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An Approach for Defining Physically Based Fire Weather Index System Classes for Ontario

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An Approach for Defining Physically Based Fire Weather Index System Classes for Ontario.

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ABSTRACT

The Fire Weather Index (FWI) System codes and indices are commonly communicated and interpreted using a classification system (i.e., Low, Moderate, High, Extreme) by fire management agencies. Adjective classes were developed provincially shortly after the FWI System was introduced nationally in 1969. Class ranges were determined using a climatological frequency analysis, the basis of which was that on 2% of fire season days the FWI values should fall within the Extreme class, and Very Low represented days with FWI values of 0. Since then, these classes have become highly integrated into fire management and are, for example, commonly used for public awareness and education, high level operational preparedness, daily briefings, training curriculum and numerous mapping products. There has been little to no change in class ranges since their inception. Recently the Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry (NDMNRF) expressed an interest in revising their class definitions, which is well timed with proposed changes to the FWI System as part of the next generation Canadian Forest Fire Danger Rating System initiatives (CFS Fire Danger Group 2021). This information report presents an approach to updating the FWI System adjective classes using a single physically defined association (e.g., rate of spread or depth of burn). Physically meaningful thresholds were then chosen based on a reanalysis of Canadian Forest Service experimental fire behavior datasets, small scale test fire ignition studies and a selection of relevant information reports and papers. The newly proposed FWI System classes were then compared to the existing classes using an updated frequency of occurrence analysis with weather station and fire data from Ontario for 1990-2018. The resultant analysis illustrated that even if NDMNRF were to retain the existing classification, modifications would still be warranted as the values no longer reflect the original frequency of occurrence expectations. The new methodology, applied to Ontario, is not intended as a prescription for any particular group of users. It is intended to associate a single physically meaningful process to each code and index such that the classes should have more interpretive power and are better linked to the processes they were intended to describe. We hope this methodology and report will encourage further discussion with other provinces on how these methods could be refined and expanded nationally.

1.0 Introduction

The Fire Weather Index (FWI) System, introduced in Canada in 1969, was developed to provide estimates of daily potential fire danger based on weather observations taken each day at 12:00 pm local standard time (Van Wagner 1987). These observations of temperature, relative humidity (both at 1.5 m height in a sheltered location), wind speed (at 10 m height in a forest clearing), and 24-hr accumulated precipitation are used to calculate three moisture codes which represent the moisture content of forest floor fuel layers. Each code is important to different aspects of fire activity in typical boreal forest fuel types: litter and other cured fine fuels (Fine Fuel Moisture Code, FFMC), loosely compacted shallow organic matter of moderate depth (Duff Moisture Code, DMC) and deep, compact organic layers (Drought Code, DC). These unitless codes represent the relative moisture content of specified layers for a standard pine forest (i.e., C-3) and have been mathematically transformed such that an increase in value represents a decrease in moisture (Van Wagner 1987). The moisture codes are used to calculate three relative indicators of fire behaviour, which follow a similar format (i.e., higher values indicate higher fire potential). The FFMC and observed wind are combined to calculate the intermediate index that represents potential rate of fire spread (Initial Spread Index, ISI). The DMC and a scaled value of the DC are combined by calculating their harmonic mean to represent a second intermediate index of total available fuel (Buildup Index, BUI). Lastly, the ISI and BUI are combined, following an approach similar to Byram (1959) to provide a unitless indicator of fireline intensity. This final index of the system, FWI, is scaled to increase similarly with flame length.

The FWI is the output most commonly used to communicate “Fire Danger” to the public. In many operational uses the numerical outputs from the FWI System are communicated and often interpreted using classes that are labeled with simple but informative adjectives (i.e., Low, Moderate, High, Extreme) (Van Wagner 1987); these adjective ratings are often called “fire danger classes”. Although the codes and indices were developed to be numeric indicators of different aspects of potential fire behavior, the ranges used for the adjective “danger classes” were determined based on frequency distribution analyses of provincial weather shortly after the FWI System introduction in 1969 (e.g., Stocks 1971, Turner 1970 and Kiil et al. 1977); there has been little change in these ranges since.

Initial discussions on re-evaluating the approach to determining the ranges associated with these adjective ratings for each FWI System output began after fire management personnel from the Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry (NDMNRF) expressed a desire to revisit their long-standing fire danger class definitions. In addition, as part of its ongoing development of a next generation of the Canadian Forest Fire Danger Rating System (CFFDRS) (CFS Fire Danger Group 2021), the Canadian Forest Service (CFS) is making some changes to the FWI System calculations. While modifications to the FWI System are being planned to reproduce the general existing range in observed outputs, some differences in the frequency of occurrence of different codes or index values may result. As part of these modifications, the CFS is therefore interested in methods to determine these adjective ratings, with the aim of developing a strong physical basis to new guidance for establishing FWI System output classifications.

There are now many decades more of historical weather and fire activity information for analysis than was available when the adjective rating ranges for Ontario were first devised. Given Ontario's interest in re-examining their current classes with this historical data, the objective of this work was to summarize recent decades of historical data using the current NDMNRF adjective rating definitions for each FWI System output and to approach defining the FWI System adjective rating classes using more physically based criteria. In developing these new definitions each FWI System code or index was associated with one physically defined process (e.g., sustainability of ignition or fire intensity) and physically meaningful thresholds were selected to define each of the class ranges. Similar to the analysis that led to the original adjective rating class definitions, the daily FWI System outputs were summarized by the frequency of occurrence of these new classes. A broader goal was to use Ontario as an initial test case to explore the impact of this revised methodology for adjective rating class definition and thereby constitute a starting point to defining new guidance for fire danger adjective rating classification that could be used nationally.

1.1 Background – Current FWI Class Definitions

Fire danger is often used to refer to the potential ignition, spread, difficulty of control and impact of a wildfire (e.g., Stocks et al. 1989; CIFFC Glossary[1]). Communicating the complete picture of fire danger is not possible with a single number or FWI System indicator. Instead, each output of the FWI System describes specific information about certain aspects of wildland fire potential (Stocks et al. 1989). To simplify use and interpretation, it is customary in fire danger rating to provide descriptive or adjective classes (e.g., Low, Moderate, High, Extreme) for individual indicators; this is especially true for communication of the FWI to the general public. However, the commonly used term "fire danger class" can be, strictly speaking, somewhat misleading given that no single FWI System output captures all those elements of fire danger as formally defined (i.e., ignition, spread, control and impact) without other contextual information (e.g., ignition sources, proximity to values). It is important to note that the NDMNRF does not uniformly use the term fire danger when communicating FWI values, and more often uses "hazard". We therefore drop the term "danger" or "hazard" to describe the classes using adjective descriptions and the class ranges that differentiate one class from another.

In Ontario, the current FWI System adjective rating class labels (i.e., Low, Moderate, High, Extreme) and the numeric ranges defined for each, are based on work by Stocks (1971 and 1974). Similar work was conducted in different jurisdictions across the country to associate similar class labels to the FWI System outputs; however, there are some differences in the number of classes in different regions (e.g., Turner 1970 for BC, Kiil et al. 1977 for Alberta). A quasi-benchmarking approach was used to determine the five original categories for FWI System codes and indices (Stocks 1971). The calibration in Ontario started with a climatological analysis of the frequency of occurrence of each FWI class using records from 85 weather stations from across the province for a six-year period (1963-1968). These original classes ranged from Very Low to Extreme and were based on the FWI output (Table 1). The assumption was made that 2% of days in the fire season should fall within the Extreme class and that Very Low represented days with FWI values of 0. With those constraints in mind, the class breakdown emerged based solely on climatology. Stocks (1971) then validated the new classes against fire

[1] https://www.ciffc.ca/glossary

records for the same time period, which included 3,159 fires; this analysis of the fire record excluded grass fires.

Table 1. FWI range for each class, percentage of days each class occurred, the percentage of fires occurring on days in each class and relative fire occurrence used to develop the classes for Ontario (as summarized and presented in Stocks 1971). Relative fire occurrence is the ratio of the percentage of fires to percentage of days in a particular FWI class.

Class	FWI range	Percent Occurrence	Cumulative Frequency	Percent Fire Frequency	Relative Fire Occurrence
Extreme	23+	2	100	13	6.5
High	11-22	14	98	31	2.2
Moderate	4-10	27	84	29	1.1
Low	1-3	29	57	19	0.7
Very Low	0	28	28	8	0.3

This work was expanded by Stocks (1974) to include more data over an overlapping seven-year period in different regions of the province using the same FWI break down as Stocks (1971). The subsequent analysis defined ranges for each of the six FWI System outputs and included 7,799 fires, excluding spring and fall fires when weather stations were not running. Although the analysis found some differences between regions, a single provincial class system was thought to be a reasonable simplification given that across all regions there was a general trend of increased fire occurrence with a rise in FWI class. The study used the same frequency of occurrence summary shown in Table 1 for the remaining five FWI System codes and indices. The resulting ranges for the FWI System classes were adopted by Ontario and are the basis of the current FWI System classes (Table 2). The only difference is the Very Low and Low classes have been combined to create a single Low class resulting in the four adjective rating classes currently used. The current classifications are used in numerous operational procedures and are also the basis for symbolizing, colour coding and mapping the FWI System components in various tabular or graphical uses (e.g., briefing maps) across fire management operations in Ontario.

Table 2. Current class ranges for each of the codes and indices of the FWI System in use by Ontario.

Class	FFMC	DMC	DC	ISI	BUI	FWI
Low	0-80	0-15	0-140	0-2.2	0-20	0-3
Moderate	81-86	16-30	141-240	2.3-5.0	21-36	4-10
High	87-90	31-50	241-340	5.1-10.0	37-60	11-22
Extreme	91+	51+	340+	10.0+	61+	23+

1.2 Interpretation and Critical Values for Fire Management in Ontario

Ultimately it is not the absolute values from the FWI System that are important, but the resulting fire behaviour on any particular day. Over the years, Ontario fire management has developed numerous interpretive descriptions and critical fire behaviour values that are associated with FWI System outputs (Table 3); these "critical" values typically represent significant changes in expected fire behaviour. These were adopted from anecdotal general rules used in everyday decision-making as well as from various reports published as interpretive guidelines, primarily for prescribed burning (e.g., de Groot 1987, Muraro 1975). In addition to those critical values used in Ontario, other critical values used around the country include: DMC >40 for crown fire development in some coniferous fuels; Initial Spread Index (ISI) >10 has been used as a rule for indicating very high Rates of Spread (ROS) as taught in the Advanced Fire Behaviour Course (CIFFC 2015). Based on these established interpretations and discussions with operational personnel, one can summarize the following primary uses of the outputs of FWI System operationally.

The FFMC is commonly associated with ignition, surface fire spread and spotting potential. DMC is used to determine the potential for lightning fire ignition as well as a potential indicator of depth of burn. DC is used to indicate depth of burn, holdover potential and difficulty of suppression including mop-up. Critical ISI values are associated with the type of fire (e.g., surface, crown) that may occur as well as with expected spread rates. BUI is an indicator of fuel consumption of heavier fuels in and on the forest floor, and hence the potential for increased fire intensity. Lastly, FWI is used as the general fire danger indicator, particularly for communication with the public, and is used as an indicator of potential fire intensity and problem fire occurrence.

