Enhanced prediction of extreme fire weather conditions in spring using the Hot-Dry-Windy Index in Alberta, Canada

by

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ABSTRACT

Fire weather indices used to forecast fire behaviour provide valuable information for wildland fire prevention, preparedness, and suppression. The primary index used in Canada, the Fire Weather Index System, provides qualitative fuel moisture and fire behaviour indices. However, the indices used to predict and forecast fuel moisture and fire behaviour do not assess the impacts of weather alone. Weather strongly influences fuel moisture, fire ignition, and fire spread. Additionally, the spring fire season in Alberta, Canada has been challenging for decades. Alberta has historically experienced extreme fire weather conditions in the spring season, leading to the occurrence of multiple disastrous wildland fires. This study examines the association between the Hot-Dry-Windy Index (HDWI) and spread days on 80 large wildland fires greater than 1,000 hectares that started in the month of May in Alberta from 1990 to 2019. HDWI values were calculated using ERA5 reanalysis weather from the 1000, 975 and 950 hPa levels. Permutation tests were used to test HDWI distributions between spread days and non-spread days. Statistically significant differences between HDWI values were found between the distributions of spread days and non-spread days over the first four days of all 80 large wildland fires in the dataset, as well as on the day of assessment of these fires. Results of this study suggest that HDWI can contribute to the prediction of significant spring wildland fire spread days in Alberta’s fire prone landscapes. A climatology of May HDWI values from 1990 to 2020 was also created for three separate locations in Alberta to provide context to HDWI values.

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BUI – Build-Up Index
CFFDRS – Canadian Forest Fire Danger Rating System
CFSR – Climate Forecast System Reanalysis
CS3 – Copernicus Climate Change Service
DC – Drought Code
DMC – Duff Moisture Code
DRG – Daily Relative Growth
ECMWF – European Center for Medium-Range Weather Forecasts
ENSO – El Niño Southern Oscillation
ERA5 – ECMWF Reanalysis Version 5
FBP – Fire Behaviour Prediction (System)
FFMC – Fine Fuel Moisture Content
FMC – Foliar Moisture Content
FWI – Fire Weather Index
HDWI – Hot-Dry-Windy Index
HFI – Head Fire Intensity
HI – Haines Index
ISI – Initial Spread Index
ISI.AR – Adjusted ISI.F to account for wind gusts
ISI.F – Initial Spread Index based on Alberta Wildfire's surface weather station network
NCEP – National Centers for Environmental Prediction
RH – Relative Humidity
VPD – Vapour Pressure Deficit
WMB – Wildfire Management Branch
WD – Wind Direction
WS – Wind Speed

CHAPTER 1 - INTRODUCTION

1.1 Preamble

1.1.1 Spring Fire Season

Wildland fires are a common and widespread disturbance in Canada, particularly in the boreal/taiga plain and shield ecozones (Stocks et al., 2002). Though wildland fires are a natural and important ecological process (Flannigan et al., 2009), Canada has been challenged with an increase in overall fire activity. This includes a lengthening fire season and increases in the occurrence of extreme fires, fire sizes and total area burned (Hanes et al., 2018). With expected increases in wildland fire activity due to climate change and expansion into the wildland-urban interface, fire management is increasingly becoming more important to public safety and the protection of personal property, natural resources (Wotton, 2009), and critical infrastructure.

In recent history, western Canada has experienced a number of disastrous fire seasons. For example, notable seasons were experienced in Alberta (2011, 2015, 2016, 2019), British Columbia (2017, 2018, 2021), Northwest Territories (2014), and Saskatchewan (2015) (Tymstra et al., 2021). In 2016, Alberta experienced the Horse River Wildfire in Fort McMurray. This incident is, to date, the costliest natural disaster in Canadian history that prompted the evacuation of 88,000 people, destroyed approximately 2,400 structures, burned over 589,000 hectares, and resulted in total insured losses of approximately $3.7 Billion (Statistics Canada, 2017; MNP, 2017). This fire, along with other examples of disastrous wildland fires in Alberta, started in May.

During the critical period between snowmelt and green-up, of all wildland fires in Alberta from 1990-2019, those that started in May account for a significant percent of annual area burned (~50%) (Tymstra et al., 2021). When green-up occurs, the deciduous foliage of the canopy and understory are fully flushed - the very high moisture content of this green deciduous vegetation greatly reduces fire spread potential (Alexander, 2010). Since spring fires occurring before this green-up stage cause nearly all structural loss, the continued understanding of the conditions contributing to spring wildland fires is important (Tymstra et al., 2019). In general, weather alters the fire environment by influencing fuel moisture content, potential ignition sources such as lightning, and varying wind speeds that control spread rates and fire behaviour (Flannigan et al., 2005).

1.1.2 Spring Fuel

Low fuel moisture content of dead organic fine fuels (ex. <1cm in diameter) and high wind speeds are the main contributors to large wildfire growth in the spring (Tymstra et al., 2019). Low fuel moisture content is a primary concern, especially when combined with an abundance of dead forest fuels in the period between snowmelt and green-up. High ignition potential and rates of spread can occur before vegetation initiates new growth and when the forest floor has abundant dead and dry fine fuels.

During early spring, live coniferous tree species undergo a process called foliar moisture content dip (or spring dip). This annual process occurs shortly before budbreak and flushing and results in a seasonal drop in the relative moisture content (%) of live conifer foliage due to the translocation of carbohydrates from the roots to the new foliage (Chrosciewicz, 1986). Spring dip occurs between mid-May and late-June but varies greatly by latitude, longitude and elevation (Hirsch, 1996). During this period, due to the low moisture content of live foliage, conifer trees are more susceptible to crown fire initiation and higher rates of crown fire spread.

Though it is known that low foliar moisture content (FMC) levels impact fire behaviour, these relationships are still poorly understood (Jolly et al., 2014, Campos-Ruiz et al., 2022). Additionally, the timing and duration of this depression in FMC depends on multiple factors such as seasonal temperature, tree species and foliage age (Chrosciewicz, 1986). The timing and quantification of the effect of FMC on crown fire rate of spread are also difficult to forecast (Alexander and Cruz, 2013). FMC can be measured by destructive sampling and drying, but this can be time consuming. The Canadian Fire Behaviour Prediction (FBP) System does however, output an estimated date of minimum FMC based on latitude, longitude, and elevation inputs.

1.1.3 Spring Weather

Fuel moisture and wind speeds influence fire behaviour (Van Wagner, 1987). Local fuel moisture is controlled by local antecedent and current weather. This weather is controlled by large-scale synoptic weather patterns, and regional and local factors such as topography, latitude (solar radiation), water bodies, and vegetation. Synoptic weather patterns are a primary focus as they are closely linked to critical fire weather (Potter and McEvoy, 2021).

A significant warming event for increased wildland fire conditions is the teleconnection El Niño Southern Oscillation (ENSO). ENSO occurrences can be detected as a warning of drying events in the spring in Alberta, but are not, however, indicative of disastrous spring wildfire seasons

(Tymstra et al., 2019). On the other hand, mesoscale synoptic weather patterns are closely linked to fire weather. In their work on synoptic and meso-scale weather patterns that influence spring fires in Alberta, Tymstra et al. (2021) identified two weather patterns that occur during spring wildfire spread days - surface troughs with an upper ridge (41%), and surface ridges with an upper ridge (36%). With this, many spread days in the spring are the result of strong winds associated with cold frontal passage after a blocking ridge has been situated over the province, or persistent dry winds associated with a ridge providing a strong south-southeast gradient over central and eastern Alberta. Frontal passages that resulted in significant spread days, such as on the Horse River Wildfire (2016), were the result of an Arctic high moving to the east of Alberta, and a north-south oriented low approaching from the west-southwest. This pattern provides strong south-southeast oriented winds ahead of the front, and strong gusty northwest winds behind the cold frontal passage, resulting in a significant shift in fire spread direction (Tymstra et al., 2021). High winds are a primary factor in large growth days (Potter and McEvoy, 2021) and increased fire behaviour in the spring may occur under or after stable ridge patterns have dried fuels and subsequent wind events occur.

Dry air masses in the spring in Alberta are the result of frozen water bodies and minimal transpiration which limits the amount of moisture being released into the atmosphere (Tymstra et al., 2021). Dry air greatly increases the rate at which fuels dry, making them easier to ignite and sustain combustion, which increases fire spread. Moisture content of fine fuels is an indicator of receptivity to ignition of surface fuels (Wotton, 2009). In the spring, this is more of a concern due to a higher amount of dead and receptive fine fuels. For example, before green-up, dead grass is highly receptive to ignition. Additionally, these fine fuels have a fast drying rate of only a few days if weather conditions promote drying. Low fuel moisture content in dead fine fuels increases the likelihood of ignitions – it is during this time that human-caused fires are more prevalent in Alberta.

