# Reviewing the “Hottest” Fire Indices Worldwide

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## Abstract

Wildfire indices are used globally to quantify and communicate a wide range of fire characteristics, including fire danger and fire behaviour. Wildfire terminologies, definitions and variables used to compute fire indices vary broadly. This makes it difficult to compare them under a common framework for regional assessment and for future improvements under changing climate and land-use/land-cover conditions. This paper reviews 24 fire indices used worldwide and proposes a simple framework within which they can be classified based on constitutive inputs used for their computation. We differentiate between constitutive inputs that are raw or directly measurable variables such as fuel, weather and topography (referred to as Level 1 inputs) and calculated constitutive inputs such as fuel moisture (as a function of ecology and hydrometeorology); fire behaviour (as a function of spread, energy, and ignition); and dynamic meteorology. These six calculated constitutive inputs are referred to as Level 2 inputs. Based on this classification, our findings indicate that the Burning Index from the United States National Fire Danger Rating System (NFDRS) and the Fire Weather Index from the Canadian Forest Fire Danger Rating System (CFFDRS), used by many countries worldwide, utilize the most comprehensive set of Level 2 inputs. In addition, the Level 2 input that is most frequently used by all fire indices is fuel moisture as a function of hydrometeorology and the least integrated input is that of fire ignition. We further group the fire indices in three types: fire weather, fire behaviour, and fire danger indices, according to the open literature definition of their predictant outputs and examine the specific constitutive inputs used in their computation. Most fire indices are based on Level 2 inputs (which use Level 1 inputs) and are predominantly fire danger and fire behaviour indices. This is followed by fire indices that use a combination of both Level 1 and Level 2 inputs, separately and are mostly fire danger indices. Only a few fire indices are computed solely with raw Level 1 inputs and are mainly fire behaviour indices. Providing a comprehensive view of the existing wildfire indices’ utilization and computational structure is expected to be a helpful resource for wildfire researchers and operational experts worldwide. 2

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Wildfire indices are used globally to quantify and communicate a wide range of fire characteristics, including fire danger and fire behaviour. Wildfire terminologies, definitions and variables used to compute fire indices vary broadly. This makes it difficult to compare them under a common framework for regional assessment and for future improvements under changing climate and land-use/land-cover conditions. This paper reviews 24 fire indices used worldwide and proposes a simple framework within which they can be classified based on constitutive inputs used for their computation. We differentiate between constitutive inputs that are raw or directly measurable variables such as fuel, weather and topography (referred to as Level 1 inputs) and calculated constitutive inputs such as fuel moisture (as a function of ecology and hydrometeorology); fire behaviour (as a function of spread, energy, and ignition); and dynamic meteorology. These six calculated constitutive inputs are referred to as Level 2 inputs. Based on this classification, our findings indicate that the *Burning Index* from the United States National Fire Danger Rating System (NFDRS) and the *Fire Weather Index* from the Canadian Forest Fire Danger Rating System (CFFDRS), used by many countries worldwide, utilize the most comprehensive set of Level 2 inputs. In addition, the Level 2 input that is most frequently used by all fire indices is fuel moisture as a function of hydrometeorology and the least integrated input is that of fire ignition. We further group the fire indices in three types: *fire weather*, *fire behaviour,* and *fire danger* indices, according to the open literature definition of their predictant outputs and examine the specific constitutive inputs used in their computation. Most fire indices are based on Level 2 inputs (which use Level 1 inputs) and are predominantly fire danger and fire behaviour indices. This is followed by fire indices that use a combination of both Level 1 and Level 2 inputs, separately and are mostly fire danger indices. Only a few fire indices are computed solely with raw Level 1 inputs and are mainly fire behaviour indices. Providing a comprehensive view of the existing wildfire indices’ utilization and computational structure is expected to be a helpful resource for wildfire researchers and operational experts worldwide.

## 1. Introduction

Observing and forecasting the danger and behaviour of wildfires requires understanding the synergistic role among weather, topography, and fuels and their interaction with each other over time. Monitoring and predicting wildfire danger and behaviour is essential for operational fire practices, protecting property and life, and guiding forest management and policy decisions. Fire emissions constitute an important Earth system component with regional and global scale impacts. The significant spatiotemporal differences among fire regimes and environmental conditions create the need to adopt different metrics to quantitatively determine potential wildland fire danger and behaviour (e.g., Keeley and Syphard, 2009). This has resulted in a wide range of terminologies, definitions and indices for wildfire assessment worldwide. While such a diversity is desirable for many reasons (e.g., relevance to local conditions, availability of data, easiness in computation, response preparedness, etc.), it also creates unnecessary confusion and limits our ability to compare and contrast those indices for future improvements.

We assert that developing a taxonomical framework within which fire indices can be categorized and compared in a broad sense could provide valuable insight on the complexity of each index and the constituents that make some indices more effective compared to others. Such a framework can also help to clarify some differences in terminology, improve communication among researchers, stakeholders, and policy makers, and provide a starting point for possible improvements as regional hydrometeorological and ecological conditions change in the future. With this motivation in mind, we present, herein, a taxonomical framework of fire indices based on the constituent inputs used in their computation. We review 24 fire indices used worldwide and classify them based on this taxonomical framework revealing the most (and least) frequently used constitutive inputs informing fire indices. We also group them into three types: *fire weather*, *fire behaviour*, and *fire danger* indices, according to the open literature definition of their predictant outputs, and analyze the constitutive inputs used as predictors in each type.

### ***Terminology and Structure***

In the wildland fire literature, terms such as ***fire danger***, ***fire danger rating***, ***fire behaviour***, ***fire danger rating system***, and ***fire indices*** are frequently used in a non-consistent manner. Here we attempt to discuss and clarify these fire terminologies (Table 1). Sharples et al. (2009) states that ***fire danger*** is a broad concept that incorporates many factors from ignition to propagation and subsequent impacts. This definition is similar to Beall (1946) who defines ***fire danger*** as including all factors that determine fire ignition, spread, damages, and difficulty of suppression. On the other hand, Chandler et al. (1983) defines ***fire danger*** as the result of the factors that affect the inception, spread, difficulty to suppress, and damages caused by a fire. Thus, while some studies define ***fire danger*** to include all factors from inception to aftermath, others define fire danger as solely the aftermath.

A ***fire danger rating*** produces a ranking score of the risk of a fire occurring and producing damage. This estimate of risk is usually over a large region or province. However, it is important to not confuse ***fire danger rating*** with ***fire behaviour*** (NWCG, 2002). In contrast to a ***fire danger rating***, ***fire behaviour*** describes the manner in which fuel ignites, flame develops, and fire spreads. ***Fire behaviour*** predictions produces outputs such as rate of spread, flame height, fire intensity, and spotting, crowning, and fire whirl potential. Unlike ***fire danger rating***, ***fire behaviour*** computes predictions at finer scales, such as in particular fields or for a specific fire. Thus, while ***fire***

***behaviour*** usually describes fire characteristics for particular fire or local area, a ***fire danger rating*** provides a ranking of potential fire danger over a large region (NWCG, 2002; Schlobohm and Brain, 2002).

There is also the term, ***fire danger rating system***. A fire danger rating system is an overarching term used for assessing fire danger. It can use models and sub-systems to simulate factors that affect fire danger, and it usually produces qualitative or quantitative metrics (indices) of fire danger. It also ranks these into discrete classes for the purpose of conveying public warning and implementing mitigation measures (NWCG, 2002).

Schlobohm and Brain (2002) suggest that ***fire danger rating systems*** comprise of five key components that include: (1) models representing the relationship between fuels, weather and topography, and wildfire impact; (2) systems to gather data to produce a fire rating; (3) a processing system to convert inputs to output components and to perform data analyses; (4) a communication system to disseminate danger rating information; and (5) a data storage system to retain data for historic reference. These danger ratings are often ranked from low to extreme and are visually plotted on maps that are user friendly and easy to interpret. Therefore, ***fire danger rating systems*** allow for a systematic evaluation of inferring ***fire danger***. It is used to identify conditions under which fires can start and spread (Merrill and Alexander, 1987; Field et al., 2015). Examples of ***fire danger rating systems*** used worldwide include the Canadian Forest Fire Danger Rating System (CFFDRS) used in Canada (Van Wagner, 1987); the United States National Fire Danger Rating System (NFDRS) (Deeming et al., 1977); and the Australian McArthur Forest Fire Danger Rating System (McArthur, 1966,1967).

***A fire danger rating system*** often comprises ***fire indices***. ***Fire indices*** are used to indicate or represent a certain aspect of wildland fire. There are many different ***fire indices*** that describe different aspects of wildland fires. For example, a fire index for predicting fire danger can be used to declare fire bans; issue fire warnings; estimate fire suppression difficulty; schedule prescribed burns, allocate resources and inform public awareness of fires; and assess fire behaviour potential in an operational setting (Sharples, 2009). ***Fire indices*** can also represent other fire behaviour characteristics, such as fire rate of spread (ROS), intensity, and flame length (Jolly et al., 2019). There are also fire weather indices that are commonly used by forecasters to predict un-favourable weather conditions that could potentially impede fire suppression tasks (Srock et al., 2018), such as the *Hot, Dry, Windy index (HDW)*, or the *Haines Index*.

***Fire danger rating systems*** and ***fire indices*** are often synonymous in the literature and are frequently used interchangeably. For example, the Canadian Forest Fire Weather Index System and the US National Fire Danger Rating Systems are sometimes referred to as fire weather "indices". We emphasize here that these are examples of an overarching ***fire rating system*** that uses ***fire indices*** (such as the *Fire Weather Index*, and the *Burning Index*, respectively), rather than being indices themselves. The variations in the terminology usage of ***fire rating systems*** and ***fire indices*** often leads to inconsistencies in fire nomenclature, adding uncertainties for wildland fire researchers and practitioners and makes it challenging to determine an even level of comparison among ***fire indices*** for regional fire assessment. For these reasons, along with the plethora of fire indices used worldwide, we focus on comparing the numerous wildfire indices by using a common taxonomical framework to alleviate some of the aforementioned challenges.