Table 3. Current interpretive descriptions and critical values (**bold**) for each of the codes and indices of the FWI System currently in use by Ontario. These are taken from various NDMNRF fire behaviour quick reference cards (unpublished). This is not meant as a complete list; there are more interpretations within various training courses such as the S200 Crew Boss course.

Code / Index	Value	Interpretative descriptions	Adjective class
FFMC	<74	Little chance of ignition	Low
	75	Some surface fire spread especially in open grass	Mod
	80	Continuous fire spread	High
	89	**Critical value – spot fires ignite readily**	High
	90	High probability of spot fires	High
DMC	<15	Low probability of lightning ignition	Low
	25	**Critical value – Fuels receptive to lightning starts**	Mod
	<30	Moderate probability of lightning fires in shallow soils	High
	50	High probability of lightning ignition; Medium fuels are available for combustion	Ext
DC	250	Expect some deep burning extending mop-up	High
	300	**Critical value – High risk of restarts and holdovers; Fires are persistent**	High
	>300	Fires are persistent, increased holdovers	High
	500	Significant subsurface fire activity, heavy fuels are available for combustion = high intensity fires likely	Ext
ISI	<7	Primarily surface fire	High
	8-15	Intermittent crown fire activity	High- Ext
	12	**Critical value – High rates of spread likely**	Ext
	>15	High probability of crown fire	Ext
BUI	20	Minimum value for fall broadcast burning	Mod
	80	**Critical value – Potential fire behaviour problems in medium and heavy fuels**	Ext
FWI	<3	Creeping surface fire activity	Low
	4-10	Low to moderate surface fire activity	Mod
	11-22	Torching, intermittent crown fire	High
	23	**Critical value - >23 active crown fire activity**	Ext
	≥33	“Blow up” conditions	Ext

2.0 Methods

2.1. Definition of Physical Relationships

The goal of this study was to provide each of the six FWI System codes and indices unique classifications based on specific observable, easily interpretable, fire behaviour characteristics rather than simply reflecting the regional climatology and frequency of occurrence of each code or index. Box 1 summarizes the primary process to be associated with each FWI System output and the source of data or models that were used to determine the important limits. These factors were selected based on both long existing relationships within the CFFDRS (Stocks et al. 1989, Forestry Canada Fire Danger Group 1992, Wotton 2009) and more recently established relationships (Wotton and Martell 2005, Beverly and Wotton 2007, de Groot et al. 2009, Hirsch and Martell 1996) in addition to critical values and general rules developed by the agencies (e.g., Table 3).

Box 1

Primary Physical Relationships Used to Define FWI Classes

FFMC –sustained flaming fire ignition based on recent reanalysis of the CFS test fire database (dataset described by Paul 1969, Beverly and Wotton 2007)

DMC – lightning ignition potential based on lightning strike and fire data analyzed by Wotton and Martell (2005)

DC – depth of burn data using data from de Groot et al. (2009) and the extended FBP System database

ISI – rate of spread derived from FBP relationships (Forestry Canada Fire Danger Group 1992)

BUI – amount of fuel available for consumption derived from FBP System database (Forestry Canada Fire Danger Group 1992)

FWI – potential frontal fire intensity (derived from FBP database, Forestry Canada fire Danger Group 1992) and its relationships that are operationally used in Canada to link intensity to limits of direct attack (as summarized in Hirsch and Martell 1996)

The FWI System was developed to be representative of conditions within a mature closed-canopy pine forest (Van Wagner 1987); this will remain the standard fuel type in proposed updates to the System (CFS Fire Danger Group 2021). Therefore, where possible, data and models were chosen to be consistent with this forest type (i.e., the C-3 fuel type in the FBP System or pine needle litter). Data and models used to develop the limits of the adjective rating class ranges, with the exception of the DMC relationship with Ontario's lightning data, are based on available data from across the country and broadly applicable models which to a large extent come from experimental burning carried out in the development of the FBP System (Forestry Canada Fire Danger Group 1992). The proposed limits associated with the classes for most codes and indices required some judgement, unless there was a published relationship with direct interpretation (e.g., Hirsch and Martell (1996) for FWI and head fire intensity for C-3).

Some general guidelines were followed when making these judgements. First, an attempt was made to maintain simplicity and use easy-to-remember whole numbers. Second, if either limit of the new class ranges differed only slightly from what is currently used, it was not changed unless the original limit was inconsistent with the interpretation of the physical threshold within the new methodology. Lastly, one set of classes was created for the entire province (e.g., no stratification of different areas for classes); the historical data analysis allows comparison of different areas in the province using this approach. In future analysis, where enough data exists, the thresholds in the physical process being tracked (e.g., fire ignition) could be used to define different class boundaries in regions where there are some well-established differences in forest fuel conditions (or other factors). The operational value of area specific thresholds would need careful consideration (e.g., use of administrational fire regions; eco-regions).

FFMC, adjective class divisions were based on the potential for a sustainable flaming ignition. These models were developed from data collected during the CFS's Small Scale Test Fire Program (Paul 1969), which began in the 1930s, and formed much of the early foundation of the hazard rating assessment systems that evolved into the FWI System. Recent analysis of a portion of this dataset has been described in Beverly and Wotton (2007); the models used here are based on a more recent, as yet unpublished, re-analysis of this dataset for the next generation of the CFFDRS (CFS Fire Danger Group 2021). For this project, a model of the probability of sustained flaming for pine needle litter in a moderately dense pine stand was used.

DMC class divisions were related to the potential for lightning to lead to ignition. The range limits for each adjective class and the interpretations of the general meaning of each class are taken from an analysis of the empirical probability of lightning fire ignition per lightning strike across Ontario, which was an initial part of the work documented by Wotton and Martel (2005). Updated versions of the probability of holdover ignition and fire arrival models developed in that study are used in the lightning fire occurrence modelling system currently used by the province. In this analysis, which relied upon fire, weather and lightning strike data only, the difference in the probability of ignition relationship between the Northwest (NW) and Northeast (NE) response regions was explored given that there are some differences in the regional interpretation of the limits that define the low end of lightning fire ignition potential. The lightning strike data and hence the empirical probability estimates shown are summarized using lightning flash information. A lightning flash is a discharge that is made up of anywhere from one to several strokes; the number of strokes in a flash is often summarized as the multiplicity of the strike.

Adjective rating class divisions for the **DC were based on expected depth of burning,** which acts as a surrogate for the suppression challenges potentially present in the mop-up phase of a fire**.** Analysis documented by de Groot et al. (2009) assembled the FBP System experimental burn dataset and measurements collected from a number of wildfires in seven different fuel types. De Groot's analysis and modelling focused on the relationship between forest floor consumption and DC, but for setting class ranges that were easy to visualize and interpret, depth of burn seemed more appropriate for this current work. There was not sufficient data on depth of burn in the C-3 fuel type (which can be quite variable); thus, all FBP System fuel types were used.

ISI class divisions were related to Rate of Spread (ROS) and characterized important transitions in overall fire behaviour (i.e., surface fire through to active crowning)**.** This interpretation used the FBP System spread rate model for mature pine (C-3), to be consistent with the FWI System's use of the standard pine forest type; however, clearly the FBP System can be used to more precisely predict expected fire behaviour when the specific local fuel type is known. Analysis also included the original observations from experimental and wildfire burns used to create the C-3 model (Forestry Canada Fire Danger Group 1992).

The intended use of the **BUI was to represent the amount of fuel available for combustion** by a moving flame front and thereby the contribution of that fuel consumption to surface fire intensity. The FBP System's Surface Fuel Consumption (SFC) output for the C-3/C-4 fuel type was chosen as a good physical indicator to inform divisions between adjective classes. While BUI is mathematically a combination of moisture indicators (DMC and DC), it is most commonly used as an indication of the extent of duff and woody debris consumption. The observed SFC values used to develop models in the FBP System were taken from experimental fires in C-3 and C-4.

The **FWI is a numerical rating of the potential frontal fire intensity**, though the increase scales similarly to how flame length increases with intensity (roughly like the square root of intensity). Having an intensity-based indicator is useful for indicating expected fire type (e.g., surface, torching, crowning) and hence providing information about potential fire suppression resource effectiveness and productivity (Hirsch and Martell 1996; Hirsch et al. 2004). Therefore, new class divisions for the FWI were based directly on the FBP System output for Head Fire intensity (HFI) in the C-3 fuel type and the limits of suppression resource effectiveness (in C-3) summarized by Hirsch and Martell (1996). Additional details are provided below for each code and index.

The adjective ratings used and number of corresponding classes follow the current ones used by NDMNRF (four classes: Low, Moderate, High and Extreme). The colour scheme chosen for these classes is slightly different from the one currently in use by NDMNRF. Green has been removed to help address interpretability for those with colour vision deficiency (Nunez et al. 2018). Low is represented by blue, Moderate by yellow, orange for High and red for Extreme.

2.2 Ontario Fire Weather and Wildfire Database

Historical NDMNRF weather station data from 1990 to 2019 were compiled to compare the frequency of occurrence between the old adjective FWI System classes (Stocks 1971 and 1974) and the new. Stations were selected for inclusion in the analysis when daily weather was reported for at least one hundred days during the fire season over a minimum of 20 years. This did provide decent coverage of the province, but there are unrepresented areas (i.e., the Hudson Bay lowlands) due to station limitations (Figure 1). Weather station and historical fire point data were combined in a GIS to find a spatial distribution of stations that provided a reasonable sampling from across the province, so that the statistical summaries produced could be considered representative of the area under fire management in Ontario and thereby reduce the impact of individual stations. Over the decades, many weather stations were repositioned and renamed for various operational reasons. To improve the spatial distribution of our subset of weather stations across the province, weather stations that were close to each other, but which each had fewer than 20 years of data, were combined and their location averaged. In total, 90 stations were selected and combined to include 75 station points across the province. To analyze fire activity, fires from the historical archive were associated with weather stations using 50 km radius buffers (Figure 1). Some station buffers overlapped, and fires within both buffers were matched to both stations; however, the relative assessment of fire occurrence used in this analysis should not be impacted by this overlap. Daily FWI System outputs were classified into adjective rating classes using either the existing classification system (Table 2) or the newly defined classes (Table 4), thereby creating two main datasets of adjective ratings across the province for the study period; summaries of both the current classification system and the newly proposed classification ranges are presented for each of the FWI System outputs in section 3.0.