1.1.4 Human-Caused Fires

There are two broad causes of wildland fire ignition in Canada; humans and lightning (Flannigan et al., 2016). Human-caused fires start as a result of human activity, either intentionally, such as arson, or unintentionally, which includes various ignition sources such as recreational activities, residential burning, industrial operations and downed or short-circuited powerlines. Across Canada, the number of human-caused fires peaks in the spring (April to May), and again in the fall (Stocks et al., 2002), where lightning-caused fires occur during the summer (June-August) (Coogan et al., 2020). Lightning is, in general, not common until the summer season begins (Tymstra et al., 2019), and accounted for 17.2% of May fires from 1990-2019 (Government of Alberta, 2019).

Of the 23.3% of total annual wildfires that started in May from 1990 to 2019, 78.7% of these were human-caused (Government of Alberta, 2019). This is in part due to a lack of atmospheric energy (i.e. thunderstorm activity) in May (Tymstra et al., 2021), and in part due to an abundance of dead and dry fine fuels that are more susceptible to ignition in the spring than in the summer. Though the occurrence of lightning caused fires is challenging to predict, wildland fire management officers can forecast the likelihood of a wildfire start from forecasted lightning events and prepare accordingly. The cause of the remaining 4.1% of fires in May (1990-2019) are categorized as undetermined.

When fuel moisture levels are susceptible to ignition, human-caused fires can be difficult to contain because they can start anytime, anywhere, and unfortunately, often close to communities. Though the occurrence of human-caused fires is related to the moisture content of fine fuels, their specific location and timing can be challenging to predict. Many disastrous spring fires in May can be described as starting in the wrong place at the wrong time. The fuel complex, strong dry winds, and other ongoing fires will influence a fire management agency's operational capacity. Multiple new wildland fires can occur in a "ramp-up cluster" in the spring, which can indicate potential increased fire activity (Tymstra et al., 2019, Pg. 19). This occurred in Alberta in 2011 when there were 22 on-going fires and then 189 new starts over 5 days from May 11th to 15th (Tymstra et al., 2019). It was during this period in 2011 when the fires associated with the historic Flat Top Complex started near Slave Lake, Alberta.

1.1.5 Spring Situation Overview

A warming climate will have serious implications on the level of wildland fire activity (Flannigan et al., 2016). The frequency and severity of wildland fires is expected to increase with current and future climate change impacts (Wotton et al., 2017, Flannigan et al., 2009). Flannigan et al. (2016) found that for every degree of warming, a 15% increase in precipitation is required to allow the moisture content of fine fuels to remain unchanged. However, Wotton et al. (2017) found no consistency with respect to trends or increases in seasonal precipitation to the end of the century. The frequency of seasons with a large number of spread days is also expected to increase, including a more than 50% increase in the number of fire spread days in western Canada (Wang et al., 2017) where there is already an observed increase in fire activity.

With an increase in the occurrence of extreme wildland fires caused by humans in the spring, there is also evidence of an earlier start to the fire season (Jain et al., 2017), and a longer spring season, especially in the Boreal Plains regions of Canada (Coogan et al., 2020). Hanes et al. (2018) completed a long-term trend analysis of fires in Canada of all sizes (1959-2015) and found the fire season was starting 9 days earlier and lengthening by over two weeks.

Spring fire season in Alberta is a challenging time due to an abundance of available volatile forest fuels, strong winds that occur with dry conditions and the occurrence of human-caused fires. Despite fire management agencies being aware of these issues for decades, prevention, preparedness and suppression planning for spring wildfires in Alberta are increasingly becoming challenging. The need for additional forecasting and decision support tools is apparent.

1.2 Decision Making

In Canada, daily wildland fire decision making is primarily based on interpreting outputs from the Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) Sub-systems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Lawson and Armitage, 2008). These systems are used in combination with local knowledge of forest conditions, seasonality, and land-use activities (e.g., recreation, industry) to support wildland fire prevention, preparedness, and suppression planning.

The FWI System is a book-keeping system that examines the effect of four weather variables on fuel moisture content. Moisture code values for tomorrow are predicted using forecasted weather and today's fuel moisture codes (Wotton, 2009), and then confirmed by current noon weather readings. Weather variables used in forecasting and the calculation of FWI values include daily noon surface values of temperature (ºC), relative humidity (%), 10-metre open wind speed (km/hr) and 24hr accumulated precipitation (mm). These weather observations are used to determine numeric ratings of three fuel moisture codes.

- Fine Fuel Moisture Code (FFMC) – moisture content of fine surface litter layer fuels (<1cm diameter). This moisture code is an indicator of ignition potential and fire spread.
- Duff Moisture Code (DMC) – moisture content of the loosely compact organic matter layer and medium fuels 1-7cm in diameter. DMC is an indicator of the probability of lightning ignition potential and fuel consumption.
- Drought Code (DC) – moisture content of the deep compact organic matter layer and heavy/large fuels >7cm in diameter. DC is an indicator of consumption of deep and heavy fuels, as well as the difficulty of extinguishment of a fire.

These fuel moisture codes provide qualitative information on daily fire behaviour potential for fire management officials and the wildland firefighters working on the ground. Using these fuel moisture codes, two qualitative fire behaviour indices are derived:

- Initial Spread Index (ISI: FFMC and Wind Speed) – represents the qualitative rate of spread.
- Build-Up Index (BUI: DMC and DC) – represents the qualitative amount of fuel available for consumption.

All five of these codes provide valuable information on expected fire behaviour and support decision making for the allocation of resources for preparedness and the chosen strategies and tactics used during the management of a fire. The FWI value, the final qualitative value of the FWI System, is a combination of ISI and BUI that represents the qualitative intensity of a fire. ISI and BUI are also inputs into the aforementioned FBP System in combination with inputs such as fuel type and topography.

Wildland fire prevention is dynamic; agencies employ multiple tools over time and space to reduce the risk of wildfires. These can include local fire advisories and ministerial orders for fire restrictions, fire bans, forest area closures and off-highway vehicle restrictions (Tymstra et al., 2021). Currently, the Provincial Fire Ban Matrix decision making tool used in Alberta is based on BUI from the FWI System, but subsequent FWI values may also be considered. BUI is essentially comprised of a combination of fuel moisture of medium and heavy forest fuels, including deeper soils (Van Wagner, 1978). However, in the spring, these deep organic layers and large fuels are either still frozen or generally saturated due to recent snow melt (Turner and Lawson, 1987). The previous fall DC value, however, can be indicative of the occurrence of human-caused fires in the following spring (Hanes et al., 2020). Due to this, large spring wildland fires in Alberta do not rely on the occurrence of very high to extreme BUI values (Tymstra et al., 2021). Instead, due to the fuel complex in the spring, fire management agencies may rely on the FFMC and subsequent ISI combined with their local knowledge to make decisions with respect to wildland fire prevention and preparedness planning.

The common drivers for extreme wildfire behaviour in the spring are very high to extreme FFMC and ISI values. FFMC is generally higher (drier) in the spring and early summer and starts to decline throughout the summer (Amiro et al., 2004). Because spring wildfires in Alberta are often wind-driven, extreme fire behaviour can develop quickly and become very challenging to manage (Tymstra et al., 2021), especially when combined with low moisture content in fine fuels. The FWI System has been used successfully for decades as a tool for forecasting fire environment conditions. However, even with significant advances in prevention, detection and suppression capabilities, extreme fire behaviour conditions can lead to increased fire behaviour that can overwhelm fire management agencies and result in losses of timber and property (Flannigan et al., 2009).