## 2. Methodology

We conducted an exhaustive literature and agency-wide search to determine the fire indices and their constitutive elements. We suggest a common framework that emerges from exploring the constitutive elements used to compute each fire index. This was done by first identifying that there are two levels of constitutive inputs that are used to produce a fire index (raw constitutive inputs called Level 1, and calculated constitutive inputs, called Level 2); see Figure 1. Level 1 comprises raw constitutive input data that are fundamental measurable inputs. These inputs often fall under weather, fuel, or topography, for which standard temperature, wind, and humidity values can be measured. It can also represent static variables such as slope, aspect, and fuel type measurements that can describe fuel loading and fuel size, (for example) as inputs. Level 2 comprises constitutive inputs that require calculations to represent some component of fire, such as calculating an aspect of fire behaviour, dynamic meteorology, or fuel moisture. Level 2 calculated constitutive inputs often use Level 1 raw constitutive inputs in its calculations. Once Level 2 calculated constitutive inputs are produced, they can be used to compute a fire index. These computation pathways are labeled as *L1* (using only Level 1 inputs), *L2* (using only Level 2 inputs; acknowledging however that some Level 2 inputs might be based on Level 1 variables) and *L1&2* (using an explicit combination of Level 1 and Level 2 constitutive inputs); see Figure. 1.

We quantitively compare the complexities among the fire indices by first identifying the number and the type of Level 2 calculated constitutive inputs used to produce each fire index; and second, determine which pathway is used to produce each fire index. The Level 2 constitutive inputs we consider are **fire behaviour (spread, energy, and ignition), dynamic meteorology**, and **fuel moisture (hydrometeorology, ecology),** and are highlighted nodes in Figure 1. **Fire behaviour**

**(spread)** describes the movement of a wildland fire, such as ROS. **Fire behaviour (energy)** describes the intensity of a fire, such as the energy released during a wildfire event. **Fire behaviour (ignition)** describes the onset of a fire and type of ignition source, such as natural or anthropogenic.

**Dynamic meteorology** constitutive inputs represent atmospheric variables that require calculations, such as atmospheric stability or vapour pressure deficit (VPD). Fire indices that comprise dynamic meteorological inputs will contain information on the state of the atmosphere such as atmospheric instability that is conducive for the development of fire plumes. The *Haines Index* is an example of a fire index that uses dynamic meteorology as one of its constitutive inputs, which explicitly calculates atmospheric stability by computing the air temperature gradient at different levels in the atmosphere. The *Hot Dry Windy Index* is another fire index that uses a dynamic meteorology constitutive input, which computes the VPD by taking the difference between the saturation vapour pressure and absolute moisture content in the atmosphere. Therefore, fire indices with dynamic meteorology constitutive inputs will explicitly contain computed meteorological parameters rather than solely using observed meteorological variables from Level 1 constitutive inputs.

Fuel moisture constitutive inputs include calculated variables related to moisture (or drought) as a function of ecology, meteorology, or hydrology. While drought as a function of meteorology is driven by precipitation deficits over extended time scales (Zargar et al., 2011) and takes into account temperature, humidity, and windspeed; hydrological droughts are described as a shortage of water supply from reduced streamflow, reservoirs and groundwater levels due to prolonged deficit in precipitation (Mallya et al., 2011). For the purpose of this study, we examined **fuel moisture (hydrometeorology)**, which is determined as a combination of both meteorological and hydrological drought. The fuel moisture calculated constitutive input driven by hydrometeorology represents moisture (or drought) that is induced from hydrological (such as streamflow) and/or meteorological (such as air temperature) parameters. The *Mark 5 Forest Fire Danger Index* is an example of a fire index that uses fuel moisture (hydrometeorology). Specifically, it computes the Keetch-Byram Drought index (KBDI), which represents daily water balance based on precipitation and soil moisture inputs. We, therefore, assess fuel moisture as a combined hydrological and meteorological components because meteorological variables, such as precipitation often influence hydrological droughts as well, making it difficult to discern meteorological drought influences from hydrological features.

The final calculated constitutive input we consider is **fuel moisture (ecology)**. Fuel moisture (ecology) describes a shortage of water supply for plant growth and can be quantified as insufficient soil moisture in root zones. Fire indices that use fuel moisture (ecology) will have explicit variables that describe fuel characteristics such as live or dead fuels, or plant water stress. For example, the *Fire Potential Index,* comprises the fuel moisture (ecology) constitutive inputs because it accounts for observed proportion of living vegetation greenness. Thus, **fuel moisture (ecology)** can represent fuel states such as fuel moisture content in live and dead fuels (Planas and Pastor, 2013). The moisture content within living vegetation can be determined by plant water stress. Increased moisture can reduce the rate of energy release and rate of spread during a fire. The moisture in live fuels makes vegetation less available to absorb heat for preheating fuel particles and for ignition. Ignition will not occur if the heat required to evaporate the fuel moisture is more than the amount available in a firebrand (Simard, 1968; Burgan and Rothermerl, 1984). Unlike live fuel, dead fuel moisture is solely controlled by changing weather conditions and is quantified by time-lag categories of 1-hour, 10- hour, 100-hour, and 1000-hour fuels, for which the fuel element diameters are a quarter to one inch, one to three inches , or greater than three inches, respectively. For example, a 1-hour fuel only takes an order of one-hour to respond to changing weather conditions (Anderson, 1982; Scott and Burgan, 2005; McGranahan, 2019). **Fuel moisture (ecology)** also represents moisture due to fuel properties, such as intrinsic fuel properties (chemical composition and thermal properties) or extrinsic fuel properties (fuel load, shape and size, bulk density compactness and arrangement).

We subsequently analyze which pathway (*L1, L2,* or *L1&2*) is used to compute each fire index, determined by their usage of Level 1 and Level 2 constitutive inputs. We also classify these fire indices by types (*fire weather* index, *fire danger* index, or *fire behaviour* index) and categorize them under their respected pathway. Classifying each fire index by type is conducted by simply determining what aspect of wildland fire the index is predicting, based on the open literature definitions. A *fire behaviour* index will determine certain characteristics of a particular fire while it is occurring, such as its movement, or its energy released, whereas *fire danger* index will provide an overarching indicator of potential fire threats, damages or difficulty to suppress a wildland fire. A *fire weather* index will determine whether meteorological conditions are favourable for the development of a wildland fire (Table 1).

The framework presented provides a simplified approach for comparisons to be conducted among various fire indices. By assessing the respective inputs and pathways for computing fire indices, our analysis is expected to provide an insightful reflection of the most important environmental states used to inform conditions related to fire weather, fire behavior, and fire danger.

## 3. Results and Discussion

Based on our literature and agency-wide search we have identified 24 fire indices (Table 2). We acknowledge that there are indices such as drought and moisture indices that are not represented in this list. This is because our list compiles only the indices related to fire danger, fire weather, or fire behaviour. Moisture and drought indices, for example, would be considered Level 2 calculated constitutive inputs.

We further acknowledge that there are additional primary fire indices that are produced in large network systems, such as NFDRS. While the NFDRS produces seven different fire indices, we only analyze the NFDRS *Burning Index (NFDRS BI).* This is because, it is the main and most frequently used index for fire danger rating in comparison to the other indices.

We also recognize that the *NFDRS BI* combines with ignition indices to produce a *Fire Severity Index*. However, we do not consider this *Fire Severity Index* in our analysis because it is rarely used in operational and managerial settings. This is mainly due to the fact that it is difficult to represent fire ignition indices from lightning and human activity because of the limitations in quantifying thunderstorm intensity and, separately, human activity. Thus, the lightning and human ignition indices are seldom included in management decisions (NWCG, 2019) and for this reason, the *Fire Severity Index* is rarely used in operational settings. For these aforementioned reasons, we choose to analyze only the *NFDRS BI*.

The 24 fire indices adopted by countries worldwide are discussed below and are presented by geographic location of their inception for regional comparison purposes. We give an overview of each of these fire indices and their interpretations along with their corresponding fire index type. A description of the Level 1 and Level 2 constitutive inputs is included in Table 3.

### ***Developed in North America***

A large number of fire indices have been developed in North America. Here we summarize eight American fire indices and one Canadian fire index. The *NFDRS BI* is considered a fire behaviour index. It is one of the final outputs from the NFDRS and is derived from a combination of the spread component (SC) and energy release component (ERC). The SC is a rating of the forward rate of spread of a head fire, and the ERC is a quantification of the available energy (BTU) per unit area (square foot) at the flaming front of a head fire (NWCG, 2002). The *NFDRS BI* is expressed as a numeric value that is closely related to the flame length. Its scale is open ended, allowing its range to adequately define fires of multiple scales (NWCG, 2019). Jolly et al. (2019) suggests that the *NFDRS BI* tends to be the primary decision index for fire danger rating, more so than other fire indices used by NFDRS, such as the ERC.

Based on the NFDRS is the *Severe Fire Danger Index (SFDI)*. The *SFDI* is a fire danger index recently developed in the US to predict extreme fire danger (Jolly et al., 2019). It uses a 39-year gridded climatology input and calculates daily ERC and *NFDRS BI* at a 4 km grid resolution. These two indices are normalized relative to their long-term location-specific climatology and merged to produce *SFDI*. The interpretation of *SFDI* contains five classes ranging from low to severe. This index is beneficial for identifying extreme conditions that might lead to firefighter fatality and cause tremendous fire damage (Jolly et al., 2019).

