or wildfires), will continue and be incorporated into newer models and technology transfer programs and ultimately further generations of the CFFDRS. The System and its capabilities must continue to be improved as fire, resource and emergency management needs change.

10.0 Acknowledgments

Discussions of changes needed to the CFFDRS have been ongoing in Canada for more than a decade. Because the CFFDRS is, by design, a modular system, development of some of the elements of the NG-CFFDRS has been ongoing over the past decade or more as well. A great deal of the structure and content described in this document owes itself to the work of and extensive discussions with fire scientists (both working and retired) and fire managers over the past decades.

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12.0 Appendices

Appendix A. Fuel types and attributes

Table A-1. Summary of existing FBP System fuel types and modelling attributes. SFC: Surface Fuel Consumption; LCBH: Live Crown Base Height; CFL: Canopy Fuel Load; PC: Percentage of conifer in mixedwood overstory; PDF: Percentage of dead balsam fir in mixedwood overstory (assuming remaining overstory is deciduous); % Cur: Percentage curing of grass fuels; GFL: Grass Fuel Load (kg m^{-2}). * indicates the valid range of user-defined variables in the existing FBP System.

Fuel Type	**Input Modifier(s)**	**Max SFC (kg m^{-2})**	**LCBH (m)**	**CFL (kg m^{-2})**
C-1 Spruce-Lichen Woodland	--	1.5	2.0	0.75
C-2 Boreal Spruce	--	5.0	3.0	0.8
C-3 Mature Jack or Lodgepole Pine	--	5.0	8.0	1.15
C-4 Immature Jack or Lodgepole Pine	--	5.0	4.0	1.2
C-5 Red and White Pine	--	5.0	18.0	1.2
C-6 Conifer Plantation	LCBH	5.0	0.1-15.0*	1.8
C-7 Ponderosa Pine - Douglas-fir	--	3.5	10.0	0.5
D-1 Leafless Aspen	--	1.5	--	--
D-2 Green Aspen	--	1.5	--	--
M-1 Boreal Mixedwood-Leafless	PC	5.0	6.0	0.8
M-2 Boreal Mixedwood-Green	PC	5.0	6.0	0.8
M-3 Dead Balsam Fir Mixedwood-Leafless	PDF	5.0	6.0	0.8
M-4 Dead Balsam Fir Mixedwood-Green	PDF	5.0	6.0	0.8
S-1 Jack or Lodgepole Pine Slash	--	8.0	--	--
S-2 Spruce-Balsam Slash	--	16.0	--	--
S-3 Coastal Cedar-Hemlock- Douglas-fir Slash	--	32.0	--	--
O-1a Matted Grass	% Cur, GFL	0.1-2.0*	--	--
O-1b Standing Grass	% Cur, GFL	0.1-2.0*	--	--

Table A-2. Summary of fuel attributes required for CFFDRS-2025 by vertical stratum, including description, units, and general use in CFFDRS-2025 is indicated (FMS: Fuel Moisture System; FBP: Fire Behaviour Prediction System). Italicized terms represent additional attributes needed beyond the minimum).