Though the FWI System is an effective forecasting tool for predicting fuel conditions and potential fire behaviour, shortfalls are apparent. For example, the FWI System outputs do not account for abrupt changes in weather (e.g., cold front passage) unless hourly weather and system outputs are used. Weather changes occurring after the noon weather readings may have large impacts on fuel moisture codes and subsequent fire behaviour indices. Several complex meteorological conditions that can have significant effects on fire behaviour such as low-level jets, inversions, instability, and other conditions within the lower levels of the atmosphere (Lawson and Armitage, 2008) are also not directly accounted for. Additionally, an assumption of the FWI System is that weather will follow a typical diurnal pattern - however, in some locations, or even certain days, the regular pattern is different than the norm (Lawson and Armitage, 2008). For example, the FWI System assumes that under the typical diurnal pattern there will be nighttime recovery of wind, temperature, and relative humidity, but at times strong, dry winds occur all day and throughout the night (Tymstra, et al., 2021). Furthermore, it is understood that wind gusts influence fire spread. However, wind speeds used in the FWI System do not account for wind gusts in the determination of fuel moisture or ISI values. Also, fuel moisture codes in the FWI System are independent and do not account for vertical movement of water or other factors or mechanisms that influence vertical or lateral movement of water in the soil (Johnson et al., 2013). Since the FWI System does not account for these number of incidences, fuel moisture codes and subsequent fire behaviour indices may not always accurately represent the conditions of the fire environment to effectively predict fire behaviour. Though these aspects may all be considered to varying degrees, it is unknown how much of an effect these events may have on fire behaviour.

The FWI System can lack predictive quality in the spring if the FWI System fuel code start-up values do not accurately reflect the spring fire weather conditions. FWI System values are not tracked over the winter, and therefore, the system undergoes a “start-up” each spring. At some point following snow melt, each weather station starts to track these values. The FWI System start-up is triggered once an area is snow free for 3 days in regions normally covered by snow, or the recorded noon temperatures of 12°C or greater occurs for 3 consecutive days in regions not normally covered by snow (Canadian Forest Service, 1984). Since these procedures do not necessarily indicate the start of fire season, some sources use other seasonal indicators instead. Other approaches include three days of maximum recorded temperatures of 12°C or greater (Wotton and Flannigan, 1993), other temperature thresholds, or even the occurrence of historic fires.

The indicators of when to start calculating FWI System values are not consistent. Even the original start-up timing described in the Canadian Forest Service (1984) can be subjective in, for example, declaring snow gone conditions. Additionally, the spring start-up values for FFMC and DMC are default starting values of 85 and 6, respectively (Lawson and Armitage, 2008). These default values may be inaccurate due to a number of factors that may affect fuel moisture such as the rate of snow melt and the timing of snow-gone declaration. For example, fine fuels may be exposed long before all snow has melted in a geographic area. If these fine fuels are exposed before FWI System values have begun calculation, fuel moisture may have already started to decline. The timelag constant of FFMC is 2/3 of a day, therefore, one or two days of drying may be adequate to reduce fuel moisture levels low enough to support increased fire behaviour (Tymstra et al., 2019).

For the start-up of DC, either a default value of 15 is assigned, or a DC start-up calculation is applied (often referred to as overwintering). DC start-up calculations, which are commonly used in western Canada, are a rough estimate of the mechanisms that affect winter and spring moisture (Hanes et al., 2020). These overwintering calculations use a carryover fraction of the previous fall DC value depending on when the tracking of FWI System values stopped (1.00, 0.75 or 0.50), and a precipitation effectiveness fraction that is dependent on broad site and ground frost definitions (0.90, 0.75 or 0.50) (Turner and Lawson, 1978). Alberta uses a constant 0.50 carryover fraction and a 0.50 precipitation effectiveness. There can be a significant difference in DC values at the time of spring start-up depending on whether the start-up calculation or the default start-up value are used, and therefore fire danger may be more severe than what is predicted (McElhinny et al, 2020).

The current DC start-up calculations also do not account for factors that would impact the timing or rate of snowmelt, or the potential run-off over frozen soil that may contribute to organic layer recharge (Hanes et al., 2020), or the absence of sufficient recharge. Potentially under or overestimating DC values results in misrepresented BUI and FWI values in the spring. As mentioned earlier, moisture content of larger fuels and deep organic materials are not prerequisites for spring fire activity.

The FWI and FBP Systems rely on 1200 LST surface weather forecasts and observations, which may not capture the impact of weather events that occur before or after these noon weather readings. The Canadian Forest Service (2021) plans to use peak burn weather in the FWI System instead of 1200 LST weather, but this approach has not been implemented. Though these systems have been employed with success for decades, shortfalls exist. In the spring, FWI System start-up values may be misrepresented due to a lack of understanding of the vertical movement of water from deep organics to the surface layer (Johnson et al., 2013), a subjective start-up date, and a lack of understanding of the effects of early and/or fast snowmelts on fuel moisture content. Additionally, the relationship between surface weather and weather aloft are imperative for a better understanding of the fire environment (Tymstra et al., 2021). Therefore, I chose to examine an additional fire-weather index that examines weather within the lower atmosphere.

1.3 The Hot-Dry-Windy Index (HDWI)

To support fire management and the ongoing challenges during spring in Alberta, I chose to examine the Hot-Dry-Windy Index (HDWI) and its relationship to spring fire spread. Atmospheric indices, calculated numeric ratings that describe the state of the atmosphere, are not used as daily indicators of fire behaviour or fire spread potential in Canada. This index was developed by Srock et al. (2018) to examine the effects of weather alone on fire spread and was selected due to its analysis of weather components of the lower levels of the atmosphere, not just surface weather as is the case with other common fire weather forecasting tools such as the FWI System.

Difficult fire conditions are some combination of "hot, dry and windy" weather. That is, ambient temperature, the moisture content of the air and wind speed as they each have significant direct effects on fuels and ongoing fires (Srock, et al., 2018). HDWI is based on the understanding of basic fire-atmosphere interactions and only examines weather variables. Therefore, other factors that contribute to wildland fire behaviour such as fuel moisture, fuel composition and topography are not included in HDWI.

Srock et al. (2018) developed the HDWI to assess wildland fire behaviour potential under the influence of synoptic and mesoscale weather while "leaving the assessment of less-certain, smaller-scale details to experts on the ground". That is, HDWI is based on large scale weather, rather than microscales such as less than 2km (Srock, et al., 2018).

HDWI is a calculated index used to analyze how the lower levels of the atmosphere affect a fire. The atmosphere generally affects a fire through three primary state variables – temperature, moisture, and wind speed, hence the "hot-dry-windy" term. However, HDWI combines atmospheric temperature and moisture into one factor, Vapour Pressure Deficit (VPD) (Srock, et al., 2018). VPD is the difference between Saturation Vapour Pressure (ES), a variable dependent solely on temperature (T) that represents the maximum amount of moisture the atmosphere can hold at that temperature, and Actual Vapour Pressure (E), a variable dependent solely on absolute moisture content (q). The units used for VPD are hPa. VPD is used instead of Relative Humidity (RH) because VPD represents the amount of possible evaporation through the difference between ES and E at a given temperature, instead of a ratio as in RH (Seager et al., 2015). VPD measures the drying power of the atmosphere.

HDWI analyses the lowest 500m of the atmosphere to assess weather below the daytime mixing layer and just above the surface (Srock, et al., 2018). The maximum VPD (hPa) and WS (m s^{-1}) from any level in the lowest 500m from the surface are selected for the calculation of HDWI. These VPD and WS maximums may occur at different levels of the atmosphere because near-surface mixing allows for VPD and WS maxima from low levels of the atmosphere to have direct impacts on a wildland fire at some time throughout the day (Srock, et al., 2018).

The maximum VPD and WS are used in the calculation of HDWI as shown in eq. (1). The HDWI value does not report units since the use of hPa and m s^{-1} units to calculate HDWI are not physically significant.

Equation 1

$$HDWI = U \times VPD\ (T,q)$$

where, U is wind speed (m s^{-1}), VPD (T,q) is the calculated VPD (hPa) at T (temperature) and q (absolute moisture content)

In their development of HDWI, Srock, et al. (2018) used the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) which has a 0.50^{o} x 0.50^{o} grid spacing. Since CFSR has a 6hr output, HDWI was calculated at 1200h, 1800h and 0000h UTC.

Pure weather indices are not used in western Canada for fire behaviour forecasting. HDWI was selected because, as discussed, it is apparent there are aspects of the atmosphere that are not well known but have direct impacts on fire behaviour. A commonly used fire-weather index in the United States is the Haines Index (HI). HI is widely used to predict weather conditions that may challenge wildland fire management efforts (Srock, et al., 2018). In their examination of HDWI on fire growth, Srock et al. (2018) found that the HDWI value reached very high levels on days with significant growth, mostly due to wind, where the HI value was not consistent at identifying those large growth days (Watts, et al., 2020). Although HI can be effective at identifying extreme fire weather, it uses a ranking system of 1-6 and therefore has a ceiling. HDWI, in comparison, is a continuous variable.