In comparing the existing and proposed adjective rating classes, the datasets were summarized both provincially and between three geographic study areas. These areas generally correspond to the Northeast and Northwest fire regions of Ontario, except for a set of northern stations that generally would have corresponded to the old Northern Boreal and Hudson Bay Zones in the 2004-2014 NDMNRF Fire Strategy. These far north stations we are calling the Northern (NO) study area, and the remainder the Northwestern (NW) and Northeastern (NE) study areas (Figure 1). At each station, the frequency of daily occurrence of each adjective rating class was estimated by totaling the number of days a particular class occurred at a station during the fire season and dividing by the overall number of days reporting for the station (Table 1). The number of fires occurring within the 50 km station buffer under each class (determined by the FWI System outputs on the estimated start date) was also totaled and divided by the total number of fires occurring overall in the station buffer. The area burned by fires (in each station buffer) was also associated with the FWI System output adjective rating class on the start date of the fire and summarized over the study period; this gave an estimate of the percentage of area burned by fires at that station point for each adjective rating class. Area burned is an imperfect metric for drawing inferences about wildfire activity because of the outsized impact of very rare large events; it is also problematic in this study where we are only examining the fire danger indices on the first day of the fire. We include it as it is a commonly discussed metric of fire activity; however one should not draw any inferences about it, however strongly implied. The FWI System values can change drastically over the duration of a fire and the majority of area burned does not occur on the start date. Therefore, it is important to keep those in mind when viewing the results. The class summary frequency statistics for each individual station and its associated 50 km buffer varied considerably (even for stations from within the same region); this variation from station to station is driven mainly by the episodic nature of fire occurrence and spread. This variability from station to station was not summarized in earlier reports on the frequency of occurrence of various classes for FWI system outputs (e.g., Stocks 1974); however, these estimated values at each station can provide a useful indication of the site-to-site variability in these simple summary statistics and can be quite useful in understanding if the differences observed from one region (or station) to another are meaningful. To capture the range of this variability, individual station estimates of class occurrence were summarized across the three regions described above. For daily occurrence and fire occurrence, the 10th percentile and 90th percentile were estimated from the distribution of values in each region; this was used to report an 80% occurrence interval for these quantities. Because of the high variability in area burned (which can be very strongly influenced by just a single fire) only a single overall value was reported for each region.

Table 4. Weather and wildfire data summary for the study period (1990-2019). Area Burned is based on fires whose centroid overlapped the buffered station within each region.

Study Areas	**Northern**	**Northeastern**	**Northwestern**	**Ontario (total)**
Number of stations	16	34	25	75
Number of fires	2,743	16,151	13,297	32,191
Total area burned (hectares)	2,305,261	297,253	907,609	3,510,123

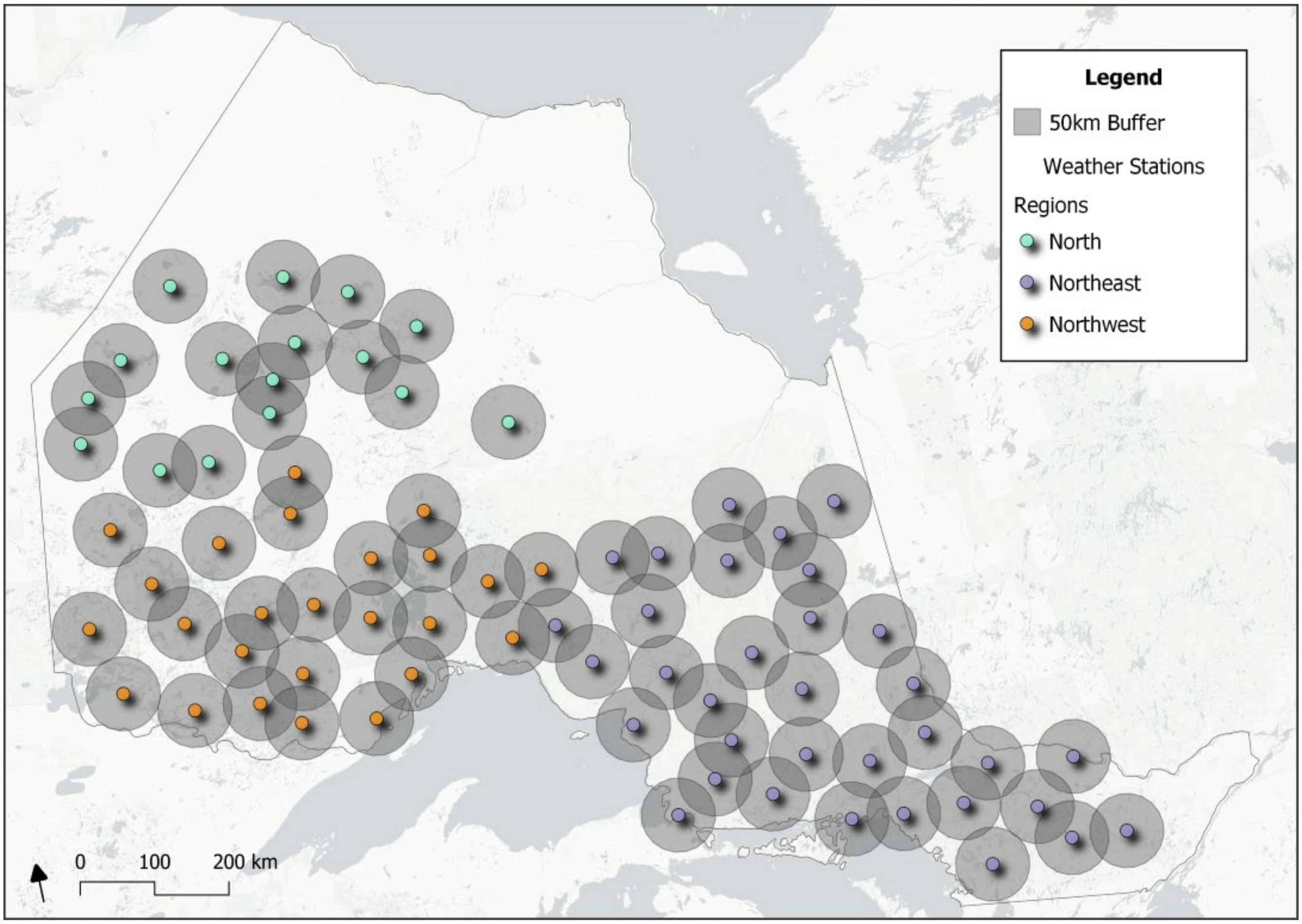

Figure 1. Station points used in the analysis and their 50km radius buffers. The colour of the points are indicative of the study area they are grouped with.

3.0. New FWI Class Definitions

The proposed new class divisions for each of the FWI System outputs are shown below in Table 5 and the details describing their development and historical occurrence follow in the subsequent sub-sections. In each of the Tables, 6 through 11, the summary presented of the current adjective rating class definitions (presented in Table 2) appear as the first table (Tables 6A-11A) and allow comparison to the statistics summarized by Stocks (1971, 1974). The 80% confidence intervals for the percent of occurrence values should allow improved assessment of the meaning of differences observed across the three study regions.

Table 5. Summary of newly defined potential class ranges for each of the codes and indices of the FWI System in use by Ontario.

Class	FFMC	DMC	DC	ISI	BUI	FWI
Low	0-75	0-10	0-70	0-4	0-20	0-3
Moderate	>75-85	>10-25	>70-190	>4-7	>20-40	>3-10
High	>85-90	>25-55	>190-300	>7-10	>40-80	>10-20
Extreme	≥90	>55	>300	>10	>80	>20

3.1 Fine Fuel Moisture Code (FFMC)

The probability of sustainable flaming ignition for needles was calculated initially based on litter moisture content data converted to FFMC using the standard equation (Van Wagner 1987) and a wind speed of 5 km/h (Figure 2). The model for probability of sustained ignition comes from currently unpublished analysis carried out as part of the development of the next generation of the CFFDRS; it corresponds to ignition in the needle litter of a moderately closed canopy pine stand. The new adjective rating class breakdowns used here reflect different probabilities of a small flaming fire brand leading to a sustained/spreading flaming ignition with some consideration to the vigor of spread of that potential ignition. These classes as defined could be used for interpretations about human-caused fire occurrence potential or spot fire potential. It is however recognized that FFMC is also commonly used by fire management as an indicator of surface fire spread; therefore, as a reference, ROS based on a wind speed of 5 km/h are also included (Figure 2). This may give some indication of spread potential should an ignition, such as a spot fire, occur under light winds; however, the FWI System's ISI should provide a fire manager with a better indication of spread rate potential.

The divisions between the adjective rating classes were selected mainly by considering the meaningful limits in the probability of ignition, with some additional information from the FBP System's ROS model for C-3 used to ensure logical consistency (Table 6B). The general rule that when FFMC is <75 there is little chance of ignition appear to hold true (Figure 2); if fires do ignite and spread under these conditions, ROS will be ~1m/min, which is relatively slow (Muraro 1975). Therefore, a FFMC of 75 was chosen as the upper limit for the Low class. The upper bound of 85 for the Moderate class was selected to maintain ignition potential below 50%. The High class is bounded by FFMC 90 with ignition potential greater than 50% and potential ROS higher than 5 m/min. Lastly, the Extreme class is FFMC >90 where ignition potential is closer to 70% and above with ROS over 6.5 m/min.

Since FFMC is being equated to the potential for sustained ignition and by extension as an indicator of fire occurrence (e.g., Woolford et al. 2021), the new classifications were examined along with historical information on human-caused fire occurrence in two ecoregions in NE and NW Ontario (Figure 3). The new class ranges appear to generally capture the critical areas of the increase in human-caused fire occurrence one expects with increasing FFMC; in particular the strongly exponential increase at values of 90 and above. Table 6B reveals that the majority of the fire season is spent within the Low and Moderate classes, while increased fire activity, in particular area burned, tends to occur predominantly in the High and Extreme categories.

Table 6. Summary of the frequency of days within the fire season (10th and 90th percentiles), human-caused fire occurrence (10th and 90th percentiles) and area burned by human-caused fires* for each of the **existing (A)** and **newly defined (B)** FFMC classes within the Northeast (NE), Northwest (NW) and Northern (NO) regions of the province for 1990-2019.

A)

FWI System Class	FFMC	Frequency of Daily Occurrence (%)			Human-caused Fire Occurrence (%)			Area Burned by Human-caused fires (%)*		
		NE	NW	NO	NE	NW	NO	NE	NW	NO
Low	≤80	44-54	48-56	49-57	14-26	8-28	0-36	1	0	0
Moderate	≥81-≤86	20-26	19-25	19-23	15-30	16-32	0-25	1	6	28
High	≥87-≤90	18-28	16-24	18-24	36-47	32-49	21-60	23	22	48
Extreme	≥91	3-9	3-8	3-8	9-21	9-25	0 - 41	75	71	24

B)

FFMC Class	FFMC	Frequency of Daily Occurrence (%)			Human-caused Fire Occurrence (%)			Area Burned by Human-caused fires			Interpretation
		NW	NO	NE	NW	NO	NE	NW	NO	NE	
Low	0-75	35-42	38-45	39-45	6-17	8-19	0-21	0	0	0	Low probability of ignition in C-3 (<15%)
Moderate	>75-85	24-32	24-30	24-29	17-30	14-29	0-29	1	6	28	Moderate probability of ignition in C-3 (<50%)
High	>85-90	24-32	22-30	23-30	40-54	40-56	21-66	23	22	48	High probability of ignition in C-3 (>50%)
Extreme	>90	3-9	3-7	3-8	9-21	9-25	0-41	76	71	24	Very high probability of ignition in C-3 (>65%)

* This represents the overall average value across all stations, as area burned was too variable from station to station to create a meaningful range. Because these values are rounded independent estimates of the median value in each category, the total does not sum to 100%, particularly for very skewed distributions such as those associated with area.