Stratum	**Fuel attribute**	**Description**	**Units**	**Use in CFFDRS-2025**
Canopy fuels (or overstory fuels)	Stand average canopy closure (CC)	It is the proportion of the sky hemisphere obscured by vegetation when viewed from a single point within the stand (Jennings et al. 1999).	%	FMS: solar radiation adjustment to fuel moisture FBP: Modelling and mapping surface vegetation (fuel)
	Stand average *(& std. dev.)* overstory trees diameter at breast height	It is the stand mean diameter of overstory trees (i.e., trees with diameter ≥ 3 cm; Alexander et al. 2004).	cm	FBP: Modelling and mapping Canopy Bulk Density (CBD)
	Stand density	It is the stand density of overstory trees (diameter ≥ 3 cm), expressed at the hectare scale.	stems ha^{-1}	FBP: Modelling and mapping Canopy Bulk Density (CBD)
	Stand average *(& std. dev.)* overstory height	It is the stand average height of dominant and codominant trees of the overstory.	m	FBP/FMS: In-stand wind model FBP: Modelling and mapping Canopy Bulk Density (CBD) FBP: Crown fuel consumption model
	Proportion of deciduous species in the stand (PD)	It is the stand level proportion of basal area of deciduous (or hardwood) tree species in the overstory.	%	FBP/FMS: In-stand wind model FBP: Crown fire behaviour in mixedwood FMS: solar radiation and surface fuel moisture adjustment
	Proportion of coniferous species in the stand per genus (PC)	It is the stand level proportion of basal area of coniferous tree species per genus in the overstory.	%	FBP: In-stand wind model FBP: Crown fire behaviour in mixedwood FMS: litter moisture
	Condition of conifer trees	Stand level percentage of coniferous trees per health condition (e.g., live, red or grey state, dead).	%	FBP/FMS: In-stand wind model FBP: Crown fire behaviour FBP: Crown fire consumption FMS: surface fuel moisture

Stratum	Fuel attribute	Description	Units	Use in CFFDRS-2025
Canopy fuels (or overstory fuels)	Stand canopy bulk density (CBD)	Stand average weight of live (branches < 1cm) canopy biomass.	kg m^{-3}	FBP: Directly in crown fire spread and consumption models
	Canopy Fuel Load (CFL)	Total Fuel Load (branchwood <1 cm and foliage) of conifers	kg m^{-2}	FBP: Crown fire intensity FMS/FBP: In-stand wind,surface fuel moisture modification
Ladder fuels	Stand effective crown base height (eCBH)	Stand average *(& std. dev.)* distance between the to of the understory vegetation and the lowest live branch of the overstory crowns	m	FBP: Directly in crown initiation and crown models
	Understory trees diameter	Trees with diameter < 3 cm and height over 1.3 m	cm	FBP: in-stand wind FBP: eCBH estimation
Ground and surface fuels	Forest floor cover type	Stand average forest floor cover, at least dominant type, *or per type* (i.e., needle, leaf, mixed (leaf/needle/annuals), lichen, grass, moss, etc.)	%	FMS: litter moisture adjustment FBP: Sustained flaming model FBP: Surface fire spread models
	Litter load	Stand average *(& std. dev.)* weight of ground litter	kg m^{-2}	FBP: Fuel consumption models
	Downed woody debris load	By size categories, <1cm, 1-7cm, and >7cm	kg m^{-2}	FBP: Fuel consumption models
	Organic layer depth	Stand average *(& std. dev.)* depth of the ground organic layer. *Separately for F-layer and H-layer.*	cm	FBP: Forest floor consumption models
	Organic layer fuel load	Stand average *(& std. dev.)* weight of the organic layer. *Separately for F-layer and H-layer.*	kg m^{-2}	FBP: Forest floor consumption models

Appendix B. Glossary of new terms and concepts

Burn Day Length—the number of hours within a daily fire cycle (starting and ending approximately at sunrise) in which the weather conditions (primarily relative humidity and fuel moisture) support significant fire activity. Note the burn day length may in some cases include the hours after midnight into the early morning hours.

Canopy Bulk Density—the amount of fuel present in the canopy (above the Live Crown Base Height) per unit volume. The mathematical result of dividing the Canopy Fuel Load by the difference of the stand height and Live Crown Base Height. Preferred unit is kilograms of dry fuel per cubic metre.

Dual-equilibrium rate of spread model—a method of predicting spread rate that uses independent spread rate models for a surface fire and a crown fire in the fuel complex. These spread rate models are coupled through a separate set of crown initiation models.

Effective Crown Base Height (eCBH)—height of the gap between surface vegetation (including shrub and small understory trees) and the lowest live overstory conifer branches. This value is always equal to or less than the Live Crown Base Height.