HDWI may be an additional tool useful for detecting days with elevated fire behaviour and increased levels of fire spread during the spring season in Alberta. Though the current daily systems used in fire behaviour forecasting are proven, there are uncertainties and a need to incorporate lower levels of the atmosphere to support decision making. HDWI will aid in capturing strong dry wind occurrences, including winds in the lower levels of the atmosphere that quickly affect the surface conditions on a wildfire.

1.4 Research Questions

1. Can HDWI be used to explain large spring wildfire spread events in Alberta?
2. How does HDWI perform compared to ISI on large spring fires in Alberta?
3. Is there a significant peak HDWI time for forecasting purposes in May in Alberta?
4. How do calculated HDWI values compare to a climatology and/or characterized recent significant spring fires such as the Horse River Wildfire (2016)?

CHAPTER 2 - METHODS

2.1 Data

2.1.1 Fires

Wildfire data for the period of 1990-2019 were obtained from the Alberta Wildfire Management Branch (WMB) (Government of Alberta, 2019). This includes all historic wildland fires within the Forest Protection Area of Alberta. The WMB is responsible for managing wildland fires on Provincial forested lands. Though Mutual-Aid is sometimes provided, fires within national parks and non-public lands are managed separately by their respective jurisdictional agencies and were excluded due to the absence of daily wildland fire data consistent to that available in Alberta. The data used includes burned area size updates (hectares and data/time of report) and fire location coordinates. Other information such as fuel type at the time of assessment is included in this dataset but were excluded due to the objective of assessing a weather-only index.

All fires that started in the month of May (1990-2019) were selected. A large fire can be classified using an area burned, for example, as in Stocks et al. (2002), greater than 200ha. To assess extreme wildland fire events, I choose to define a large wildland fire as one that had burned 1,000ha or more by the time of extinguishment as used in Tymstra et al. (2021). This resulted in 80 large wildland fires that started in May during this 30-year (1990-2019) study period (Figure 1 and Appendix A).

Of the 80 large wildland fires in this dataset, ~25% of their total area burned occurred during the first four days following ignition (Tymstra et al., 2021). The first four days of a wildfire are critical for gaining control if a fire requires suppression due to threatened values at risk. The first day being imperative, and as the fire continues to grow over the following three days, it becomes increasingly challenging to manage due to the increased complexity, area burned and perimeter growth. With few exceptions, these fires were all assessed and actioned by wildfire management staff on the day they were reported. HDWI calculations focused on the first four days of each fire, with Day 1 being the day it was assessed.

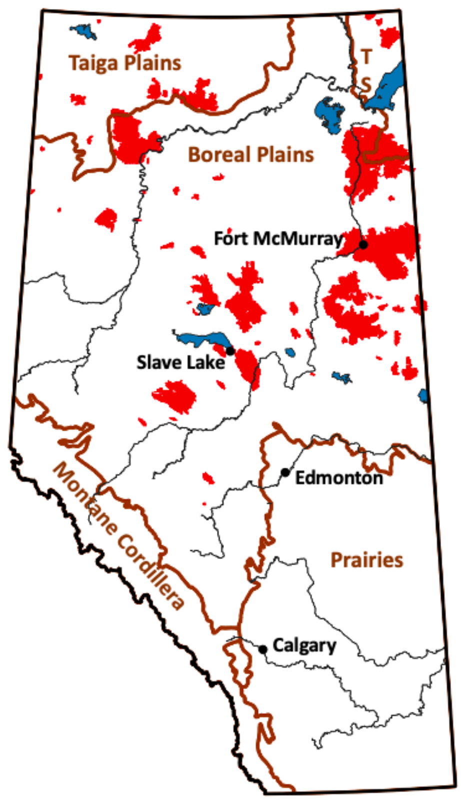

Figure 1. May wildfires in Alberta (1990-2019) >1,000ha at the time of extinguishment from Tymstra et al. (2021).

2.1.2 Weather

Weather data were obtained from the Copernicus Climate Change Service (CS3) Climate Data Store (CDS). The dataset (ERA5 hourly data on pressure levels from 1959 to present) is the 5th generation climate reanalysis from the European Centre for Medium-Range Weather Forecasts

(ECMWF) (CS3 Online CDS). Climate reanalysis products such as ERA5 offer modelled historic to near-recent weather at multiple levels of the atmosphere. Climate reanalysis products have been used in studies of fire weather such as recalculating FWI System values including overwintering DC (McElhinny et al., 2020), examining trends in extreme fire weather and fuel moisture (Jain et al., 2017, Ellis et al., 2022) as well as daily fire occurrence and area burned prediction (Bedia et al. 2014).

ERA5 is a gridded product with a lat-long grid resolution of 0.25° by 0.25°. During the development of HDWI, Srock et al. (2018) used weather data in the first 50 hPa above the surface from NCEP's Climate Forecast System Reanalysis (CFSR) which provides grids at a 0.50° x 0.50° resolution. Four weather variables were used from three upper levels of the atmosphere (1000 hPa, 975 hPa and 950 hPa) to calculate HDWI.

Hourly temperature in Kelvin (Tk), relative humidity (RH%), and two wind components (U-Component and V-Component) (WS) from 1100h to 2000h MDT were obtained for the three pressure levels. This timeframe provides suitable coverage during the primary burn period used by the Alberta Wildfire Management Branch (1000h MDT to 1800h MDT). 1000h MDT data were excluded and the burn period end time extended by two hours due to the relatively less favourable burning conditions in the morning, as well as more active burning conditions and more intense fire behaviour that can be experienced in the early evening when temperature, humidity and wind speeds are still likely to support active fire growth.

Each of the 80 fires was manually assigned an ERA5 grid cell based on the latitude and longitude coordinates recorded in the WMB fire database. The weather associated with each assigned grid cell from all three levels of the atmosphere were recorded to allow for the calculation of hourly HDWI for the first 4 days of each fire in the dataset.

A database of historic weather (1200h MST) and FWI System values was available from the WMB. Weather variables from representative weather stations that were observed on Day 1 of each fire at 1200h MDT (i.e. T^{o}C and RH%) were used to calculate noon HDWI at the surface (HDWI.noon.Surface).

2.1.3 ISI

Within the WMB historic weather database (1200h MST), observed weather and daily FWI System codes and indices for weather stations in Alberta were also used. Weather stations closest to the 80 fires in the dataset were selected to represent local conditions. The database attributes used in this study include temperature (Tc), relative humidity (%), wind speed (km/hr) and ISI. The ISI values from the WMB database over the first 4 days of all 80 fires are referred to as ISI.F (ISI FIRES).

To account for the impact that wind gusts have on fire spread and the calculation of FFMC and ISI values, Tymstra et al (2021) suggested an ISI adjustment to incorporate the impact of gusts on the input wind speeds used to calculate ISI. These ISI values were calculated using the ERA5 reanalysis in McElhinny et al. (2020) from 1979-2018 (for 1990-2018) in combination with wind gusts recorded from WMB weather stations and are referred to as ISI.AR. To include the 2019 season, Tymstra et al. (2021) calculated FWI System values using ERA5 temperature and dewpoint temperature (^{o}C) variables used to calculate relative humidity (RH%), wind speed (km/hr), and 24hr precipitation (mm).

To incorporate wind gusts into wind speeds, Tymstra et al. (2021) converted the 10 minute average wind speed using a piecewise linear function to a probable maximum of 1 minute average wind speed. These adjusted wind speeds were then used to recalculate FFMC and ISI values.

2.2 HDWI Calculations

Hourly temperature in Celsius (Tc) was calculated from the ERA5 temperature in Kelvin (Tk) for 1100-2000h MDT for all 3 levels. With this, I calculated Saturation Vapour Pressure (ES) from Tc using the below formula (eq. 2) fitted to Wexler's formula when Tc is between -30^{o}C and 35^{o}C (Bolton, 1980).

Equation 2

$$ES = 6.112 \times \exp((17.625 \times Tc) / (Tc + 243.5))$$

where ES is saturation vapour pressure in hPa and Tc is temperature in degrees Celsius.

To calculate Vapour Pressure Deficit (VPD), the Actual Vapour Pressure (E) is required. E was calculated using eq. (3).

Equation 3

$$RH\% = E / ES * 100$$

therefore; $E = RH\% \times ES / 100$

where E is Actual Vapour Pressure in hPa, RH% is relative humidity expressed as a fraction, and ES is Saturation Vapour Pressure in hPa.

With a calculated ES and E, Vapour Pressure Deficit (VPD) is calculated using eq. (4).