Another index based on the NFDRS is the wildland *Fire Danger Index (FDI)*. It is used by the Florida Forest Service in the United States. While not much is available in the open literature regarding the inception of this index, it uses ERC and relative humidity to estimate the start of fire on any given day. What it does not consider, however, is the rate of growth of a fire, or the level of suppression difficulty (Florida Department of Agriculture and Consumer Services, 2020).

The *Fosberg Fire Weather Index (FFWI)* was developed by Fosberg (1978). This fire weather index assesses the effects of short-term and small-scale weather variations on fire potential. It is also very sensitive to changes in fine fuel moisture. Furthermore, *FFWI* is related to fire occurrence in the northeastern and southwestern USA (WSL, 2012). *FFWI* has a fuel moisture component expressed by calculating an equilibrium moisture content, as a function of air temperature and humidity, and based on Simard (1968). *FFWI* also has a rate of spread component based on the Rothermel (1972) model (Goodrick, 2002; WSL, 2012). This index requires hourly observed inputs of humidity, temperature, and windspeed. However, it lacks rainfall input and was, thereby, deemed problematic for its ability to capture regional spatial variations in fire potential. A *modified FFWI (mFFWI)* was implemented by Goodrick (2002) that took into consideration a fuel availability factor (FAF) that assessed drought on fuels. FAF is also a function of the Keetch-Byram drought index (KBDI) and has an initial starting condition that requires the soil layer to be saturated with at least eight inches of water for a one-week duration after a rainfall event. FAF is multiplied by *FFWI* to produce the *mFFWI* (WSL, 2012).

The *Fire Potential Index (FPI)* is provided by the US Geological Survey (USGS) and provides daily relative measure of fuel flammability across the United States at a 1 km resolution. *FPI* can be considered a fire behaviour index because it determines the onset of a fire due to vegetation.

*FPI* is a moisture-based vegetation indicator and is a function of current living vegetation greenness to the maximum greenness. In addition, it is a function of current 10-hour dead fuel moisture, proportionate to the moisture of extinction. *FPI* is interpreted on a scale of 0 to 100. When living vegetation is mostly or completely cured and the 10-hour dead fuel moisture is low, the *FPI* is ranked high on the scale. *FPI* does not consider a wind component due to the spatial variability of wind. In addition, *FPI* does not indicate the chance that a large fire will occur (USGS, 2020).

*Chandler Burning Index (CBI)* was developed by Chandler et al. (1983). It utilizes temperature and relative humidity inputs to produce a fire danger index. *CBI* can provide the effects of average monthly temperature and humidity on fire intensity and rate of spread. Both the intensity and spread of the index is linearly related to temperature, that is, as temperature increases so does the value of the overall index. However, spread and intensity are exponentially related to humidity, for example, a small decrease in humidity results in a large increase in the index value. This relatively less computationally intensive index is, thereby, used in real-time measurement updates. The *CBI* has five classifications which rank from low (less than 50) to extreme (values greater than 97.5) (Sasquatchstation, 2017; Wagenborgen, 2019).

The *Haines Index (HI),* also known as the *Lower Atmospheric Severity Index* was developed by Haines (1988). *HI* is a fire weather index that provides a measure of the likelihood for plume-driven fires to become large and erratic in behaviour by evaluating the potential contribution of dry and unstable air (Winkler et al., 2007). The index is calculated by taking the sum of a stability and humidity component. Stability is calculated from the lower atmosphere environmental lapse rate, and humidity is calculated from the dewpoint depression. *HI* accounts for regional variations in surface elevation. The resulting index ranges from 2 (very low potential of large or erratic plume-dominated behaviour) to 6 (very high potential). This index is a widely used tool in wildfire forecasting and monitoring in the United States. It is regularly used by the National Weather Service daily fire weather forecast and the United States Department of Agriculture (USDA) Forest Service's Wildland Fire Assessment System (WFAS) (Winkler et al., 2007).

A recently developed index is the *Hot-Dry-Windy-Index (HDW)* by Srock et al. (2018). *HDW* is computed by meteorological variables that govern the atmospheric influence on fire. This fire weather index can identify days when synoptic and meso-alpha scale meteorological variables are favourable for fire development. *HDW* calculates vapour pressure deficit (VPD) by the wind and is the product of the largest VPD and the highest wind speed in a 500 m layer above the surface. *HDW* tends to perform well for different regions that span a range of environmental conditions (Srock et al., 2018).

Finally, the *Fire Weather Index (FWI)* comprises the Canadian Forest Fire Weather Index System developed in Canada by Van Wagner, 1977 and is an integral component of the overarching CFFDRS. *FWI* predicts fire danger throughout Canada by comprising three fuel moisture codes and three fire behaviour indices. *FWI* combines the initial spread index (ISI) and build up index (BUI) to provide an overall rating system of a fire line intensity and is, therefore, considered a fire behaviour index. Values greater than 30 are considered extreme (NRC, 2020). Though developed in Canada, *FWI* is used worldwide because it can be adapted to local conditions in other regions, such as northern regions of the United States and parts of Southeast Asia (WSL, 2012).

### *Developed in South America*

The *Meteorological Fire Danger Index (MFDI)* was developed by Sismanoglu and Setzer (2004) in Brazil and is considered a fire danger index. *MFDI* is operationally used to assess fire danger and represents how predisposed vegetation is to burn on a given day. *MFDI* is based on vegetation cover, daily maximum temperature, minimum relative humidity, and accumulated precipitation. These raw inputs are used to calculate drought day index (DD); base danger (BD); humidity, and temperature factors. *MFDI* assesses fire danger in five classes that ranges from minimum (less than 0.15) to critical (greater than 0.95) (Silva et al., 2016).

### *Developed in Europe*

Seven European fire indices are presented. The *Angstrom Index (AI)* is a fire behaviour index developed in Sweden. It has a pure climatic approach (Arpaci et al., 2013). It simply uses relative humidity and temperature to predict fire occurrence. The fire occurrence is interpreted by four classes that range from unlikely to a very likely fire occurrence. This index has been used in some parts of Scandinavia for indicating expected fire start days (Chandler et al., 1983). *AI* does not use a model to calculate fuel moisture and does not accumulate fire danger ratings over time, nor does it consider wind effects. It instead, represents simple day-to-day fire danger due to dryness of air; (NWCG, 2002; Arpaci et al., 2013).

The *Baumgartner Index (BI)* was developed by Baumgartner et al. (1967) in Germany. *BI* is a fire danger index that assesses fire danger susceptibility based on fuel dryness as a function of evapotranspiration. The index is calculated on a daily basis with evapotranspiration measurements recorded at 2 PM each day. There are five fire danger classes that rank from low to very high and the output index value in each class varies monthly from March through September. It is believed that this index does not perform well during spring when dead litter flammability depends less on precipitation than short-term drought conditions (WSL 2012; Stagl et al., 2016).

The *Orieux Index (OI)* is a fire danger index and was developed by Orieux (1974). It is used to predict fire danger in southeastern France in a Mediterranean climate. Its raw inputs include wind speed, soil moisture, temperature and precipitation to calculate soil moisture reserve and forecast next day windspeed. The estimated soil water reserve determines the daily balance between rainfall and evapotranspiration, which is considered saturated when water content reaches 150 mm. This estimate is combined with the next day's wind speed forecast to determine fire danger. The estimates of water reserves fall under a certain range that is compared to predicted wind speed in a certain range. For example, estimated reserve between 100-150 mm with a windspeed less than 20 km/h will have a corresponding index value of 0, while an estimated water reserve less than 30 mm and a wind speed greater than 40 km/h will have an index value of 3. The danger classes are, thus, divided into four classes from low (0) to very high (3). It is suggested that *OI* is mostly suitable for summer months (Sol, 1989; WSL, 2012).

*Carrega I87 (I87)* was developed by Carrega (1988, 1991) and is a fire behaviour index used in Southern France. Calculated on an hourly basis, it uses meteorological variables to determine fire occurrence and fire spread. Raw inputs include wind, air humidity, temperature, and surface and deep soil water reserves and are used to calculate potential evapotranspiration, similar to that used by *OI* (Arpaci et al., 2013). *I87* has values that are above 100, indicating a very high fire danger rating (WSL, 2012).

The *Nesterov Index (NI)* was developed by Nesterov in 1949 in Russia. This fire behaviour index represents ignition of potential fire as a function of mid-day and dewpoint temperatures, and the number of wet days since the last rainfall (greater than 3 mm). Rainfall events above 3 mm reset the index to zero. The classification is usually ranked with minimal fire danger producing a value less than 300, and extreme fire danger greater than 4000 (Nogueira et al., 2017). A *modified Nesterov Index (mNI)* was developed by Venevsky et al. (2002). While *mNI* is very similar to *NI*, it contains one additional variable (K), which is a scale coefficient between 0 and 1. This variable controls the resetting value when rainfall events occur. It is equal to 1 when no rainfall occurs and is equal to 0 when daily rainfall is above 20 mm. K gradually decreases between 1 (when no rainfall occurs) to 0 (when daily rainfall is equal or greater than 20 mm).

*M68* was developed by Kase (1969) in Germany. *M68* is a fire behaviour index that produces a fire occurrence probability, ranging from less than 3% to greater than 60% (WSL, 2012). It is used to predict fire danger in the Scots pine stands in Brandenburg, Germany and is based on *NI*. Its raw inputs include temperature, rainfall, and vegetation conditions to calculate vapour pressure deficit (Arpaci et al., 2013). *M68dwd* is a modification of *M68* by the German weather service (Apraci et al., 2013) and includes phenological processes. This fire behaviour index was developed to simulate impact of phenological stage and seasons for fire danger. It uses the greening and sprouting dates of certain fuel species, such as European Birch and Black Locust to determine environmental features that could decrease fire danger due to higher moisture content in green vegetation (Apraci et al., 2013).