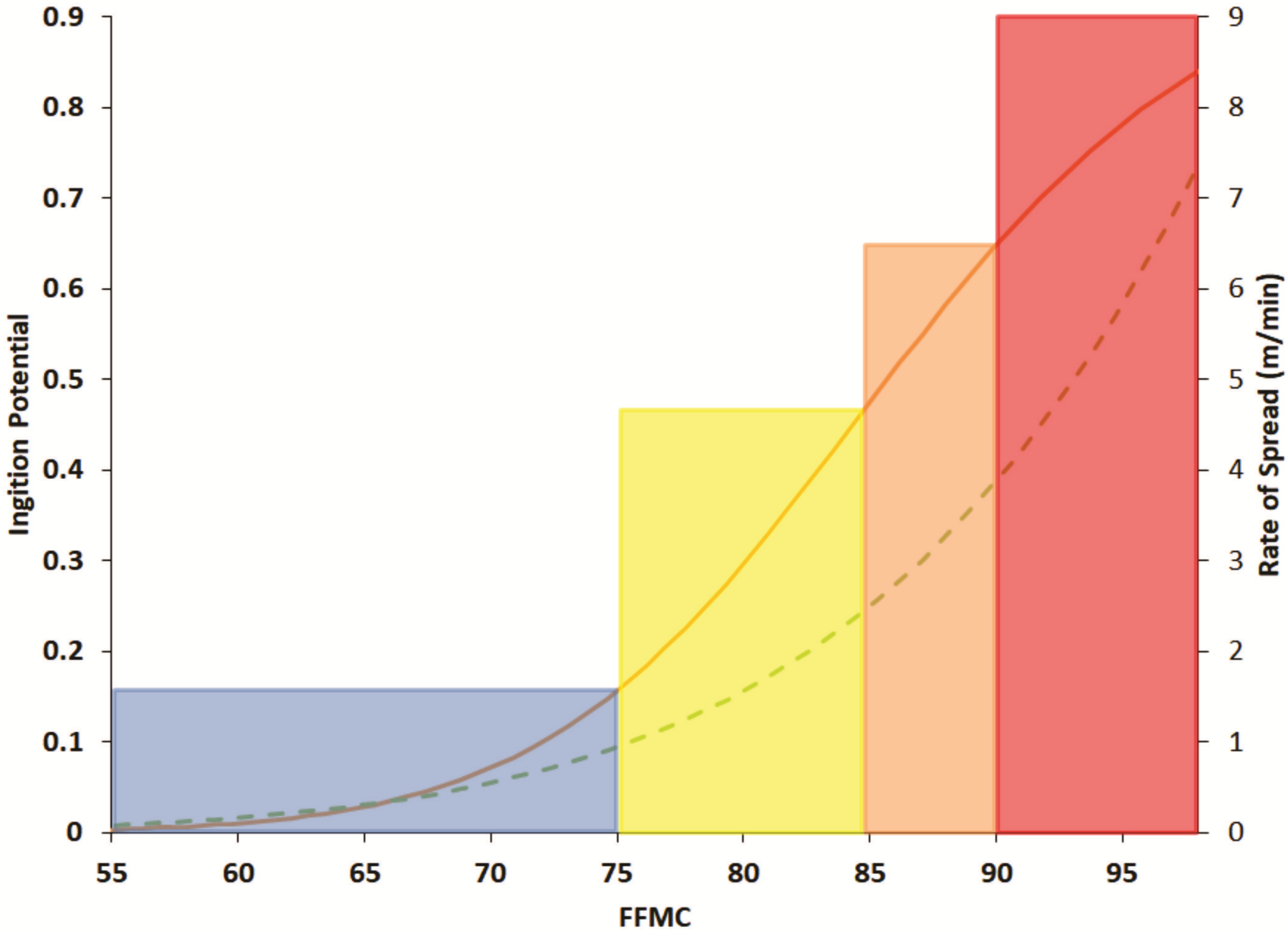

Figure 2. FFMC and sustained flaming ignition potential in a closed canopy; pine is the solid orange line. Rate of spread, in a closed canopy pine stand, based on a 5 km/h wind is the green dashed line. The scale for FFMC is not shown to zero because ignition potential does not rise to above 1% until FFMC ~60. The new FFMC classes are shown by the colour bars, where Low = blue; Moderate = yellow; High = orange and Extreme = red.

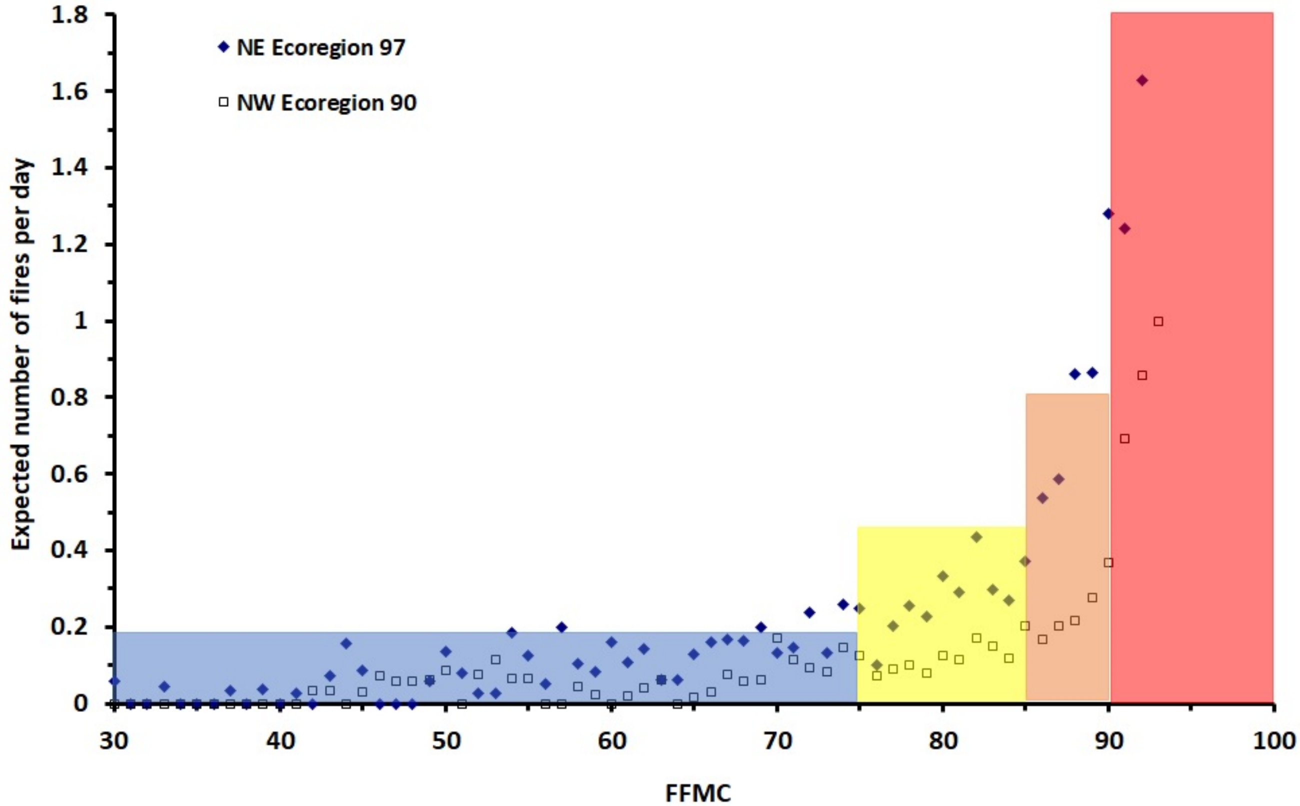

Figure 3. Human-caused fire occurrence for Ontario based on residential and railway fires with primary ignition in standing forest fuel types. Shown are models for an ecoregion in the NE near Sudbury and another in the NW near Red Lake. FFMC classes are blocked out corresponding to the ranges, where Low = blue; Moderate = yellow; High = orange and Extreme = red.

3.2 Duff Moisture Code (DMC)

Although there appear to be some differences in the probability of lightning fire ignition per lightning strike between the NE and NW parts of the province (Figure 4), the new classes proposed for this report were defined for the whole province, and represent a compromise between the NE and NW regions. If operations desire separate range definitions, they could be developed for different regions using the dataset; however the summaries presented in Tables 7A and 7B show considerable overlap in the 10^{th} to 90^{th} percentile range and therefore suggest there may be little practical value in the added complexity of two separate classification definitions for the province. The limits of the categories are taken from the empirical lightning fire to lightning strike data shown in Figure 4. The probability of ignition in the Low category, below DMC=10, is quite consistent between the NE and NW; the top of this class represents the point where, on average, one thousand lightning strikes occur for every one sustained and detected lightning fire. The top of the Moderate category, DMC=25, translates to the point where about one in 200 lightning strikes lead to a fire occurrence, or five times the occurrence rate as in the Low category. Figure 4 shows that this level of ignition potential is achieved at a lower DMC in the West and higher in the East, which is also the trend for the High and Extreme classes up to a DMC value of 65, at which point the forest floor is very dry and the difference between the regions is gone. The upper range for the High adjective rating class is DMC=55, which represents about one fire per 50 lightning strikes (or about four times the rate at the top end of Moderate and 20 times the rate of the Low category). In the Extreme class, DMC >55, on average fewer than 50 lightning strikes are needed per lightning fire ignition.