Equation 4

$$VPD = ES - E$$

where VPD is Vapour Pressure Deficit in hPa, ES is Saturation Vapour Pressure in hPa, and E is Actual Vapour Pressure in hPa.

As mentioned earlier, the U-Component of wind (UWS) and V-Component of wind (VWS) were also collected from the ERA5 database and are provided in m/s. The units for WS for the calculation of HDWI are also m/s. WS was calculated using eq. (5).

Equation 5

$$WS = \mathrm{sqrt}((UWS^2) + (VWS^2))$$

where WS is wind speed in m/s, UWS is the U-Component of wind and VWS is the V-component of wind.

These weather variables were calculated hourly from 1100h MDT to 2000h MDT at the 1000 hPa, 975 hPa and 950 hPa levels. Hourly maximums of VPD and WS were selected from either of the 3 levels of the atmosphere. That is, the maximum VPD and WS selected for the hourly calculation of HDWI did not always come from the same level but are often a combination of levels. With the hourly maximums selected, the hourly HDWI for 1100h MDT-2000h MDT for the first 4 days of all 80 large May wildland fires were calculated using eq. (1).

$$HDWI = WS * VPD$$

where HDWI is Hot-Dry-Windy Index with no units, WS is Wind Speed in m/s and VPD is Vapour Pressure Deficit in hPa.

2.3 Spread Day Determination and HDWI Selection

With respect to HDWI, spread days were analyzed as an indicator of the level of difficulty of managing a wildfire. A spread day occurs when a fire actively spreads and significantly increases in fire size (Podur and Wotton, 2011). Spread days describe those days when fire behaviour limits the effectiveness of suppression efforts resulting in continued growth of a fire (Wang et al., 2015). A "non-spread day" is a day where limited fire growth is observed and suppression efforts are likely to succeed. It is hypothesized that the HDWI values for the spread and non-spread days do not come from the same distribution (i.e., HDWI values for the spread days are significantly greater than the HDWI values for the non-spread days).

There are different approaches to identify spread days and non-spread days, including the use of classified MODIS hotspots (Podur and Wotton, 2011), linear spread, and increases in area burned. To classify each day as a spread day or a non-spread day, an area burned mixed approach was used similar to that used by Tymstra et al. (2021). If the fire size was reported as 200ha or greater on day 1, it was classified as a spread day. For days 2 to 4, a spread day occurred if the fire doubled in size between 2 or more reported size updates). This was completed using a calculated Daily Relative Growth (DRG%) calculation, where a value of 100% represents a doubling in fire size (eq. 6).

Equation 6

$$DRG\% = \frac{\text{Second Size Update (ha)} - \text{First Size Update (ha)}}{\text{First Size Update (ha)}} \times 100$$

where DRG% is Daily Relative Growth expressed as a percentage

An assessment of the first 4 days of each large wildland fire in the 80 fire dataset resulted in a total of 320 possible spread or non-spread days. However, due to the relative growth aspect of this approach, days with only one reported fire size were excluded from the spread day analysis. To negate overnight fire growth impacting the analysis, only those days with at least two fire size updates were used. For those days with more than 2 size update reports, the first and last update were selected to assess fire spread over a longer time-period in a single day. The spread day analysis resulted in 114 observations.

From the calculated hourly HDWI for the first 4 days of each fire, the maximum HDWI was selected during the time period between the two or more same day reported size updates. If a greater HDWI value occurred outside of the size update report times, it was not used as it would not represent the growth observed.

From the hourly HDWI calculations I also identified the 1200h MDT and daily maximum HDWI values between 1100h and 2000h MDT to analyze if these values would represent spread days. The daily maximum HDWI values were sometimes the HDWI value selected in spread day analysis, but sometimes fell outside of those timeframes. The 1200h MDT HDWI values were calculated using local weather stations which may not represent maxima throughout the day due to diurnal heating. Additionally, fires within the database may not have yet started, and therefore the 1200h HDWI value would not represent fire spread. Therefore, selecting the hourly maximum HDWI value throughout the fire size report time was the preferred method.

2.4 Assumptions

It is expected that all, or a large majority of the selected 80 large fires were actively suppressed to some degree over the first four days. Due to the nature of large active wildfires and spread events, suppression at the head of these fires is not effective. Additionally, ignition tactics are sometimes employed during these escaped fire events, and the growth that would have resulted in these tactics is not accounted for. Therefore, it is assumed that suppression would not impact growth on the main areas contributing to the majority of fire growth (i.e., head of the fire).

It is important to note that most fire sizes recorded in the WMB database are ocular assessments of size, especially at the time of assessment and through the first few hours to first few days of a large, escaped wildland fire. When fire management staff are assessing or actively operating on a wildfire, size updates are reported to their Fire Center for the purpose of describing or giving an update to fire management officials of how an incident may or may not be expanding in size and complexity. Ocular assessments of size can be difficult due to smoke obscuring visualization of the fire perimeter, or due to inexperience completing ocular assessments. Recording a flown GPS track of an active wildfire for the purpose of determining an accurate fire size is not a primary concern during these initial days. Reporting an ocular estimation is acceptable for fire management officials in their respective Fire Centers to get an idea of what is happening, thus eliminating the need to interrupt aerial operations by performing a low-level flight of the fire perimeter. However, these fire size update flights are sometimes planned and completed in the early morning or late evening to collect accurate information for the incident, such as more accurate perimeter and size, but it is assumed in this analysis that these flights rarely happened, and a majority of these size updates are ocular estimates.

There are known limitations due to the grid sizes with the ERA5 weather data, specifically wind speed. Local scale weather variables may be masked due to an averaging effect over these large grid cells. This was also shown in Betts et al. (2019), where ERA5 reanalysis data underestimated near-surface wind speeds compared to local weather station data. Further, in Tymstra et al. (2021) mean wind speeds were underestimated by 0.8m/s (~2.9km/hr) in ERA5 reanalysis. When weather variables such as wind are averaged over a 0.25^{o} x 0.25^{o} grid, the result is potentially misrepresented locally low (or high) winds that may have resulted in a small (or large) impact on a fire.

HDWI calculations using wind speeds recorded in the WMB database were also completed to assess the use of locally observed surface wind speeds. However, these weather readings are only reported at 1200h MST and therefore do not represent fire spread on days where a fire ignited or was actively burning before or after noon weather readings. The timing of these recordings are therefore not expected to represent maxima or significant events that may have contributed to fire spread due to factors such as increased winds, daytime heating or frontal passage later in the day when a fire may have been actively growing. Additionally, the WMB operates Remote Automated Weather Stations (RAWS), which includes weather records based on fifteen to sixty minute intervals, and these data are available. As of 2022, the WMB has approximately 141 active RAWS (Government of Alberta, Forecasts and Observations). However, this system of RAWS is relatively new and data are not available for many of the large fires within the study time-period.

Six total outliers in HDWI values calculated from ERA5 weather data were identified. These include four during spread days and two during non-spread days. The weather variables used to calculate these HDWI outliers were examined to determine if there were data processing or entry errors and if the outliers should be removed. It was determined that none of the weather variables used to calculate these HDWI values were abnormal and did not appear to be miscalculated or misreported. Therefore, outliers in HDWI values were not removed and all calculated values on days with at least 2 size updates are included in the analysis.

2.5 Spread Day Analysis

All statistical analysis was completed using R statistical software (R Core Team 2020), including graphic creation through Wickham ggplot2 (2016). Permutation tests were used to analyze HDWI during spread days and non-spread days. The null hypothesis is that the two distributions are the same. This test was selected over Mann-Whitney-Wilcoxon tests due to unequal sample sizes between the spread day and non-spread day groups.

Multiple cases were tested to examine different days since ignition for the 80 wildland fires. The maximum HDWI within the fire size report period was tested for the first 4 days on all fires, with Day 1 and Days 2 to 4 being separate cases. This approach was chosen to determine HDWI value thresholds for spread days over the core period of the first four days. The isolation of Day 1 allowed for the determination of different thresholds of HDWI values on the day of ignition. Additionally, isolating Days 2 to 4 allowed for the determination of HDWI thresholds for ongoing, active fires. HDWI was calculated using three approaches: i) ERA5 weather data, ii) WMB noon surface weather data, and iii) combination of approaches i) and ii). The combination approach is based on calculations of HDWI using 1200h MDT weather from both ERA5 and WMB surface weather. All cases tested can be found in Appendix B.