The *Fire Severity Index (FSI)* is used in the England and Wales Meteorological Office. This fire behaviour index provides an assessment of how severe a fire could become if it were to start. It does not assess the risk of wildfires occurring. *FSI* is based on a similar approach as the Canadian Fire danger Rating system. It is calculated by ingesting information of wind speed, temperature, time of year, and rainfall, and uses weather information from the Met Office operational forecast model. *FSI* maps indicate the current day's fire severity and provides a forecast of likely fire severity over the next five days. The *FSI* values range from one (low fire severity) to five (exceptional fire severity) (Met Office, 2020).

### ***Developed in Australia***

We present three of Australia's popular fire indices. The *Mark 5 Forest Fire Danger Index (FFDI5)* was developed by McArthur (1967) and has been widely used in Eastern Australia to assess fire danger for eucalypt fuel types (Sharples et al., 2009). The *FFDI5* has five classification schemes, ranging from low (0-5) to extreme (greater than 50). *FFDI5* has a comprehensive network of Level 2 constitutive inputs, such as a drought factor that incorporates the KBDI. *FFDI5* also comprises raw input of dry-bulb temperature, relative humidity, and wind speed at 10 m height, and measured at 3 PM (Matthews, 2009; Sharples et al., 2009; WSL, 2012).

Similar to *FFDI5*, the *Mark 5 Grassland Fire Danger Index (GFDI5)* was also developed in Australia by McArthur in 1977. This fire behaviour index predicts the severity and difficulty of fire suppression. It uses the grassland fire danger meter Mark 5, which aids in the prediction of fire behaviour in a wide variety of grassland fuel types. The *GFDI5* uses raw Level 1 inputs, such as dry-bulb temperature, relative humidity, wind speed, and degree of grass curing as a percentage (Sharples et al., 2009).

A relatively recent and less computational fire index, *Fire Danger Index (F),* was developed by Sharples et al. (2009). The purpose of *F* is to assesses fire danger in eucalypt forests in southern Australia in a simplistic, yet effective way, similar to the more complex fire indices used in Australia. *F* can be interpreted by five categories, low (0.0-0.5) to extreme (greater than 0.75) (Sharples et al., 2009). *F* is calculated using a fuel moisture index (FMI) and wind speed, for which FMI is dependent on only hydrometeorological factors of temperature and humidity. It is acknowledged that FMI assesses short-term changes in fuel moisture. Therefore, Sharples et al. (2009) produced a *modified Fire Danger Index (mFD).* The *mFD* incorporates a drought factor (DF) in addition to using the FMI. The DF takes into account long-term moisture effects due to fuel availability. The DF is also a function of KBDI. DF also considers the number of days since the last rain event and its corresponding total (WSL, 2012).

### ***Comparison among Fire Indices***

We apply our taxonomical framework to the 24 fire indices by identifying the six Level 2 calculated constitutive inputs: **fuel moisture (ecology, hydrology)**; **dynamic meteorology**; **fire behaviour (spread, energy, ignition)** that contribute to the fire indices. Figure 2 (read horizontally), indicates which Level 2 calculated constitutive inputs are used in each fire index. For example, it is evident that *F* solely uses **fuel moisture (hydrometeorology)**, whereas the *NFDRS BI* uses all but the **dynamic meteorology** and ignition Level 2 calculated constitutive inputs. Read vertically, Figure 2 also indicates the number of fire indices that use each of the Level 2 calculated constitutive inputs. It is evident that fuel moisture, both as a function of ecology and hydrometeorology, as well as **dynamic meteorology** are more frequently used by fire indices in comparison to the behaviour Level 2 calculated constitutive inputs. **Ignition**, by contrast is not used explicitly by any of the fire indices analyzed.

Furthermore, Figure 2 indicates the fire index type: fire danger (D), fire behaviour (B), or a fire weather (W), based on what aspect of fire the index is predicting, defined in Table 1. The pie graph in Figure 2 shows that most of the fire indices used worldwide represent fire danger (over 45%) and fire behaviour (over 40%). Fire weather indices account for less than 15% of all fire indices analyzed.

Figure 3 shows the number of Level 2 calculated constitutive inputs used in each fire index. Five distinct fire index groups emerge from Figure 3 that use no Level 2 calculated constitutive inputs (Group 1) to those that use four or more of the six Level 2 constitutive inputs analyzed (Group 5). In addition, the type of fire index: fire danger (D), fire behaviour (B), or fire weather index (W) is also denoted for each fire index. In Group 1, *AI, CBI*, *NI* and *mNI* do not use any Level 2 calculated constitutive inputs and only use Level 1 inputs directly. These fire indices are a combination of both fire behaviour and fire danger index types. The majority of fire indices (nine of the 24 analyzed) are in Group 2 and only use one of the Level 2 calculated constitutive inputs. The indices in this group are a mixture of fire weather, fire behaviour, and fire danger indices. All fire weather index types fall into this group, which only uses one Level 2 calculated constitutive input. Groups 3 and 4 use two and three Level 2 calculated constitutive inputs, respectively. These fire indices contain a combination of both fire behaviour and fire danger index types. Group 5 represents the fire indices that use the most (four) Level 2 calculated inputs. The *NFDRS BI* and the *SFDI* both use the greatest number of Level 2 calculated inputs and represent a fire behaviour and fire danger index type, respectively. They rank similarly because they are both based off of the NFDRS and are derived using similar Level 2 calculated constitutive inputs.

The most used fire indices worldwide are the *FWI* and the *NFDRS BI*. Perhaps the comprehensive use of the many Level 2 calculated constitutive inputs could be the reason why they are widely used across the world. Their complexity and integration of the many Level 1 and 2 constitutive inputs make these two fire indices more sophisticated for fire prediction applications. *FWI*, is often adopted worldwide in fire-prone regions of Europe, South-East Asia, Central and South American countries because it is computationally easy to use, it is robust in a variety of environments, and it has strong interpretive outputs (Taylor and Alexander, 2006; Plans and Pastor, 2013).

Figure 4 shows the number of fire indices that use each of the Level 2 calculated constitutive input analyzed. **Fuel moisture (hydrometeorology)** is the most used Level 2 calculated constitutive input by fire indices, followed by **fuel moisture (ecology)**, **dynamic meteorology**, **spread**, **energy**, and **ignition**. Over 12 of the analyzed fire indices use fuel moisture driven by hydrometeorology. This is probably because acquiring hydrometeorological measurements is perhaps more attainable in comparison to fuel moisture as a function of ecology because they are less computationally and empirically challenging to acquire. Meteorological variables are also fundamental and frequently used Level 1 raw inputs, making it more efficient to derive Level 2 calculated constitutive inputs for fire weather, fire behaviour, and fire danger indices.

**Fuel moisture (ecology)** Level 2 calculated constitutive inputs are less used by the fire indices (only by 10 of the fire indices). This may be due to the fact that at the landscape scale there are large variations in the type, structure, physical and chemical characteristics of vegetation. These attributes may contribute to some of the challenges in predicting fire behaviour driven by ecological processes. Australia, for example has two separate well used fire indices for different vegetation type (*FFDI5* and *GFDI5*) and are used in different regions of Australia. It is almost impossible to produce a global classification of fuel models (Plans and Pastor, 2013). For this reason, different countries have to adopt different fuel models, or modify an adopted index, such as the Canadian *FWI*, to fit their respective landscape. The countries where most work has been done to characterize fuels in terms of fire behaviour responses are the United States, Canada, and Australia (Plans and Pastor, 2013; LF, 2020).

To a lesser extent, Level 2 calculated constitutive inputs of **spread** and **energy** are used by five and three fire indices, respectively. Fire indices with these behaviour characteristics are used less frequently. For example, a survey of the indices published through the Weather Information Management System (WIMS) on the WFAS for 15 July 2019 showed that out of 1907 Remote Automated Weather Stations reporting, 1012 used the *NFDRS BI* as their primary decision index; 888 used the energy release component (ERC) from NFDRS and only six used the NFDRS Spread Component (Jolly et al., 2019).

Furthermore, the **ignition** Level 2 calculated constitutive input is not used by any of the fire indices. An ignition component is often challenging and difficult to integrate into a fire index since it is frequently due to societal or human induced factors such as by campfires. Human-started wildfires account for over 80% of ignitions (Balch et al., 2017). These anthropogenic behaviours can be challenging to integrate into physics-based models. For example, the NFDRS has an ignition component but it is often not used in the overall rating system for operational predictions due to these aforementioned constraints. This emphasizes the potential need for including an additional socio-economic component to evaluate wildfire danger and risks in future fire danger indices. We also acknowledge that the *NI, mNI*, and *M68* are fire behaviour indices that represent ignition or fire occurrence; however, they do not explicitly use a Level 2 calculated constitutive input that calculates ignition.

We further analyze the pathways in which each fire index type is produced. Most fire indices use pathway *(L2)*, followed by pathway *(L1&2)* and pathway *(L1)* (Table 4). We find that most of the fire indices analyzed are derived from pathway *(L2)*, which uses Level 2 calculated constitutive inputs that are computed by Level 1 raw constitutive inputs. Eleven of the 24 fire indices fall under this category. There are an equal number of fire behaviour indices and fire danger indices that are computed using only pathway *L2*.

Fire indices that are derived from pathway *(L1&2)* use a combination of Level 2 calculated constitutive inputs, in addition to Level 1 raw constitutive inputs, separately. Nine of the 24 fire indices fall under this category. This pathway is most frequently used to calculate fire danger indices, and to a lesser extent, fire behaviour and fire weather indices.

Fire indices computed from Level 1 raw input variables (pathway *L1*) are the least frequent, with only 4 out of the 24 indices analyzed. Of the four fire indices, three are fire behaviour indices and one is fire danger. This, relatively less complex pathway is used to calculate *AI* and *CBI, NI,* and *mNI.* These four indices also do not use any Level 2 calculated indices, suggesting that these are less computationally intensive fire indices to calculate.