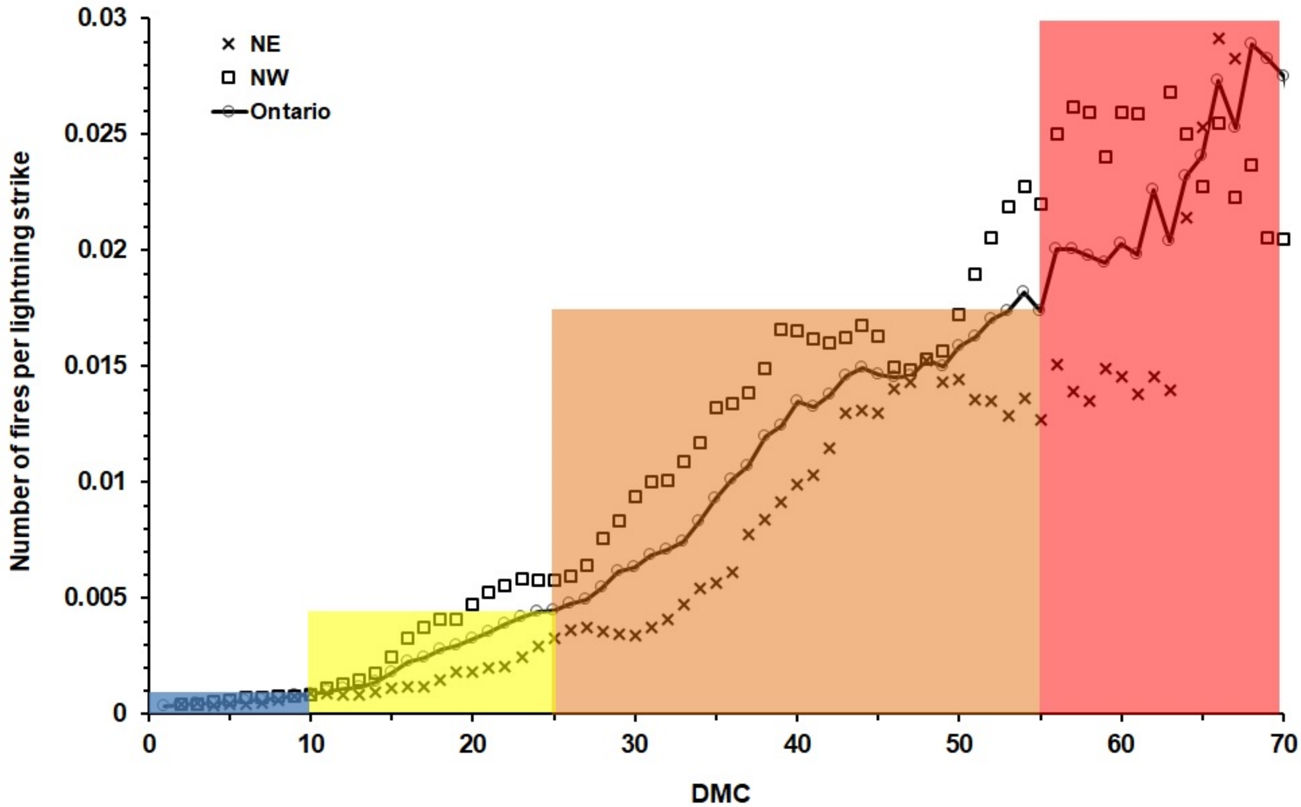

Figure 4. New classes for Ontario based on the DMC relationship to number of fires per lightning strike (circles). Also provided are strikes for NE (crosses) and NW Ontario (squares), but class ranges were based on the Ontario relationship. Adjective classes are Low = blue; Moderate = yellow; High = orange; Extreme = red.

While around a third to half of the days in the province are classified as having Low lightning fire ignition potential (Table 7B), the greatest percentage of fire occurrence is within the Moderate to High classes, although the majority of area burned due to lightning fires occurs within the High class, particularly for the NO. Within the NE there is a greater area burned in the extreme class (46%) compared to the NW (16%) and NO (17%). This difference may have something to do with the spike in number of fires per lightning strike at the very high end of the DMC scale in the NE (Figure 4), or simply be a result of variability associated with the rarity of days when DMC is >55 and the low frequency and high impact of large fires to begin with. Overall, these class ranges appear to reasonably represent the ignition potential of lightning-caused fires.

The performance of the lighting detection sensor network is inherently reflected in these empirical relationships of strike to fire ratio. Two different sensor networks running at the same time could potentially result in different strike detection densities and therefore different absolute relationships. The data summarized here use lightning flash information; that is, a single lightning "strike" is more formally defined as a single "flash" that could have multiple return strokes. This should be consistent with both the original lightning detection network in Ontario used prior to 2013 and also the data type provided by Ontario's current lightning strike detection services as of 2020. Therefore, the strike to fire ratios used here are more descriptive than predictive, given the variation of lightning detection systems and performance through the previous decades.

Table 7. Summary of the frequency of days within the fire season (10th and 90th percentiles), lightning fire occurrence (10th and 90th percentiles) and area burned by lightning-caused fires* for each of the **existing (A)** and **newly defined (B)** DMC classes within the Northeast (NE), Northwest (NW) and Northern (NO) fire regions of the province for 1990-2019.

A)

FWI System Class		Frequency of Daily Occurrence (%)			Lightning-caused Fire Occurrence (%)			Area Burned by Lightning-caused (%)*		
	DMC	**NE**	**NW**	**NO**	**NE**	**NW**	**NO**	**NE**	**NW**	**NO**
Low	0-15	41-56	46-57	48-63	9-18	9-23	4-22	1	21	3
Moderate	16-30	29-34	29-34	27-33	17-38	28-48	22-47	12	18	20
High	31-50	11-18	10-15	7-15	20-42	20-38	19-43	41	34	41
Extreme	>50	3-7	2-5	2-5	11-45	7-25	6-28	47	28	36

B)

DMC Class	DMC	Frequency of Daily Occurrence (%) NW	NO	NE	Lightning-caused Fire Occurrence (%) NW	NO	NE	Area Burned by Lightning-caused (%)* NW	NO	NE	Interpretation
Low	0-10	24-38	29-40	29-46	1-8	2-11	1-9	0	0	0	High number of strikes on average per fire (e.g., >1000 strikes**); ignition is unlikely
Moderate	>10-25	40-44	40-45	39-44	18-41	26-44	22-43	3	30	16	Moderate number of strikes on average per fire (e.g., >200 but <1000**); some ignitions are possible
High	>25-55	19-28	17-25	13-24	35-60	35-53	38-63	51	53	66	Low number of strikes per fire on average (e.g., >50 but <200**); increased probability of multiple ignitions
Extreme	>55	2-5	1-3	1-4	7-39	2-23	4-23	46	16	17	Very low number of strikes needed per fire on average (e.g., <50**); very high probability of multiple ignitions

* This represents the overall median value across all stations, as area burned was too variable from station to station to create a meaningful range. Because these values are rounded independent estimates of the median value in each category, the total does not sum to 100%, particularly for very skewed distributions such as those associated with area.

**** These are notional relationships based on the lightning detection systems used for the analysis; they could change with different detector systems; they are not to be interpreted as strict rules.**

3.3 Drought Code (DC)

Depth of burn was used to give some indication of persistent burning and potential mop-up problems in relation to the DC. Data used to define the relationship between depth of burn and DC were taken from FBP System experimental burning datasets for a range of conifer and mixedwood fuel types. There is a lot of scatter in the data (Figure 5), even within some individual fuel types, yet one can start to visualize class ranges associated with the trends increasing depth of burning in the forest floor. In some locations, forest floor consumption would be limited by the available fuel (i.e., the depth of the forest floor itself); therefore, interpretations of these classes only apply in areas where there is sufficient depth of organic material to sustain smoldering combustion. The top of the Low category, DC=70, was chosen to represent burning in only the top few centimeters of duff (Figure 5). This corresponds to a forest floor consumption of <0.5 kg/m^2 (de Groot et al. 2009) and is likely consistent with no extended smouldering after the passage of the main fire front. The Moderate class, DC range 70-190, is associated with burning of up to 5 cm depth (<1.0 kg/m^2 forest floor consumption), which for thin duff layers may indeed take combustion down to mineral soil but should not provide extensive mop-up problems. A DC of 300 was chosen as the top of the High class, which was indicative of potential deeper burning of just under 15 cm (<1.5 kg/m^2 forest floor consumption). The Extreme class therefore occurred when DC was >300 and is an upper range where others have noted that extensive mop-up problems may exist (Hirsch and Martell 1996, Muraro 1975) and depth of burn has the potential to exceed 15 cm (Figure 5).

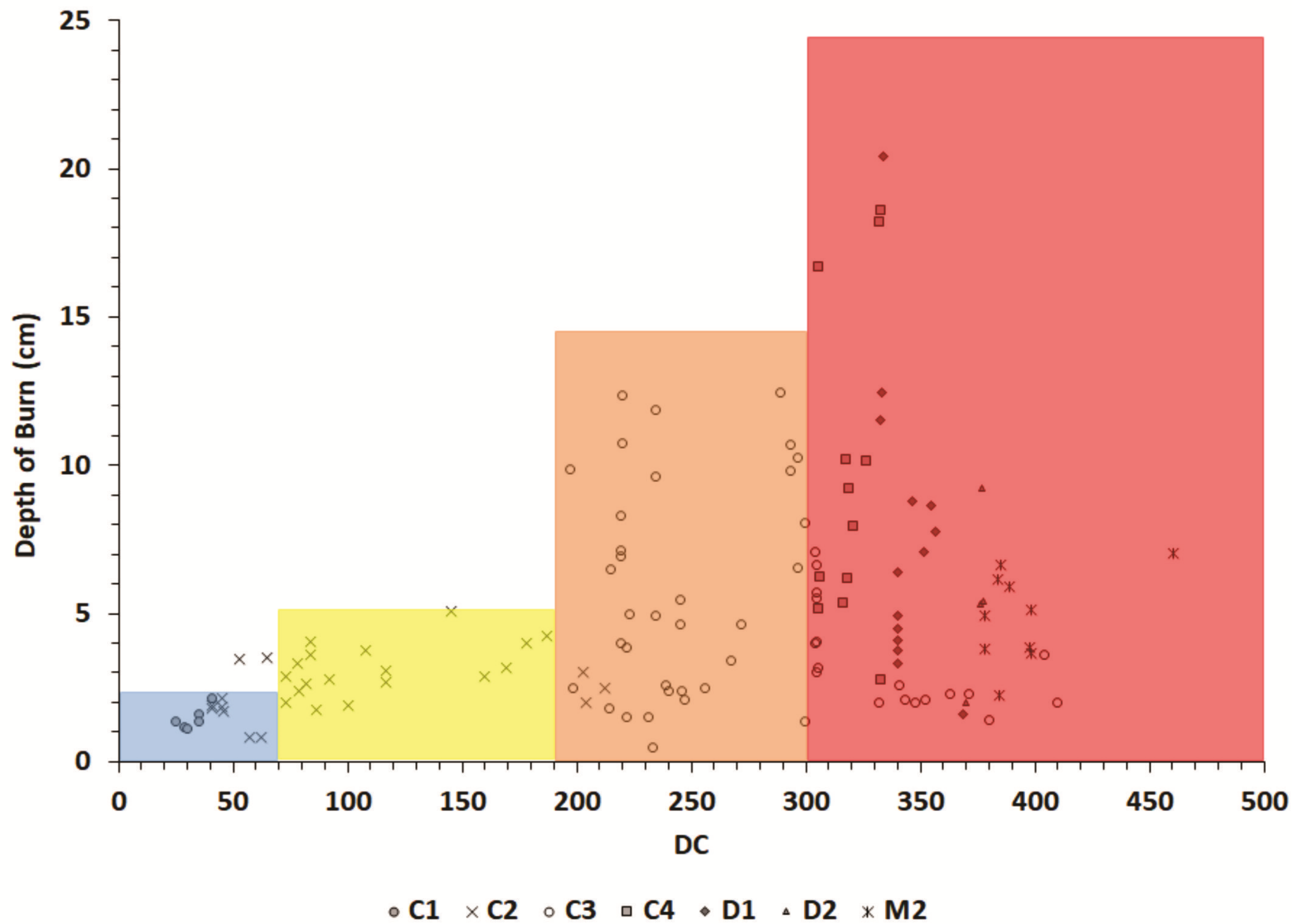

Figure 5. Drought Code (DC) related depth of burn by FBP System fuel types taken from de Groot et al. (2009). Adjective classes are Low = blue; Moderate = yellow; High = orange; Extreme = red

The resultant adjective rating classes start at a lower DC than those used currently (Table 2, Table 8A), but the resultant fire occurrence is reasonably spread out over the fire season (Table 8B) with the greatest occurrence at the Moderate class where the majority of area burned occurs as well. The NW has 53% area burned at the Moderate to High DC class. Area burned was highest within the Moderate class.