In each case, the difference in the mean HDWI values for spread days and non-spread days was calculated (original test statistic). Then, all HDWI values from both groups (spread days and non-spread days) were pooled together and randomly selected into the appropriate original group sizes for spread days and non-spread days. The difference in means between the two groups of randomly selected HDWI values was calculated. Resampling was set to 10,000 in all cases. A null distribution of the difference of means between the two groups was then generated. To test the null hypothesis that the means of the two groups are equal, the number of observations in the tail with the least observations greater or less than the original test statistic is multiplied by 2 and divided by n+1 to determine the p-value in a two-tailed test ($\alpha = 0.05$).

Permutation tests were used to analyze ISI during spread days and non-spread days to compare the HDWI's performance during spring fire season in Alberta. Daily ISI values from actual surface weather conditions (ISI.F) as well as those calculated from the ERA5 reanalysis with gusts observed at weather stations incorporated into wind speeds (ISI.AR) from Tymstra et al. (2021) were all analyzed to compare this FWI System value to HDWI. In this analysis of ISI, the same spread day classification was used as in the analysis of HDWI.

2.6 HDWI Forecasting

To identify a standard forecast time for the application of HDWI in an operational setting, the daily maximum HDWI for each of the first 4 days of all 80 large spring fires and the corresponding times of occurrence were recorded (320 observations). Some of these HDWI values fell outside of the report time used in the spread day analysis but were selected for the sole purpose of assessing when the daily maximum HDWI occurred.

Srock et al. (2018) calculated HDWI values for 1200h, 1800h and 0000h UTC, and selected the maximum value from these three values. Due to diurnal heating, the maximum HDWI is expected to occur at 0000h UTC. Daily maximums of HDWI were analyzed over the 80 wildland fires between 1100-2000h MDT for the purpose of determining the time when maximum values are likely to occur in Alberta. This was done to examine at standard forecast time for fire management decision support, instead of examining the entire day. To analyze this, a one-sample t-test was completed on the dataset of hours when daily maximum HDWI peaked to test if peak burn of 1700h MDT ($H_{0:}$ mu = 1700) was the time at which daily maximum HDWI occurred (α = 0.05).

2.7 May HDWI Climatology

As with any fuel moisture or fire weather indices, fire management officials require information on what constitutes conditions for increased, or high, fire behaviour potential. Though the purpose of the spread day analysis was to provide thresholds of HDWI for this purpose, creating a climatology provides a framework for fire management officials to use HDWI in an operational setting (McDonald et al., 2018). To provide this context, a 31-year climatology of HDWI for the month of May (1990-2020) was created for three locations in Alberta.

Climatologies were built for Fort McMurray (56.75^{o} x 111.50^{o}), Slave Lake (55.25^{o} x 114.75^{o}) and Peace River (56.25^{o} x 117.25^{o}). These climatologies represent three different longitudinal locations across the boreal forest of the province. Weather data for the calculation of HDWI was from the same ERA5 source as the spread day analysis. For each of the 3 locations, the same process as described in "2.2 - Calculations" was used to calculate hourly HDWI (1100-2000h MDT) for each day in May for the period of 1990 to 2020. These climatologies extend to 2020, beyond 2019 as in the analysis, due to available weather data. Maximum hourly HDWI values from each day within this time-period were selected to represent that day of May in each year (Maximum Daily HDWI).

A climatology for each of the 3 locations was constructed to show Maximum Daily HDWI, Mean Daily HDWI, Minimum Daily HDWI, 95^{th} Percentile, 90^{th} Percentile, 75^{th} Percentile and 50^{th} Percentile of HDWI for each day in May (1990-2020). These climatologies were built to provide multiple thresholds of HDWI for indications of moderate to extreme fire weather potential.

McDonald et al. (2018) constructed HDWI climatologies for multiple locations in the United States. However, their climatologies can only be compared as a relative measure, not as a literal comparison of values due to geographic and climatic differences. Additionally, the ERA5 reanalysis has a finer spatial resolution than the NCEP CFRS reanalysis used to create their climatologies.

CHAPTER 3 - RESULTS

3.1 Large Spring Wildland Fires in Alberta

Between the years of 1990 and 2019, the province of Alberta experienced almost 38,000 wildland fires which burned approximately 5.25 million hectares total (Government of Alberta, 2019). Of these fires, 23.3% started in the month of May. Of the almost 8,900 fires that started in May, 78.7% of these were human-caused (Government of Alberta, 2019). Wildland fires that started in May during this time-period accounted for 48.7% of the total annual area burned in the province (Government of Alberta, 2019).

As Stocks et al. (2002) reported, for the period of 1959 to 1997, fires greater than 200ha accounted for approximately 3.1% of all fires in Canada. In Alberta (1990-2019), fires greater than 200ha accounted for 1.6% of the number of fires, those greater than 1,000ha accounted for 0.8% of the number of fires, and May fires greater than 1,000ha accounted for 0.2% of the number of fires (Government of Alberta, 2019). Of the fires in the Stocks et al. (2002), those greater than 1,000ha accounted for 96.8% of the area burned. Within the Boreal Plains Ecozone alone, fires greater than 1,000ha accounted for 95.7% of mean annual area burned in Canada. This is consistent with the data for Alberta (Government of Alberta, 2019), where fires greater than 1,000ha accounted for 95.6% of area burned in all months (1990-2019), and fires greater than 1,000ha that started in May accounted for 97.7% of the total area burned by all May fires.

Approximately 86% of the large spring wildfires in this dataset occurred in the Boreal Plains ecozone of Canada. The other 14% occurred in the Taiga Plains Ecozone (10%) and the Taiga Shield ecozone (4%).

3.1 Spread Day Analysis

The analysis of HDWI for spread days and non-spread days using permutation tests indicates the difference between the means of the two distributions is statistically significant for Case 4 (HDWI All 4 days) and Case 6 (HDWI Day 1 Only) (Appendix B) for the 80 wildland fires that started in May and exceeded 1,000 ha in final size in Alberta for the period 1990-2019. HDWI values were higher on the spread days compared to the non-spread days ($\rho = 0.02$ for Case 4 and $\rho = 0.01$ for Case 6). The mean HDWI values were 102.8 and 81.0 respectively for spread and non-spread days (Case 4) and 110.0 and 77.8 respectively for spread non-spread days (Case 6).

There was a total of 114 observations (66 spread days and 48 non-spread days) of the 320 total possible observations over the first 4 days (Case 4, 9, and 10). The total number of observations for day 1 (Case 6, 11, and 20) is 69 of a total possible 80 observations. There were 42 spread day and 27 non-spread day observations in Case 6.

The total number of observations for days 2-4 (Case 14, 12, and 21) is 45 of a total possible 240 observations. These include 24 spread day and 21 non-spread day observations. The lack of multiple size updates over days 2 to 4 may be the result of ongoing escaped fire operations, where providing one report per day is sufficient for gaining an understanding of the growing size or complexity of a fire as described in section “2.4 Assumptions”.

The distributions of HDWI values on spread days and non-spread days were not significantly different when days 2-4 were isolated (Case 14) ($\rho = 0.75$) (Table 1). This may be due to smaller sample sizes for spread days and non-spread days (24 and 21, respectively), the difficulty in recording and reporting multiple size updates during escaped fire operations and extended attack incidents. Additionally, though it is assumed that these large fires were very difficult to manage, suppression may have had some impact on overall growth on days 2-4, in that growth on flanks or near the head was slowed due to suppression, even on elevated HDWI days.

The distributions of HDWI when calculated using the WMB noon surface weather records were not significantly different. This may be due to the pressure level where these readings are taken (e.g., the surface) or the timing of noon weather readings in that weather occurrences later in the day are more impactful on fire spread.

Table 1. Selected cases with group observations, group means, and p-values for HDWI, ISI.F and ISI.AR.

	Number of Observations		Mean		Permutation Test
Case	**Spread Days**	**Non-Spread Days**	**Spread Days**	**Non-Spread Days**	**p-value**
HDWI All 4 Days	66	48	102.8	81.0	**0.02**
HDWI Day 1 Only	42	27	110.0	77.8	**0.01**
HDWI Day 2-4	24	21	90.3	85.2	0.75
ISI.F All 4 Days	66	48	12.0	12.3	0.83
ISI.F Day 1 Only	42	27	13.1	10.6	0.24
ISI.F Days 2-4	24	21	10.0	14.5	0.07
ISI.AR All 4 Days	66	48	17.0	17.1	0.98
ISI.AR Day 1 Only	42	27	17.3	15.1	0.49
ISI.AR Days 2-4	24	21	16.4	19.6	0.38

As also shown in Table 1, ISI.F and ISI.AR did not have significantly different distributions between spread days and non-spread days as defined in the approach chosen (isolating day 1 size >200ha, day 2-4 DRG% >100%). The lack of significant cases with respect to ISI is consistent with Hanes et al. (2020), who found that ISI had a positive relationship with the probability of a fire escaping initial attack and growing to over 4 ha in size, but only in 2 of 4 Forest Areas in Alberta (1979-2018).