In summary, fire indices are most frequently derived using pathway *L2* and least frequently derived using the less complex pathway, pathway *(L1)*. Fire behaviour indices are most frequently derived using pathway *(L2)*; fire danger indices are most frequently derived using both pathway *(L2)* and *(L1&2)*; and fire weather indices are more frequently derived using pathway *(L1&2)*.

Despite the differing levels of complexities, it is interesting to note that many of the original sources of the fire indices discussed above date back to over 50 years ago, such as Nesterov (1949) and McArthur (1967). Eastaugh, et al. (2014) have recognized that numerous fire indices have been developed over the past 50 years, beginning with purely empirical meteorological indices, such as Angstrom and Nesterov in the 1940s. These seminal approaches have been modified over the years to account for vegetation types, for example Kase (1969) or to account for soil moisture, using the Keetch and Byram (1968) Level 2 calculated constitutive inputs. More sophisticated indices have evolved, such as the *FWI* Van Wagner (1987) that connects meteorological conditions to soil moisture in different fire fuel layers (Eastaugh et al., 2014). This suggests that the fundamental physical approaches used over half a century ago are still the seminal approaches used in many of today's fire indices.

## 4. Conclusions

We summarize 24 fire indices and discuss their level of complexity based on a proposed taxonomical framework informed by the constituent inputs used to compute these fire indices. We defined three computational pathways for fire indices: pathway *L1* (fed by Level 1 raw variables), pathway *L2* (fed by Level 2 computed constitutive inputs) and *L1&2* (fed by a combination of constitutive inputs). The Level 2 calculated constitutive inputs include **fuel moisture (hydrometeorology**, and **ecology)**; **dynamic meteorology**; **fire behaviour** (**spread**, **energy**, and **ignition)**.

By applying this taxonomical framework, we are able to compare the 24 fire indices across a standardized baseline. We examine the number and types of Level 2 inputs used in each fire index, along with pathways in which these fire indices are computed. We find that most fire indices use fuel moisture as function of hydrometeorology, followed by fuel moisture as a function of ecology. Furthermore, the National Fire Danger Rating System's *Burning Index* and the Canadian Forest Fire Danger Rating System's *Fire Weather Index* are the most comprehensive and documented fire indices adopted worldwide. In addition, most fire indices are derived using pathway *L2*, with an equal number comprising fire behaviour indices and fire danger indices.

While we believe that this is an exhaustive and comprehensive analysis of the fire indices used worldwide, we acknowledge that there may be additional indices, such as the *numerical risk index* and the *Portuguese Index*; however, there was insufficient information available for the inclusion in our analysis. We also recognize that there are other Level 2 calculated constitutive inputs, such as the Palmer drought index, or the standardized precipitation evapotranspiration index (SPEI). However, they were excluded from this study because they were not integrated into any of the overarching fire indices analyzed in this paper. In addition, there are a few useful online sources that present some of the fire danger rating systems and fire indices, which were presented here. These helpful sources include the Weather Information Management System (WIMS) and the Wildland Fire Assessment System (WFAS).

Finally, we recognize that the seminal approaches from the past 50 years are still used as the basis of many current fire indices. Perhaps what has changed in producing the fire indices is not the fundamental physics, but rather the data retrieval measurements of Level 1 raw constitutive inputs and the data assimilation techniques for Level 2 calculated constitutive inputs. Today, satellite derived data, along with a network of ground-based weather observation stations and reanalysis models, are assimilated to calculate fire indices. There are also nascent advances in improving empirical and physics-based models by integrating machine learning approaches for wildfire predictions. As the demand for wildfire predictions continue, due to changes in climate and land use land cover, increased sophistication in fire indices along with innovative methods in data collection and data assimilation will become additionally important in future wildland fire operations and scientific wildfire pursuit.

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**Table 1.** Definitions of wildland fire terminology used in the current paper

| **Term** | **Definition** |
|---|---|
| Fire danger | Fire danger is the combination of constant factors (fuel and topography) and variable factors (weather) affecting the inception, spread, difficulty of control, and potential to do damage (Chandler et al., 1983; NWCG, 2002). |
| Fire danger rating | A ***fire danger rating*** produces a ranking score of the risk of a fire occurring and producing damage. This estimate of risk is usually over a large region or province (NWCG, 2002). |
| Fire behaviour | ***fire behaviour*** describes the manner in which fuel ignites, flame develops, and fire spreads, over a relatively smaller region such as a field or particular fire (NWCG, 2002). |
| Fire danger rating system | A ***fire danger rating system*** is an overarching term used for assessing fire danger. It can use models and sub-systems to simulate factors that affect fire danger, and it usually produces indices of fire danger. It also ranks these into discrete classes for the purpose of conveying public warning and implementing mitigation measures (NWCG, 2002); examples include. ***Canadian Forest Fire Danger Rating System (CFFDRS)***; US. ***National Fire Danger Rating System (NFDRS)***; ***McArthur Fire Danger Rating System*** used in Australia. |
| Fire index | A ***fire index*** is used to indicate or represent a certain aspect of wildland fires and can be used to help declare fire bans, issue fire warnings, estimate fire suppression, assess fire behaviour potential (Sharples 2009); examples include ***Fire weather index; Burning Index; Forest Fire Danger Index*** |
| Fire behaviour index | ***A fire behaviour index*** indicates certain characteristics of a particular fire such as its spread rate. |
| Fire weather index | ***A fire weather index*** indicates whether meteorological conditions are favourable for the development of a wildland fire. |
| Fire danger index | ***A fire danger index*** gives an overarching indicator of potential fire threat or damage and often describes the difficulty to control or supress wildland fires. |

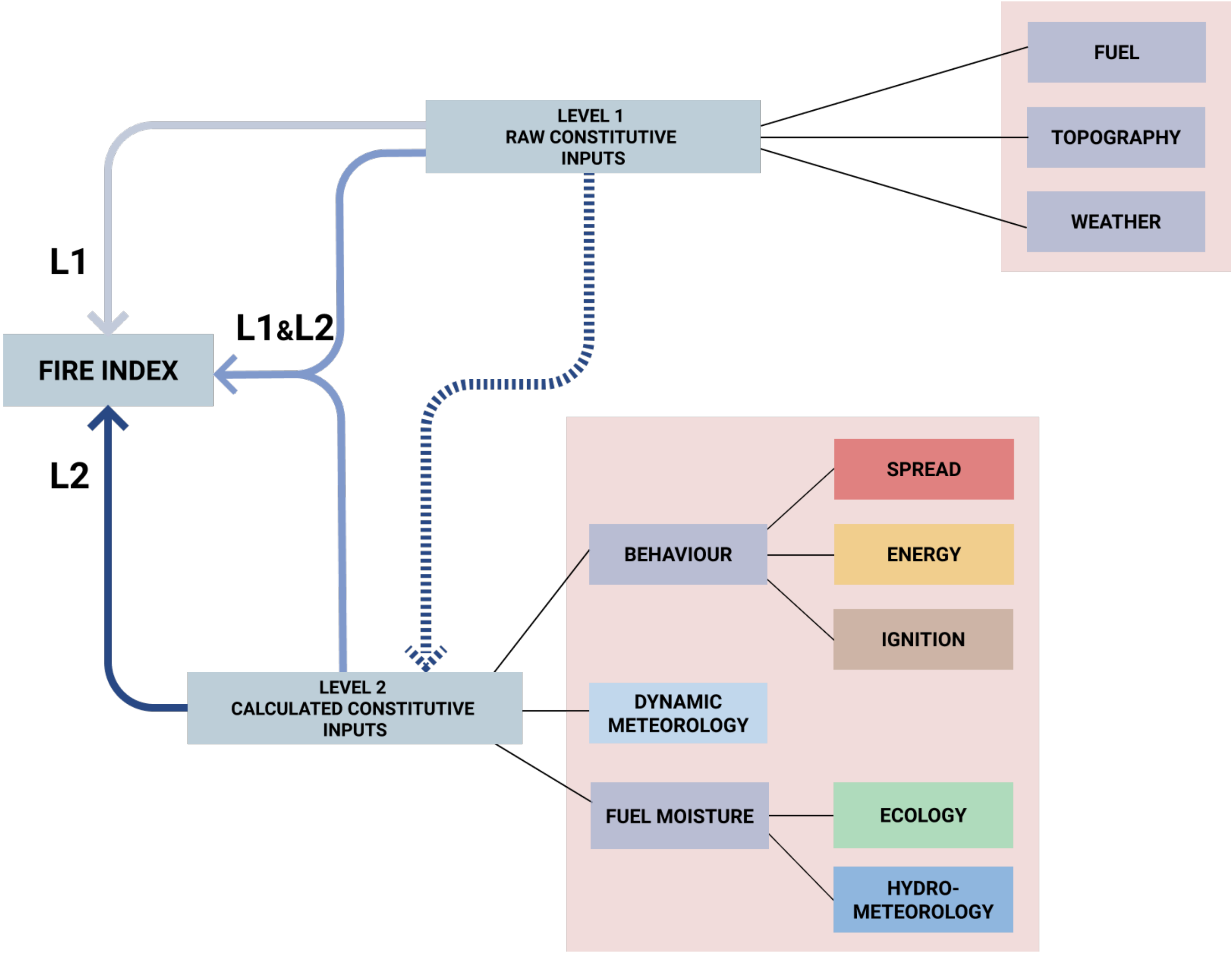


**Figure 1.** The taxonomical framework used to categorize the 24 fire indices. Level 1 raw constitutive inputs are represented by fuel, topography, and weather and can be used directly to produce a fire index (*L1* pathway; lightest shaded solid arrow) or to compute Level 2 constitutive inputs (dashed arrow). Level 2 inputs comprise behaviour (spread, energy, ignition); dynamic meteorology; fuel moisture (ecology, and hydrometeorology), which are used to produce a fire index (*L2* pathway; darkest shaded solid arrow). These colour coded level 2 constitutive inputs are used to assess the computational complexity of each fire index. Level 1 and Level 2 inputs can be combined to produce a fire index (*L1&2* pathway; medium shaded solid arrow).