Table 8. Summary of the frequency of days within the fire season (10th and 90th percentiles), fire occurrence (10th and 90th percentiles) and area burned* based on depth of burn for each of the **existing (A)** and **newly defined (B)** DC classes within the Northeast (NE), Northwest (NW) and Northern (NO) fire regions of the province for 1990-2019.

A)

FWI System Class		Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*		
	DC	NE	NW	NO	NE	NW	NO	NE	NW	NO
Low	0-140	43-55	50-63	48-61	17-44	21-47	19-50	60	52	31
Moderate	141-240	24-35	24-33	30-36	20-37	22-44	23-51	24	33	35
High	241-340	12-19	8-15	8-16	12-32	15-30	13-31	11	10	30
Extreme	>340	3-8	1-6	1-4	7-28	4-20	0-10	6	5	4

B)

ISI Class		Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*			Interpretation
	DC	NW	NO	NE	NW	NO	NE	NW	NO	NE	
Low	0-70	19-29	24-34	20-29	4-25	5-23	2-22	21	29	3	Expect burning in top few centimeters of duff
Moderate	>70-190	40-45	42-48	44-53	21-38	28-48	36-51	53	45	45	Burning up to 5 cm, may be down to mineral soil in some regions
High	>190-300	22-27	17-24	19-28	21-36	22-40	20-43	17	19	39	Deeper burning up to 15 cm, where fuel depth permits
Extreme	>300	6-14	3-11	3-8	16-40	9-33	0-20	9	7	12	Much deeper burning possible where fuel loads permit, extensive mop-up possible

* This represents the overall median value across all stations, as area burned was too variable from station to station to create a meaningful range.

3.4 Initial Spread Index (ISI)

The ISI association with ROS is well established and is the intended use of the index (Van Wagner 1987); however, in thinking about adjective ratings the question remains, what speed is a concern to fire managers? Hirsch (1996) provides a table that relates fire intensity to general fire behaviour characteristics similar to the table in Hirsch and Martell (1996) for initial attack effectiveness. To calculate fire intensity from ROS the fuel consumed was required. After trying a few different values, a constant SFC of 2.4 kg/m^2 was selected; this was the maximum consumption in C-3 surface fires in the FBP database, and gives an idea of the high end of consumption in a surface fire. Based on this constant level of consumption, a low intensity fire (<500 kW/m) has an upper limit ROS of ≈0.5 m/min, ≈3 m/min is the upper limit of moderate intensity fire (500-2000 kW/m), 5.6 m/min for a high intensity fire (2000-4000 kW/m) and anything greater than 5.6 m/min for a fast-spreading intermittent crowning fire in C-3 (>4000 kW/m). These values seem appropriate when compared to Muraro's (1975) spread ranking system for prescribed burns: moderately slow 1.5 m/min, moderately fast 3 m/min, and fast 10 m/min.

The upper limit of each adjective ISI class was rounded down in order to provide memorable whole numbers, which encourage a risk-averse approach to code interpretation (Table 9B). Figure 6A shows only the bottom end of the ISI scale. When all the points are included that make up the FBP System relationship, an ISI of 10 appears to be around the transition from predominately surface fire activity to predominately crown fires (Figure 6B). The intensity associated with this category also corresponds to the onset of crowning as indicated by the FBP System's Critical Surface Intensity model.

These ISI adjective rating classes resulted in the majority of fire occurrence within the Low class (Table 9B) for all three regions. The Low class also resulted in the highest percentage of fire occurrence. Therefore, some further adjustment of this class may be necessary depending on the intended use by Ontario fire management. This Low class resulted in the largest percentage of area burned for the NW and NO; the greatest area burned was within the Extreme class for the NE region. It is important to again keep in mind that area burned within a given class is associated with the start date of the fire, which may not be representative of the ISI values on the primary spread days of the fire, which will contribute the most to area burned.

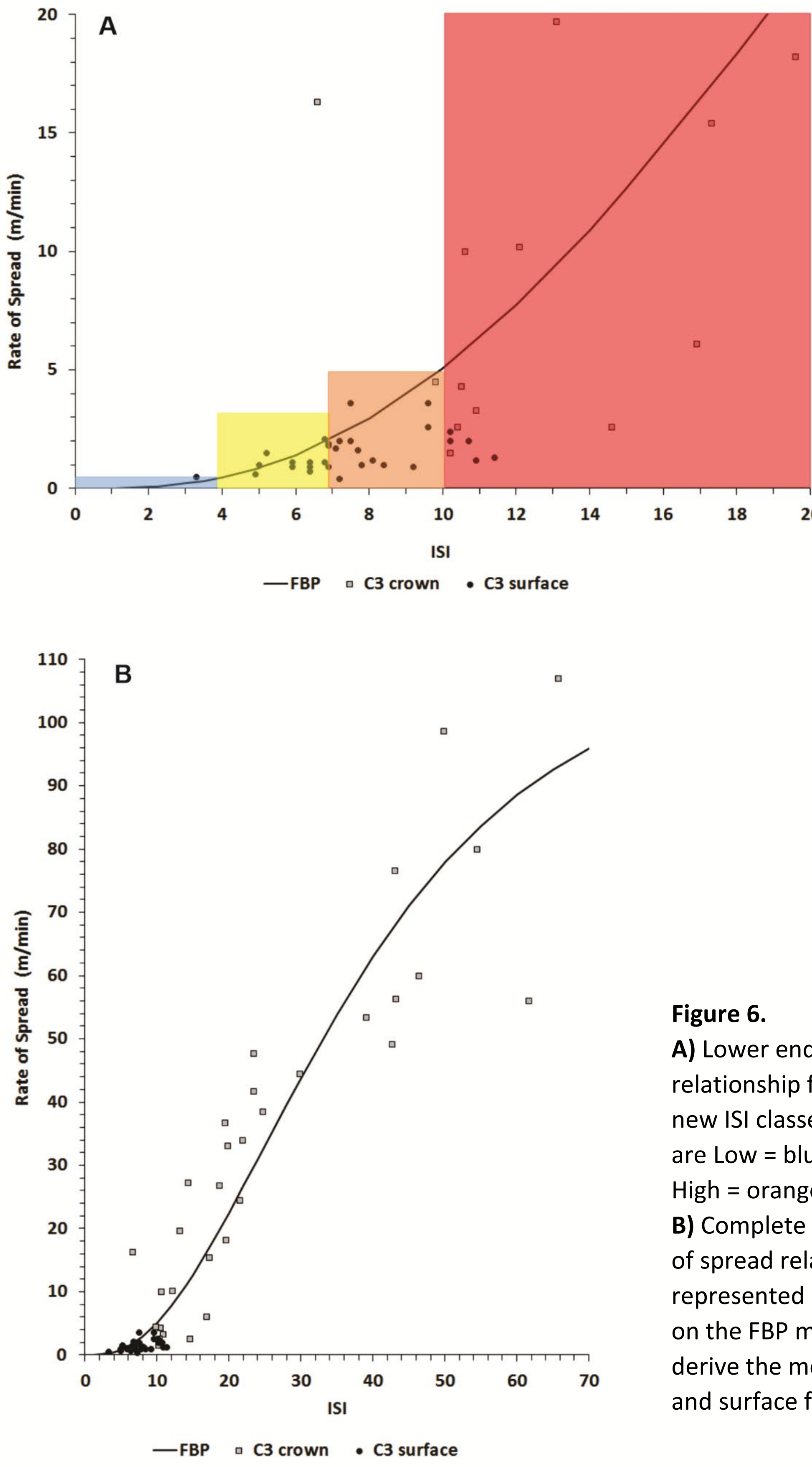

Figure 6.
A) Lower end of the ISI, rate of spread relationship for C-3 used to define the new ISI classes, where danger classes are Low = blue; Moderate = yellow; High = orange; Extreme = red.
B) Complete range of the ISI and rate of spread relationship for C-3 fuel type represented by the smooth line (based on the FBP model). Data points used to derive the model are show for crown and surface fires.

Table 9. Summary of the frequency of days within the fire season (10th and 90th percentiles), fire occurrence (10th and 90th percentiles) and area burned* for each of the **existing (A)** and **newly defined (B)** ISI classes, based on rates of spread in pine (C-3), within the Northeast (NE) (n=35), Northwest (NW) (n=25) and Northern (NO) (n=16) fire regions of the province for 1990-2019.

A)

FWI System Class	ISI	Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*		
		NE	NW	NO	NE	NW	NO	NE	NW	NO
Low	0-2.2	46-58	50-60	49-57	19-34	21-39	13-27	5	11	30
Moderate	2.3-5	22-28	22-28	21-25	19-28	22-35	14-33	4	31	24
High	5.1-10	16-28	15-24	17-24	28-49	27-44	28-53	41	44	32
Extreme	>10	1-5	1-4	1-6	2-5	2-11	2-25	50	13	14

B)

ISI Class	ISI	Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*			Interpretation
		NW	NO	NE	NW	NO	NE	NW	NO	NE	
Low	0-4	68-83	73-83	71-80	40-66	46-69	32-53	9	42	54	Slow moving surface fire, spread rates <0.5 m/min in C-3
Moderate	>4-7	13-20	11-17	12-18	22-36	21-32	19-40	21	36	20	Moderately slow surface fire, spread up to ~3 m/min in C-3
High	>7-10	3-8	3-6	4-8	5-15	6-14	8-22	20	8	12	Fast moving surface fire, spread up to 5 m/min, crowning possible in fuels with good vertical continuity in C-3
Extreme	>10	1-5	1-4	1-6	2-14	2-11	2-25	50	13	13	Very fast moving fire, greater potential for crown fire activity, spread > 5m/min in C-3

* This represents the overall average value across all stations, as area burned was too variable from station to station to create a meaningful range. Because these values are rounded independent estimates of the median value in each category, the total does not sum to 100%, particularly for very skewed distributions such as those associated with area.