As shown in Figure 2, the two cases that had statistically significant differences between spread day and non-spread day distributions have an original test statistic that sits much farther from zero (e.g., a) HDWI over all 4 days and b) HDWI on day 1. This is because there is a significant difference between values in the spread day and non-spread day distributions compared to the other cases that had little variation between values of their respective groups. Cases that were not significant have an original test statistic that is positioned closer to 0 (Figure 2).

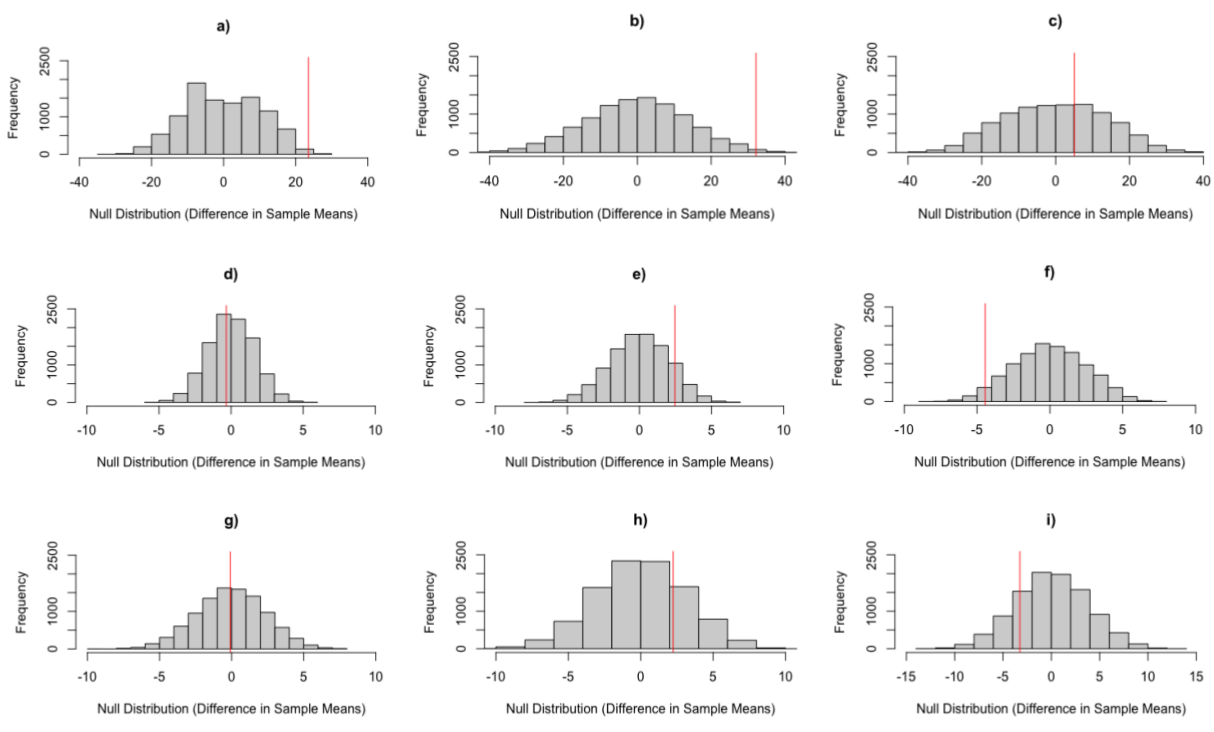

Figure 2. Null distributions from permutation tests. The red line indicates the original test statistic for a) HDWI over all 4 days, b) HDWI on day 1, c) HDWI on days 2-4, d) ISI.F over all 4 days, e) ISI.F on day 1, f) ISI.F on days 2-4, g) ISI.AR over all 4 days, h) ISI.AR on day 1, and i) ISI.AR on days 2-4.

HDWI value ranges on spread days and non-spread days are shown in Table 2 for examination of values and percentiles. Distributions of HDWI values over the 3 cases are shown in Figure 3.

Table 2. HDWI value ranges on spread days and non-spread days.

	Spread Days					Non-Spread Days				
Case	Min	25th Percentile	Mean	95th Percentile	Max	Min	25th Percentile	Mean	95th Percentile	Max
HDWI All Days	25.9	71.5	102.8	199.8	304.7	3.1	53.8	81.0	159.2	307.6
HDWI Day 1	29.8	73.2	110.0	240.1	304.7	3.1	50.8	77.8	159.9	186.0
HDWI Day 2-4	25.9	70.9	90.3	134.0	137.1	18.4	63.8	85.2	148.8	307.6

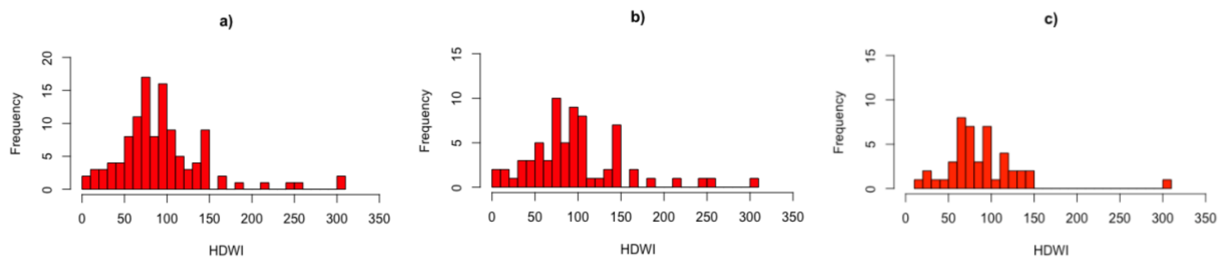

Figure 3. HDWI value distributions over a) all 4 days, b) day 1, and c) days 2 to 4.

Using the spread day classification method in this analysis, ISI values, both those recorded in the WMB's FIRES program and those calculated by Tymstra et al. (2021) that included an adjusted increase in wind speed to account for any reported wind gusts did not have significantly different distributions between spread days and non-spread days. As shown in Table 3, all ISI values were elevated through both spread days and non-spread days, with the means, and in most cases even 25th percentiles, being in the very high (8.1-15.0) to extreme (15.1+) ranges as defined by the FWI Code Hazard Levels for Alberta (Government of Alberta, Understanding Fire Weather, 2023). Additionally, mean ISI values are above the threshold (ISI of 10) for expecting crown fire development in most conifer fuel types as defined here. In all cases, the mean ISI values during spread days and non-spread days are at or above this threshold (Table 3). It is also important to note that mean ISI values in most cases were greater on non-spread days than on spread days, with the only exception being when day 1 was isolated. However, 95th percentile ISI values were higher on spread days than non-spread days, indicating a few observations may have been greater on non-spread days. Distributions for ISI.F and ISI.AR in the 3 cases examined are shown in Figure 4.

Table 3. ISI value ranges on spread days and non-spread days.

	Spread Days					Non-Spread Days				
Case Name	Min	25th Percentile	Mean	95th Percentile	Max	Min	25th Percentile	Mean	95th Percentile	Max
ISI.F All 4 Days	1.00	6.73	11.95	32.00	40.60	2.90	7.98	12.29	23.15	46.00
ISI.F Day 1	1.00	6.33	13.06	37.18	40.60	3.00	8.25	10.60	19.26	21.00
ISI.F Days 2-4	1.40	7.40	10.01	17.29	20.00	2.90	8.00	14.45	38.50	46.00
ISI.AR All 4 Days	0.10	8.28	16.97	45.58	68.40	1.90	9.68	17.06	39.81	50.90
ISI.AR Day 1	0.10	5.78	17.32	43.82	68.40	1.90	8.40	15.08	30.51	41.70
ISI.AR Days 2-4	0.80	9.93	16.36	43.65	49.30	5.80	10.40	19.61	50.10	50.90