**Table 2.** List of the 24 fire indices analyzed with their corresponding sources and country of development

| | **FIRE INDICES** | **SOURCE** | **COUNTRY of DEVELOPMENT** |
|---|---|---|---|
| 1 | **AI (Angstrom Index)** | Chandler et al., 1983 | Sweden |
| 2 | **BI (Baumgartner Index)** | Baumgartner et al., 1967 | Germany |
| 3 | **CBI (Chandler Burning Index)** | Chandler et al., 1983 | USA |
| 4 | **F (Fire Danger Index)** | Sharples et al., 2009 | Australia |
| 5 | **FDI (Wildland Fire Danger Index)** | Florida Department of Agriculture and Consumer Services | Florida, United States |
| 6 | **FFDI5 (Mark 5 Forest Fire Danger Index)** | McArthur, 1967 | Australia |
| 7 | **FFWI (Fosberg Fire Weather Index)** | Fosberg, 1978 | United States |
| 8 | **FPI (Fire Potential Index)** | United States Geological Survey | United States |
| 9 | **FSI (Fire Severity Index)** | Met Office, 2003 | United Kingdom |
| 10 | **FWI (Fire Weather Index)** | Van Wagner, 1977 | Canada |
| 11 | **GFDI5 ( Mark 5 Grassland Fire Danger Index)** | McArthur, 1967 | Australia |
| 12 | **Haines Index** | Haines, 1988 | United States |
| 13 | **HDW (Hot Dry Windy)** | Srock et al., 2018 | United States |
| 14 | **I87** | Carrega, 1988; 1991 | France |
| 15 | **M68** | Kase, 1969 | Germany |
| 16 | **M68dwd** | German Weather Service | Germany |
| 17 | **MFDI (Meteorological Fire Danger Index)** | Sismanoglu and Setzer, 2004 | Brazil |
| 18 | **mFD (Modified Fire Danger Index)** | Sharples et al., 2009 | Australia |
| 19 | **mFFWI ( Modified Fosberg Fire Weather Index)** | Goodrick, 2002 | United sStates |
| 20 | **mNI (Modified Nesterov Index)** | Venevsky et al., 2002 | Russia |
| 21 | **NFDRS BI (Burning Index)** | Deeming et al., 1977 | United States |
| 22 | **NI (Nesterov Index)** | Nesterov, 1949 | Russia |
| 23 | **OI (Orieux Index)** | Orieux, 1974 | France |
| 24 | **SFDI (Severe Fire Danger Index)** | Jolly et al., 2019 | United States |

**Table 3.** Description of each fire index and the corresponding Level 1 and Level 2 constitutive inputs

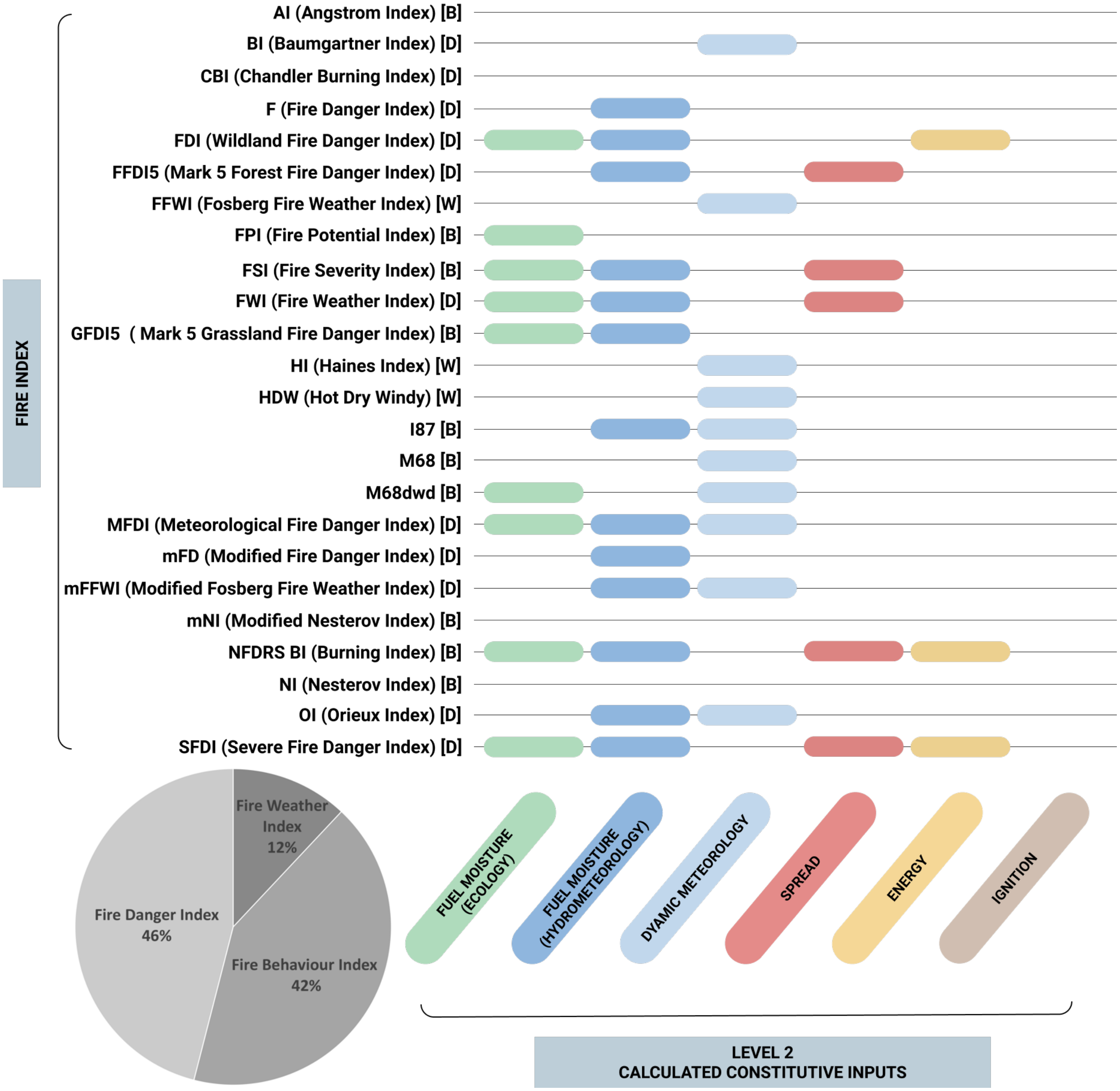
| Fire Index | Level 2 | Level 1 | Description of Inputs |
|---|---|---|---|
| **AI (Angstrom Index)** | | Relative humidity<br>Air temperature | AI is calculated directly from meteorological inputs |
| **BI (Baumgartner Index)** | Potential evapotranspiration | Wind speed<br>Humidity<br>Incident solar radiation | Used to assess fuel dryness by calculating evapotranspiration |
| | | Precipitation | Total precipitation for last 5 days |
| **CBI (Chandler Burning Index)** | | Relative humidity<br>Temperature | Describes spread and intensity linearly to temperature and exponential to humidity |
| **F (Fire Danger Index)** | FMI (Fuel Moisture Index) | Temperature<br>Humidity | Assesses short term change in fuel moisture |
| | | Wind speed | Maximum wind speed (km/h) and a threshold windspeed is also used to ensure that fire danger rating is greater than zero |
| **FDI (Wildland Fire Danger Index)** | ERC (Energy Release Component) | Cloudiness<br>Temperature<br>Windspeed<br>Relative Humidity<br>Latitude<br>Slope<br>Rainfall | Amount of heat per area released during flaming; depends on **KBDI** and fuel moisture from dead and living fuel |
| | | Relative Humidity | Ratio of water vapor present in atmosphere to saturation vapor density at the same temperature |
| **FFDI5 (Mark 5 Forest Fire Danger Index)** | FFDM (Forest Fire Danger Meter) | Dry-bulb temperature<br>Relative humidity<br>Wind speed | Fire spread as a function of drought |
| | Drought Factor sub model | Number of days since last rainfall | The drought factor, which ranges from 1 to 10, gives an estimate of the fine fuel available for combustion<br>Also based on KBDI input |
| | KBDI (Keetch-Byram Drought Index) | Maximum temperature<br>Rainfall<br>Cloudiness<br>Wind<br>Fuel load<br>Relative humidity | The scale ranges from 0 (no moisture deficit) to 800 |
| | Rate of spread model sub model | | Function of KBDI and drought factor or fine fuel availability |