3. 5 Buildup Index (BUI)

From a modelling point of view the BUI is most strongly related to ground fuel consumption, as it reflects the moisture levels in these heavier fuels. Operationally, the BUI is commonly used to inform pre-suppression planning (de Groot 1987). The divisions between adjective rating classes were chosen using the SFC model for C-3 from the FBP System (Figure 7A), which directly relates BUI to SFC. The upper limit of the Low class was defined at a minimum SFC in C-3 of approximately 0.25 kg/m^2; similar to the nominal litter load in the FWI System and representative of very little consumption of larger material. This low consumption value corresponds to a BUI of 20. Below a BUI of 20 there is little to no SFC (Figure 7C), and if one applies the FBP System's Buildup Effect on ROS, surface fire spread rate is reduced by more than 60% (Figure 7B). The Moderate class is defined to represent SFC up to ≈1.0 kg/m^2 which occurs in the C-3 fuel type while BUI is below 40; this upper limit of the Moderate category was the average SFC in C-3 (based on the FBP database). At the top of this category, the FBP System's Buildup Effect on spread rate reduces equilibrium rate of spread by 10%. This limiting value between the Moderate and High class is also a critical value (Hirsch and Martel 1996) above which it is expected that extensive mop-up may be required in forest types with deeper fuels. The High class, which spans BUIs from 40 to 80 in the newly defined range, corresponds to a surface consumption that tops out at ≈2.5 kg/m^2; this value is close to the maximum SFC for surface fires in the C-3 database and 50% of the maximum value possible for SFC in the FBP System's C-3 model for surface fuel consumption. On average across the range in this category the Buildup Effect does not have a very strong influence on spread rate (<10% change). Given this limit for the top end of the High class, the Extreme class (BUI>80) the SFC represents is more likely to exceed 2.5 kg/m^2 (Figure 7A).

The Low danger class remains unchanged from the current category and the number of days in this BUI class makes up about 50% of daily occurrence (Table 10A and B). In Ontario, BUIs exceeding 80 are rare (<2% of days overall) and resulted in <12% of fires and area burned in all three regions. The majority of area burned and fire occurrence are associated with BUIs in the Moderate and High BUI classes. Given that BUIs above 80 (i.e., Extreme) are rare in Ontario, the value defining the limit between the High and Extreme category may require adjustment for the province, though nationally it seems a reasonable limit.

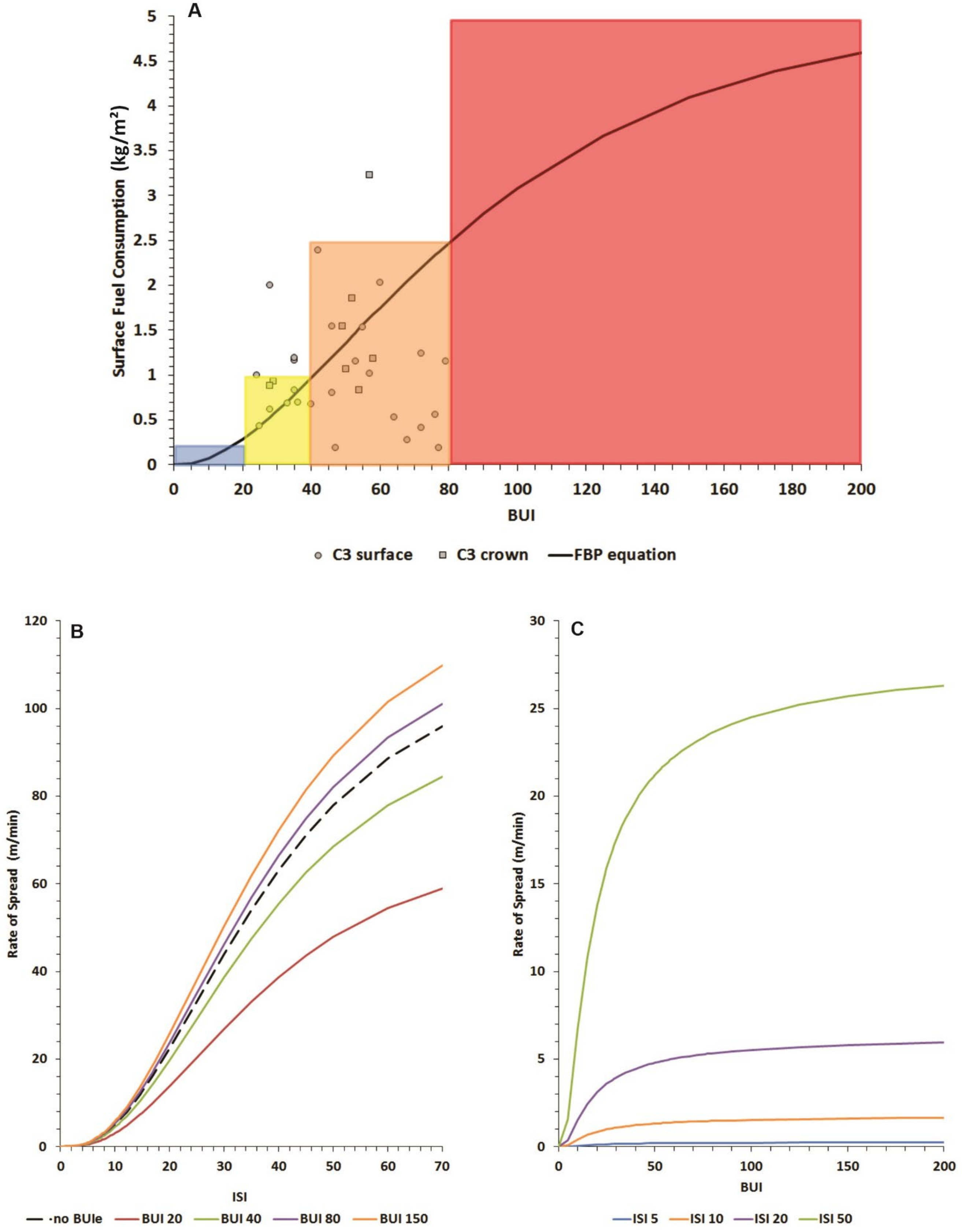

Figure 7. A) Relationship between BUI and SFC for C-3 with surface and crown fire points differentiated. The solid line represents the FBP model for C-3. **B)** ROS and ISI relationship without the BUI effect (dashed line) and with various BUI value including the BUI effect. **C)** Effect of BUI on ROS at different ISI values.

Table 10. Summary of the frequency of days within the fire season (10th and 90th percentiles), fire occurrence (10th and 90th percentiles) and area burned for each of the **existing (A)** and **newly defined (B)** BUI classes, based on Surface Fuel Consumption (SFC) in pine (C-3), within the Northeast (NE), Northwest (NW) and Northern (NO) fire regions of the province for 1990-2019.

A)

FWI System Class		Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*		
	BUI	NE	NW	NO	NE	NW	NO	NE	NW	NO
Low	≤20	35-50	40-53	41-59	8-26	9-27	6-19	2	18	4
Moderate	21-36	29-33	28-32	28-34	18-32	24-37	23-42	9	25	15
High	37-60	16-24	14-21	11-21	16-46	29-41	29-48	59	33	49
Extreme	>61	4-10	3-7	3-5	10-37	10-24	6-26	31	23	32

B)

BUI Class		Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*			Interpretation
	BUI	NW	NO	NE	NW	NO	NE	NW	NO	NE	
Low	0-20	35-50	40-53	41-59	8-26	9-27	6-19	2	18	4	Little to no SFC in C-3 (<0.2 kg/m^2)
Moderate	>20-40	34-38	33-37	32-39	22-41	31-44	31-50	30	33	23	Average SFC in C-3 (<1.0 kg/m^2)
High	>40-80	15-24	13-20	9-19	31-56	31-50	27-57	62	42	67	High SFC in C-3 especially for surface fires (<2.5 kg/m^2), potentially extensive mop-up
Extreme	>80	1-4	0-2	0-1	1-20	1-15	1-11	6	6	6	Top end of SFC in C-3 (>2.5 kg/m^2)

* This represents the overall average value across all stations, as area burned was too variable from station to station to create a meaningful range. Because these values are rounded independent estimates of the median value in each category, the total does not sum to 100%, particularly for very skewed distributions such as those associated with area.

3. 6 Fire Weather Index (FWI)

Fire Intensity class definitions have existed in Canada for some time (Alexander and de Groot 1988, Taylor et al. 1997), though their definitions rely on a limited body of research carried out outside the boreal forest. Hirsch and Martell (1996) provide a good review of the origins of these thresholds and the interpretations that have evolved over time. The upper limit of Intensity class 1 is typically 10 kW/m which is described as representing a barely sustainable ignition; intensity class 1 is often associated with smoldering fire. In the FBP System C-3 database, there are no observations of Frontal Fire Intensity < 10 kW/m. In fact, there are no fires within the FBP System database for C-3 for FWI values lower than 8; however, the point source ignition work by McRae et al. (2017) suggests FWI=3 is a reasonable level to represent the lowest frontal fire intensity observable from a spreading fire, which agrees with the currently used value. The Moderate class, FWI >3-10 covers intensity <500 kW/m (typically known as Intensity class 2) and is associated with creeping or gentle surface fires. The High class, FWI >10-20 corresponds to fires that generally range in intensity between 500-2000 kW/m meant to represent low vigour to high intensity surface fires with some small amount of intermittent crowning (i.e., torching) possible (Figure 8B) (i.e., higher intensity possible but less likely). Although the onset of torching in C-3 can start closer to 4000 kW/m, crown fire initiation can begin at lower intensities in the boreal spruce fuel type (C-2) and higher intensity fires are more likely at FWI>20. Therefore, this division between High and Extreme is a reasonable compromise between these two dominant conifer forest types. The Extreme class, FWI >20 corresponded to fires more likely to be in the 4000 kW/m range with intermittent to active crown fire development even more likely at higher intensities, especially in C-2.

Based on these new FWI danger classes the majority of daily occurrence is at the low end (Table 11B). Percent fire occurrence is relatively evenly distributed between Low, Moderate and High classes, while area burned occurs mostly within the High to Extreme class. The relative frequency of FWI values across the classes is still relatively similar to that established by Stocks (1971) (Table 1) even with some minor adjustment to the High and Extreme class ranges (Table 11B) and the stronger physical basis. It should be noted that this definition of FWI for which the class ranges have been adjusted is related to suppression resource effectiveness class ranges adopted in the Fire Intensity class categorizations. The use of this particular definition for establishing ranges may need to be revised when considering the use of the FWI as the main general public indicator of fire danger levels.