Elevated Fine Fuel Moisture Code—a code representing the fuel moisture content of fine fuels elevated above the forest floor, such as fine dead branchwood in the canopy, standing grass, or elevated lichens. These fuels dry much faster than FFMC fuels (e.g., needle litter on the forest floor) with a moisture content similarly dependent on temperature, humidity, in-stand wind speed.

Flaming Residence Time—the duration of continuous flaming at a given point during the passage of a fire front. The term is used to describe flaming duration in both canopy and surface fuels independently.

Fuel Complex—a specific combination, or arrangement, of fuel structural attributes. For example: 8 m tall pure black spruce high canopy closure and feathermoss surface fuels is a distinct fuel complex from 4 m tall pure black spruce with moderate canopy closure and a mixed needle and leaf surface fuel type.

Fuel Moisture System—a formal collection of the models used in the CFFDRS to predict fuel moisture content (%) at an hourly scale that allows the user to adjust for the effects of stand structure (e.g., canopy closure), forest floor type, and solar radiation at the forest floor. Also includes models to predict live fuel moisture (i.e., deciduous green-up and grass curing) seasonally.

Grass Fire Weather Index—an index of predicted grass head fire intensity that incorporates curing state and a fixed fuel load.

Grass Initial Spread Index—an index of the predicted grass fire forward rate of spread. GISI values are proportional to rate of spread, so a doubling of the GISI corresponds to a doubling in rate of spread. Curing of grass is a required input.

Grass Moisture Code—a moisture code for matted grass conceptually similar to the Fine Fuel Moisture Code, but also includes the effect of solar radiation. The Grass Moisture Code represents the faster drying rates observed in matted grass as compared to the FFMC. For standing grass, the Elevated Fine Fuel Moisture Code is used.

Ignition Probability—the likelihood of a single firebrand achieving sustained flaming given a combination of surface fuel type, surface fuel moisture content, and in-stand wind.

In-stand wind—the horizontal wind speed near the forest floor. Represents the wind available to surface fires, and is required for modelling surface fire rate of spread in the NEW FBP. Is dependent on the Canopy Fuel Load and conifer percentage of the overstory.

Live Crown Base Height (LCBH)—height from the ground surface to the lowest live overstory conifer branches branch of conifer trees. Always greater than or equal to the effective Crown Base Height. Specifically does not account for shrubs or understory trees.

Overnight Recovery Index—an index of the relative overnight fire spread potential based on hourly weather, relative to peak burning conditions from the afternoon prior.

Peat Moisture Code—a component of the Fuel Moisture System that is currently in development, but will indicate whether peatlands (also known as muskeg) are sufficiently dry to carry fire at rates similar to well-drained (non-peatland) adjacent forest fuels.

Phenology—the seasonal (days to months) patterns of vegetation growth. Can be a long-term average pattern for a location, or else a model that varies year to year. Applies to grass curing models, but also spring dip and deciduous leaf-out models.

Solar radiation—the amount of solar heating and drying of surface fuels above and beyond the drying of fuels that occurs due to low humidity. This additional drying varies both by canopy openness as well as slope and aspect.

Sustained Flaming—the ability of a flaming ignition established in surface fuels to continue to propagate through the fuel complex via flaming combustion under the current fire environment conditions.

Appendix C. List of acronyms

AFMS—Accessory Fuel Moisture System

BUI—Buildup Index

CFFDRS—Canadian Forest Fire Danger Rating System

CFS—Canadian Forest Service

DC—Drought Code

DMC—Duff Moisture Code

ECBH—effective Crown Base Height

FBP—Fire Behaviour Prediction system

FFMC—Fine Fuel Moisture Code

FMS—Fuel Moisture System

FOP—Fire Occurrence Prediction system

FWI—Fire Weather Index system

GFWI—Grass Fire Weather Index

GISI—Grass Initial Spread Index

GMC—Grass Moisture Code

ISI—Initial Spread Index

PMC—Peat Moisture Code

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