| | | | |
|---|---|---|---|
| | Suppression difficulty sub model | | Function of fuel moisture and rate of spread |
| | Fuel moisture sub model | Temperature<br>Relative humidity | |
| **FFWI (Fosberg Fire Weather Index)** | Equilibrium moisture content | Dry-bulb temperature<br>Relative humidity | Changes depending on humidity threshold and as a function of temperature and humidity |
| | | Windspeed | |
| **FPI (Fire Potential Index)** | Current living vegetation index | | Proportion of living vegetation greenness |
| | Maximum greenness | | |
| | 10-h dead fuel moisture | | |
| | Moisture extinction | | Fuel moisture content weighted over all fuel classes, for which fire will not spread |
| **FSI (Fire Severity Index)** | FFMC (Fine Fuel Moisture Code) | Air temperature<br>Relative air humidity<br>Wind<br>Rainfall | FSI is dependent on the FWI<br>A numeric rating of the moisture content of litter and other cured fine fuels and indicates the relative ease of ignition and the flammability of fine fuel |
| | DMC (Duff Moisture Code) | Air temperature<br>Relative air humidity<br>Wind<br>Rainfall | A numeric rating of the average moisture content of loosely compacted organic layers of moderate depth and indicates fuel consumption in moderate duff layers and medium-size woody material |
| | DC (Drought Code) | Air Temperature<br>Rainfall | A numeric rating of the average moisture content of deep, compact organic layers and indicates seasonal drought effects on forest fuels and the amount of smoldering in deep duff layers and large logs |
| | ISI (Initial Spread Index) | Wind<br>Air temperature<br>Relative air humidity<br>Rainfall | A numeric rating of the expected rate of fire spread wind and FFMC on rate of spread without the influence of variable quantities of fuel |
| | BUI (Build Up Index) | Air temperature<br>Relative air humidity<br>Rainfall | A numeric rating of the total amount of fuel available for combustion, by combing DMC and the DC |
| **FWI (Fire Weather Index)** | FFMC (Fine Fuel Moisture Code) | Air temperature<br>Relative air humidity<br>Wind<br>Rainfall | A numeric rating of the moisture content of litter and other cured fine fuels and indicates the relative ease of ignition and the flammability of fine fuel |
| | DMC (Duff Moisture Code) | Air temperature<br>Relative air humidity<br>Wind<br>Rainfall | A numeric rating of the average moisture content of loosely compacted organic layers of moderate depth and indicates fuel consumption in moderate |

| | | | |
|---|---|---|---|
| | | | duff layers and medium-size woody material |
| | DC (Drought Code) | Air Temperature<br>Rainfall | A numeric rating of the average moisture content of deep, compact organic layers and indicates seasonal drought effects on forest fuels and the amount of smoldering in deep duff layers and large logs |
| | ISI (Initial Spread Index) | Wind<br>Air temperature<br>Relative air humidity<br>Rainfall | A numeric rating of the expected rate of fire spread wind and FFMC on rate of spread without the influence of variable quantities of fuel |
| | BUI (Build Up Index) | Air temperature<br>Relative air humidity<br>Rainfall | A numeric rating of the total amount of fuel available for combustion, by combing DMC and the DC |
| **GFDI5 (Mark 5 Grassland Fire Danger Index)** | Fuel moisture content | Dry-bulb temperature<br>Relative humidity<br>Degree of grass curing | Fuel moisture is combined with fuel weight and windspeed to produce GFDI5 |
| | | Fuel weight | |
| | | Windspeed | |
| **HI (Haines Index)** | Atmospheric Stability | Temperature | Difference in air temperature at low elevation (950-850 mb); mid elevation (850-700 mb); high elevation (700-500mb) |
| | Humidity | Temperature<br>Dew point | The difference between air temperature and dewpoint temperature at 850 mb (low and mid elevation) or 700 mb (at high elevation) |
| **HDW (Hot Dry Windy)** | VPD (Vapour Pressure Deficit) | Saturation vapour pressure<br>Absolute moisture content<br>Temperature | Difference between saturation vapour pressure and absolute moisture content (large VPD = fast evaporation rate) |
| | | Windspeed | Windspeed is multiplied by VPD directly to produce HDW |

| | | | |
|---|---|---|---|
| **I87 (Carrega I87)** | Deep soil water reserve | Precipitation | Function of maximum saturation (150 mm) and evapotranspiration |
| | Evapotranspiration | Temperature<br>Coefficient related to latitude and season | |
| | | Relative humidity | |
| | | Windspeed | |
| **M68** | Vapour pressure deficit | Temperature<br>Rainfall<br>Vegetation condition | |
| **M68dwd** | Vapour pressure deficit | Temperature<br>Rainfall<br>Vegetation condition | |
| | | Greening and sprouting dates certain fuels | Describes phenological stage and seasons for fire danger |
| **MFDI (Meteorological Fire Danger Index)** | DD (Drought Days Index) | Precipitation | Cumulative rainfall over 11 preceding periods |
| | BD (Base Danger) | | Combines DD to produce a curve representing phenology of vegetation |
| | Humidity factor | Relative humidity | Calculated using RH and constants |
| | Temperature factor | Air temperature | Calculated using air temperature and constants |
| **[m] FD (Modified Fire Danger Index)** | FMI (Fuel Moisture Index | Temperature<br>Humidity | Assesses short term change in fuel moisture 09 |
| | DF (Drought Factor) | Number of days since last rainfall<br>Total precipitation since last rainfall<br>Maximum daily temperature<br>Annually averaged precipitation | Long-term moisture assessment due to fuel availability<br>Based on KBDI |
| | KBDI (Keetch-Byram Drought Index) | Maximum temperature<br>Rainfall<br>Cloudiness<br>Wind<br>Fuel load | |
| **mFFWI (Modified Fosberg Fire Weather Index)** | Equilibrium moisture content | Dry-bulb temperature<br>Relative humidity | Changes depending on humidity threshold and as a function of temperature and humidity |
| | KBDI (Keetch-Byram Drought Index) | Maximum temperature<br>Rainfall<br>Cloudiness<br>Wind<br>Fuel load | Soil saturation of 8 inches for one week is required before index starts |
| | FAF (Fuel Availability Factor) | | Assesses drought on fuels, function of the KBDI<br>Product of FAF and FFWI produces mFFWI |

| | | | |
|---|---|---|---|
| | | | |
| | | Windspeed | |
| **[m] NI (Modified Nesterov Index)** | | Mean temperature<br>Dewpoint temperature | Difference between mean temperature and dewpoint temperature |
| | | Rainfall | Number of days since last rainfall greater than 3 mm |
| | | K (control coefficient) | controls the resetting value when rainfall events occur |
| **NDFRS BI (Burning Index)** | ERC (Energy Release Component) | Cloudiness<br>Temperature<br>Windspeed<br>Relative Humidity<br>Latitude<br>Slope<br>Rainfall | Amount of heat per area released during flaming; depends on KBDI and fuel moisture from dead and living fuel |
| | SC (Spread Component) | Cloudiness<br>Temperature<br>Windspeed<br>Relative Humidity<br>Latitude<br>Slope<br>Rainfall | Dependent on live and dead fuels; dependent on KBDI |
| | KBDI (Keech Byram drought index) | | Depends on moisture from live and dead fuel moisture |
| **Nesterov Index** | | Mean temperature<br>Dewpoint temperature | Difference between mean temperature and dewpoint temperature |
| | | Rainfall | Number of days since last rainfall greater than 3 mm |
| **OI (Orieux Index)** | Drought Index (Deep soil reserves) | Available water capacity in the soil | Determines the daily balance between rainfall and evapotranspiration, saturated when water content reaches 150 mm |
| | Potential Evapotranspiration | Temperature<br>Number of days calculated<br>Average day length | |
| | | Windspeed | |
| **SFDI (Severe Fire Danger Index)** | ERC (Energy Release Component) | Cloudiness<br>Temperature<br>Windspeed<br>Relative Humidity<br>Latitude<br>Slope<br>Rainfall | Amount of heat per area released during flaming; depends on KBDI and fuel moisture from dead and living fuel |
| | BI (Burning Index) | | Flame length and dependent on ERC and SC |



| FIRE INDEX | FUEL MOISTURE (ECOLOGY) | FUEL MOISTURE (HYDROMETEOROLOGY) | DYAMIC METEOROLOGY | SPREAD | ENERGY | IGNITION |
|---|---|---|---|---|---|---|
| AI (Angstrom Index) [B] | | | | | | |
| BI (Baumgartner Index) [D] | | | ● | | | |
| CBI (Chandler Burning Index) [D] | | | | | | |
| F (Fire Danger Index) [D] | | ● | | | | |
| FDI (Wildland Fire Danger Index) [D] | ● | ● | | | ● | |
| FFDI5 (Mark 5 Forest Fire Danger Index) [D] | | ● | | ● | | |
| FFWI (Fosberg Fire Weather Index) [W] | | | ● | | | |
| FPI (Fire Potential Index) [B] | ● | | | | | |
| FSI (Fire Severity Index) [B] | ● | ● | | ● | | |
| FWI (Fire Weather Index) [D] | ● | ● | | ● | | |
| GFDI5 ( Mark 5 Grassland Fire Danger Index) [B] | ● | ● | | | | |
| HI (Haines Index) [W] | | | ● | | | |
| HDW (Hot Dry Windy) [W] | | | ● | | | |
| I87 [B] | | ● | ● | | | |
| M68 [B] | | | ● | | | |
| M68dwd [B] | ● | | ● | | | |
| MFDI (Meteorological Fire Danger Index) [D] | ● | ● | ● | | | |
| mFD (Modified Fire Danger Index) [D] | | ● | | | | |
| mFFWI (Modified Fosberg Fire Weather Index) [D] | | ● | ● | | | |
| mNI (Modified Nesterov Index) [B] | | | | | | |
| NFDRS BI (Burning Index) [B] | ● | ● | | ● | ● | |
| NI (Nesterov Index) [B] | | | | | | |
| OI (Orieux Index) [D] | | ● | ● | | | |
| SFDI (Severe Fire Danger Index) [D] | ● | ● | | ● | ● | |

**Figure 2.** The 24 fire indices and their corresponding Level 2 constitutive inputs used for their computation. Colour coded according to Level 2 inputs in Figure 1. This summary reveals the relative use of each class of constitutive inputs in computing popular fire indices, with the most used input being fuel moisture (hydrometeorology) and the least used input being fire ignition. Each index is denoted as either a fire danger index [D], a fire behaviour index [B], or a fire weather index [W], and respectively represents 46%, 42%, and 12% of the fire indices analyzed, as denoted by the pie chart.