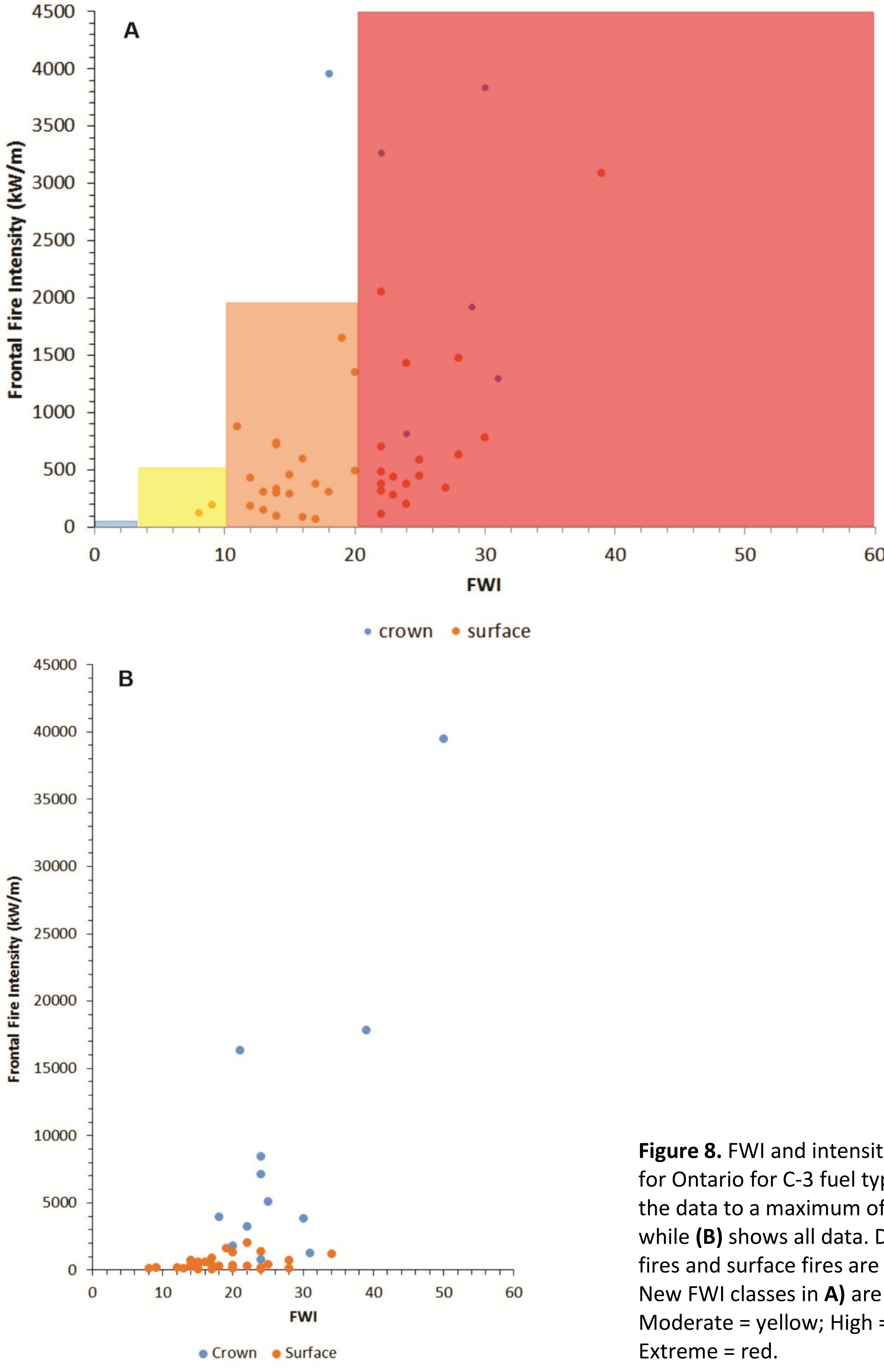

Figure 8. FWI and intensity relationships for Ontario for C-3 fuel types. **A)** shows the data to a maximum of 4500 kW/m, while **(B)** shows all data. Data for crown fires and surface fires are differentiated. New FWI classes in **A)** are Low = blue; Moderate = yellow; High = orange; Extreme = red.

Table 11. Summary of the frequency of days within the fire season (10th and 90th percentiles), fire occurrence (10th and 90th percentiles) and area burned for each of the **existing (A)** and **newly defined (B)** FWI classes, based on fire intensity, within the Northeast (NE), Northwest (NW) and Northern (NO) fire regions of the province for 1990-2019.

A)

FWI System Class		Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*		
	FWI	NE	NW	NO	NE	NW	NO	NE	NW	NO
Low	≤3	44-57	49-60	50-58	15-29	20-34	9-23	3	27	9
Moderate	4-10	24-29	25-28	24-28	20-35	22-34	18-34	5	12	36
High	11-22	15-26	13-22	15-22	30-46	29-44	33-55	28	50	35
Extreme	≥23	1-6	1-3	1-5	5-18	3-11	3-26	64	12	19

B)

FWI Class		Frequency of Daily Occurrence (%)			Fire Occurrence (%)			Area Burned by fires (%)*			Interpretation
	FWI	NW	NO	NE	NW	NO	NE	NW	NO	NE	
Low	0-3	44-57	49-60	50-58	15-29	20-34	9-23	3	27	9	Low intensity fire in C-3 (<10 kW/m)
Moderate	>3-10	25-29	25-28	24-28	20-35	22-34	18-34	5	12	36	Creeping or gentle surface fires in C-3 dominate (10-500 kW/m)
High	>10-20	14-24	13-21	14-20	29-42	28-40	32-48	18	38	34	Low vigor to high intensity surface fires in C-3: crown fires possible, most likely in insect-damaged fuels (500-2000 kW/m)
Extreme	>20	2-8	2-4	2-6	8-25	6-16	8-35	74	23	21	Intermittent to active crown fire development is likely in C-3 (>2000 kW/m)

* This represents the overall average value across all stations, as area burned was too variable from station to station to create a meaningful range. Because these values are rounded independent estimates of the median value in each category, the total does not sum to 100%, particularly for very skewed distributions such as those associated with area.

4.0 Discussion

The goal of this report is to provide the starting point for the discussion of changes to the FWI System adjective rating classes as reflected in Tables 6 through 11. These changes provide not only a characterization of how the existing method of classification captures elements of fire activity (using the most recent decades of fire weather information), but also allows evaluation of the impact of the newly defined classifications in comparison to the frequency analysis. Where there are changes to the adjective rating class boundaries, that shift should capture the physical process better.

A core decision in this work was to associate class divisions with physically tangible quantities, where each FWI System output should be primarily associated with one specific process or factor in the fire environment. For example, the adjective rating classifications for FFMC are strictly interpreted from data and modelling of the probability of a sustainable flaming ignition in the litter on the forest floor; operational interpretations about other important factors such as the potential for human-caused ignitions or spot fire formation follow from the classification, but are not part of defining it. This was done to provide clarity and consistency in interpretation of these outputs; however, this assumption may mean that some interpretations of the new adjective ratings may not be consistent with how they are being interpreted currently.

If the NDMNRF were to retain the use of frequency-based classifications, these thresholds should be regularly evaluated with new fire weather data and updated when needed. Given that these are a type of historical benchmarking, as seen in Tables 6-11 the original class boundaries no longer correspond to the same percentage of frequency (e.g., Extreme may no longer correspond to the worst 2% of days). However, any update that results in a change in class boundaries may affect the mental models of staff who learn what occurs in different classes as currently defined. That being said, Tables 6A-11A also reveal that there is considerable variability, even just within a specific region, in the frequency of occurrence of specific adjective rating classes. This suggests that small changes in class boundaries might have little practical impact on their interpretation. It should be noted that, with this observed variability physical quantities like ignition probability (Figures 2 and 4), spread rate (Figure 6A) and fuel consumption (Figure 7A) vary with FWI System outputs in a relatively smooth and continuous fashion. One can, for the sake of creating a small number of categories, create different class levels at logical breakpoints; however, the reality is that these divisions are artificial constructs. Any such classification of a smoothly varying continuous field into a small number of discrete categories will cause information loss; that information loss is most impactful close to the classification boundaries.

The FWI System classes are highly integrated into fire management in Ontario. Prior to implementing a change, the improvement must be weighed against the cost and other implications of making such a change. The FWI System was designed to be nationally consistent and provide a common method and terminology to characterize critical elements of the fire environment. It is important that with the sharing of staff between agencies, the FWI classes mean relatively the same thing across Canada. Its outputs are calculated the same everywhere, but are intended to be interpreted regionally to account for local differences (e.g., in some provinces/regions a fuel type other than C-3 may be appropriate).

Therefore, the class boundaries may be different across Canada but the interpretation should be consistent by using the same physically based methods.

In the operational use of adjective ratings of the FWI System outputs, we expect that each decision maker is using a particular value (observed or forecast) as a consistent and objectively derived baseline indicator of the general situation; they then apply other information, such as their own experience and understanding of the specific conditions and situation, to refine their overall assessment of the current and developing conditions. Interpretations and adjective classes are taught as building blocks in that information synthesis process. Clarity in the definition and subsequent interpretation of the adjective rating classes may provide, for newer staff, a more consistent foundation of understanding of the relationships between FWI System outputs and wildland fire activity.

This project was carried out with data and the models of various fire processes that were available and reasonably well-established; additional fire data from the province or improved models from those data could be used to improve some of the class boundary definitions. For instance, the DC class definitions may be improved with analysis of mop-up duration (e.g., the duration between Being Held and Out times) to provide better estimates of extended suppression requirement problems in conjunction with the depth of burn data**. It is important to remember that the FWI System was designed to be a set of unitless relative indicators used to capture various aspects of potential fire behaviour on any particular day for a single common conifer fuel type. The FWI System is for many a first and simple pathway to understanding how weather influences the day-to-day potential for wildfire ignition and spread. As one advances to needing to understand fuel-type-specific differences in fire potential or the expected diurnal change in fire behaviour, the FBP System is required.**

It should be noted that we assumed the same number of classifications as are currently used in Ontario. Several jurisdictions in Canada include a fifth “Very High” category in their adjective ratings. In future, there may be value in considering adding more classes to specific FWI System outputs, if they differentiate important states in the overall physically based process each FWI System output is defined to represent. In some jurisdictions internationally a “Catastrophic” class, above “Extreme”, has been proposed or implemented. Such adjectives (even “Extreme” for that matter) begin to suggest the integration of potential impact, which adds an extra element to the definition. From the fire management perspective, in an area of high urban interface, an FFMC at Extreme would likely be thought to include both likelihood of a human-caused fire and the potential impact should it occur. There are other elements to consider when classifying model outputs. Boychuk et al. (in prep) address many of these points (e.g., precision of data, number of classes, scaling and class boundaries in data, colouring) which could be considered.

Lastly, there are other critical values and associations (Table 3) that are not included in the suggested class methodology. We have not explored the suitability of these associations or critical values with the current state of the research (e.g., probability of spot fires and FFMC). We recognize that the FWI System components are good predictors of many conditions of interest to fire management and having evidence-based associations are important. More important is that these critical values are reviewed regularly for their suitability.

5.0 New FWI Class Application

This report is a first attempt to outline a new approach to providing a common and consistent process-based method for delineating adjective rating classes for FWI System outputs. In developing this new classification methodology our goal was simply to provide a method that clearly and consistently defined FWI System output classifications. In developing this approach we worked closely with fire management staff. It is important that both researchers and fire management staff exchange knowledge so that foundational guidance in the use of the science is useful to agencies. This work focused on exploring the impacts of these changes to the established adjective rating classifications used operationally in the province of Ontario, which were developed primarily based on an original climatological frequency analysis. By associating a single physically meaningful process to each code and index of the FWI System, the classes could have more interpretive power in the daily decision-making of fire operations personnel. We acknowledge that this may not meet all operational needs, however, we hope this will encourage further dialogue both within NDMNRF and with other provincial agencies.

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