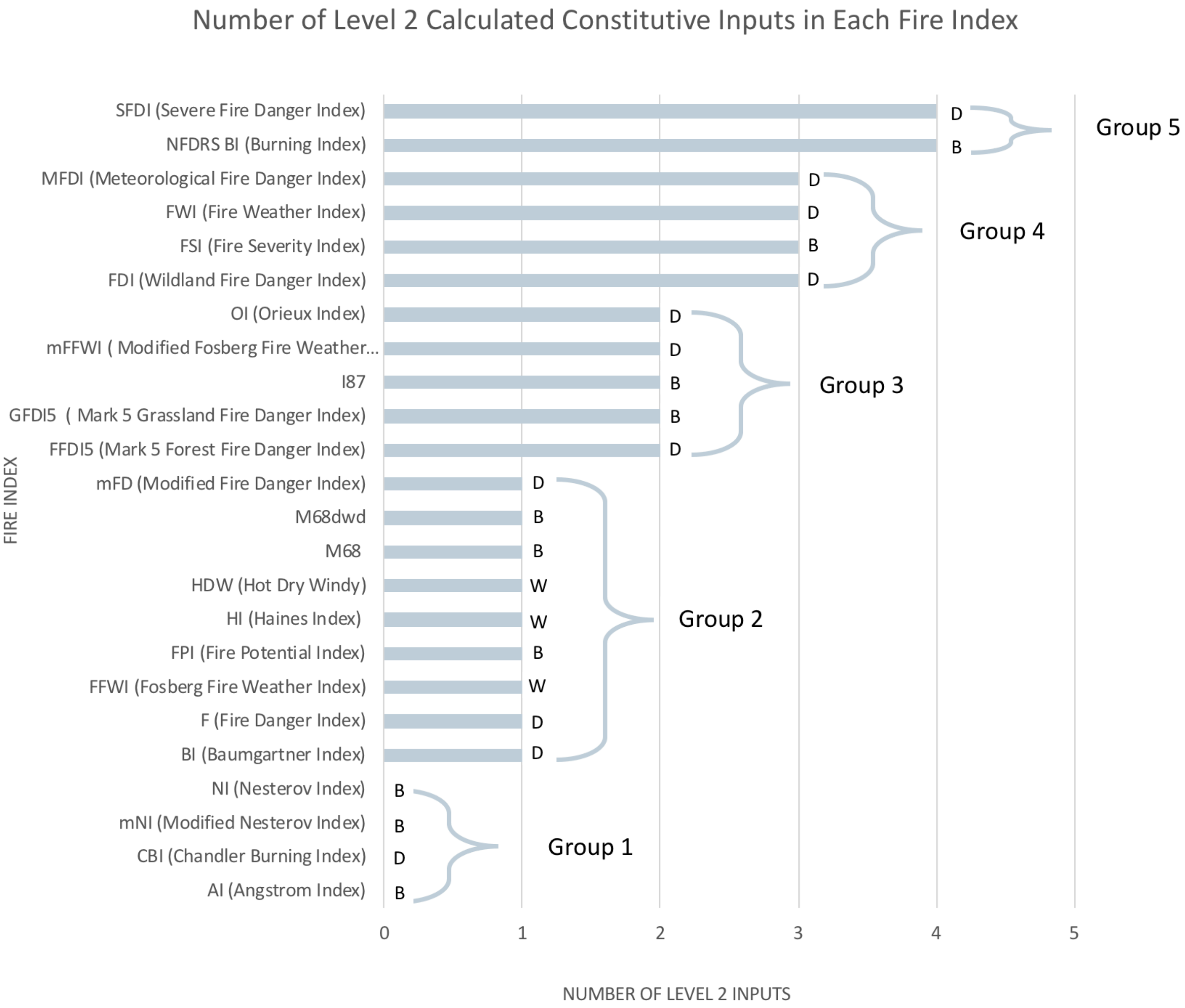


**Figure 3.** The fire indices ranked according to the number of Level 2 constitutive inputs used in their computation, with their corresponding fire index type denoted: fire danger index (D), fire behaviour index, (B), and fire weather index (W). The majority of fire indices (9 out of 24) use only one type of Level 2 constitutive inputs (Group 1) and are a combination of fire danger, fire behaviour, and fire weather index types. All the fire weather indices fall within this group. Only 2 of the 24 indices are the most computationally complex, using 4 out of 6 types of Level 2 inputs (Group 5) (see Figure 2 for the 6 types of Level 2 constitutive inputs).

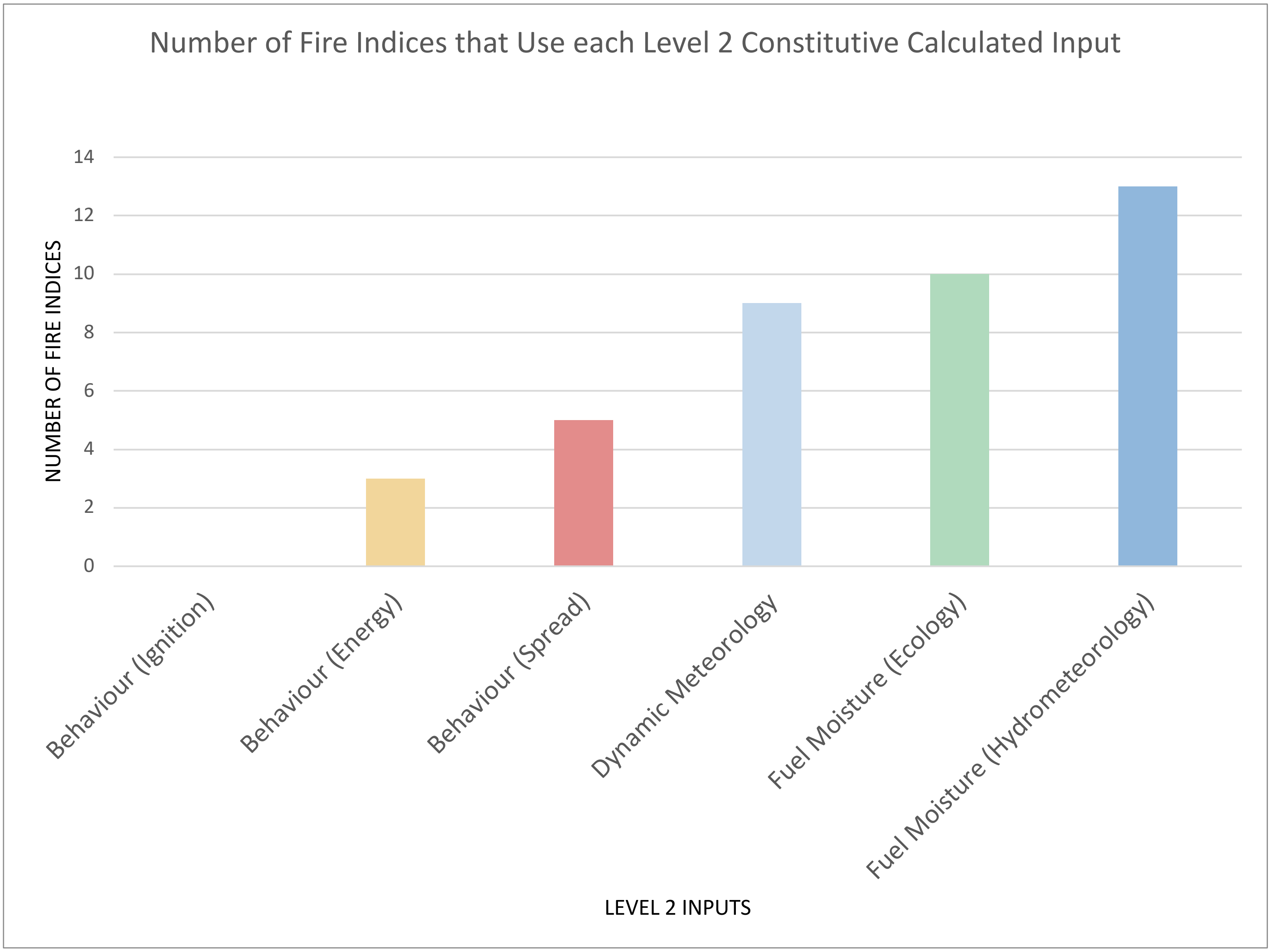


**Figure 4.** The number of fire indices that use each of the six types of Level 2 constitutive inputs in this study (see Figure 2 for fire indices that use each Level 2 constitutive input).

**Table 4.** Grouping of fire indices according to their fire type: *fire danger* index, *fire behaviour* index, or *fire weather* index, and their corresponding pathways used for their computation (*L1*: only raw variables as inputs*;* *L2*: calculated variables as inputs, or *L1&2*: both raw and calculated variables as inputs)

| Fire Index Type | Pathway L1 | Pathway L2 | Pathway L1&2 |
|---|---|---|---|
| Fire Danger Index | CBI (Chandler Burning Index) | FFDI5 (Mark 5 Forest Fire Danger Index)<br>FWI (Fire Weather Index)<br>MFDI (Meteorological Fire Danger Index)<br>mFD (Modified Fire Danger Index)<br>SFDI (Severe Fire Danger Index) | BI (Baumgartner Index)<br>F (Fire Danger Index)<br>FDI (Wildland Fire Danger Index)<br>mFFWI (Modified Fosberg Fire Weather Index)<br>OI (Orieux Index) |
| Fire Behaviour Index | AI (Angstrom Index)<br>mNI (Modified Nesterov Index)<br>NI (Nesterov Index) | FPI (Fire Potential Index)<br>FSI (Fire Severity Index)<br>NFDRS BI (Burning Index)<br>M68<br>M68dwd | GFDI5 (Mark 5 Grassland Fire Danger Index)<br>I87 |
| Fire Weather Index | | HI (Haines Index) | FFWI (Fosberg Fire Weather Index)<br>HDW (Hot Dry Windy) |

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