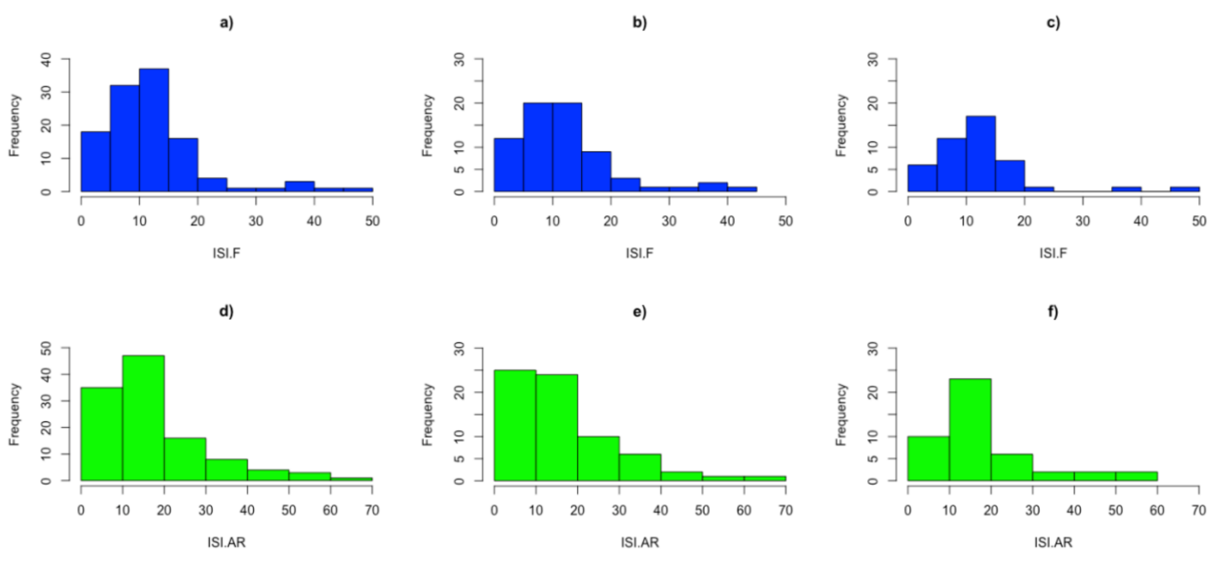

Figure 4. ISI value distributions showing a) ISI.F over all 4 days, b) ISI.F on day 1, c) ISI.F over days 2 to 4, d) ISI.AR over all 4 days, e) ISI.AR on day 1, and f) ISI.AR over days 2 to 4.

Vapour pressure deficit (VPD) and windspeed (WS) impacts the drying of fuels, and in particular, the fine fuels since they have a short equilibrium timelag. Additionally, on wildfire spread days in the spring in Alberta, there may be a coupled effect of both HDWI and ISI. The relationship between HDWI and ISI.F on spread days and non-spread days is shown in Figure 5. HDWI and ISI.F have low positive correlation coefficients on spread days and non-spread days (0.39 and 0.42, respectively). This is also the case for HDWI and ISI.AR (0.35 and 0.47, respectively). When spread days and non-spread days were examined together, HDWI also had a low positive correlation coefficient with ISI.F (0.39) and ISI.AR (0.39).

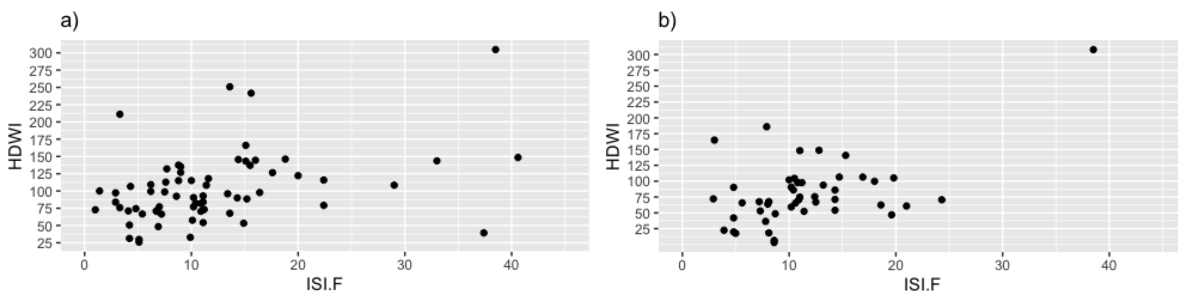

Figure 5. Scatter plots of HDWI and ISI.F over all 4 days on a) spread days and b) non-spread days.

Though I would expect ISI to be the primary driver of fire spread in the spring fire environment in Alberta, this suggests that ISI may not be the only indicator of potentially dangerous spring fire behaviour. This supports my initial hypothesis that there is more to spring fire spread potential than fine fuel moisture content and 10m open wind speed, and that the lower levels of the atmosphere may provide additional information for the occurrence of increased conditions for significant fire spread in the spring. However, as mentioned, ISI values over the first 4 days of these large May wildfires are elevated (mean ISI>10 on both spread days and non-spread days). Furthermore, ISI values are calculated using 1200h LST weather observations – diurnal heating influences vertical mixing into the atmosphere which increases turbulence, including surface wind speeds and wind gusts. Wind events after 1200h LST are not captured by ISI calculations, whereas HDWI values forecasted/calculated later into the burning period may capture these events.

3.2 HDWI Forecasting

To determine a standard forecast time for the application of HDWI in a daily forecast mode, the time of maximum HDWI occurrence over the first 4 days of all 80 large spring fires was recorded (Figure 6). The maximum daily HDWI often occurred over the period of approximately 4 core hours (1600-1900h MDT) over 320 observations.

The core period of 1600-1900h MDT is consistent with weather observed in Alberta. Through the one-sample t-test employed (H_0: mu = 1700h MDT), it was determined that 1700h MDT is significant, (due to failing to reject the null hypothesis, $\rho = 0.09$). The mean time of maximum HDWI occurrence (1711h MDT) is also consistent with the peak burn time of 1700h MDT in Alberta. However, the timeframe of 1600-1900h MDT where the time of max HDWI occurrence peaks is the recommended forecast timeframe as shown in Figure 6.

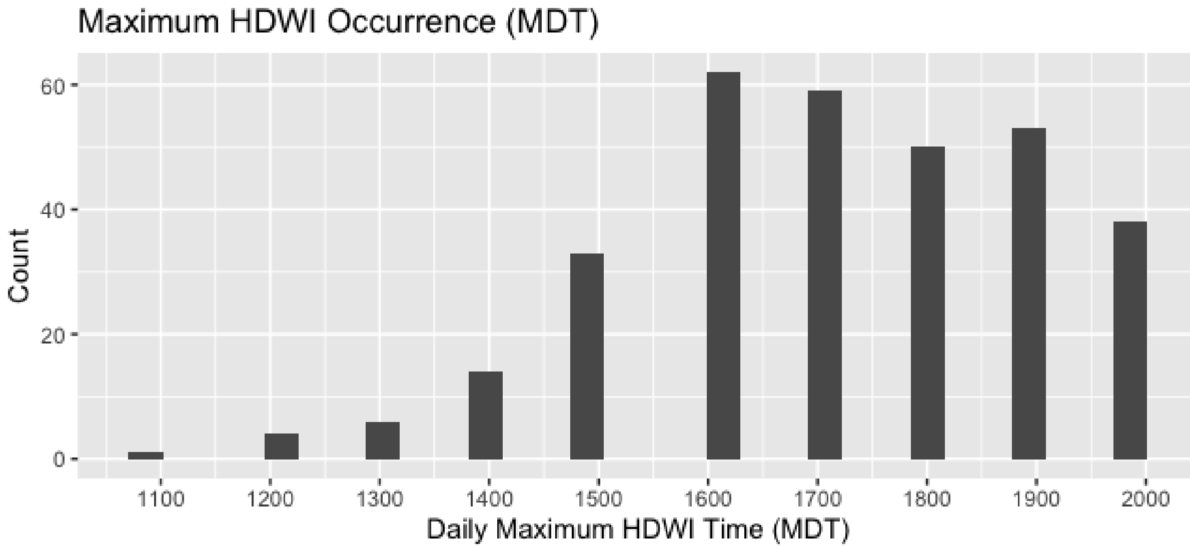

Figure 6. Time of Daily Maximum HDWI Occurrence (MDT) over the first 4 days of all 80 large (>1,000ha) Alberta spring wildfires (1990-2019).

3.3 May HDWI Climatology

A 31-year climatology was produced for the month of May for 3 separate locations (Fort McMurray, Slave Lake, and Peace River) in Alberta, Canada (1990-2020). I believe these climatologies can provide valuable information to fire management officials with respect to forecasting HDWI and dangerous fire behaviour potential (McDonald et al., 2018).

These HDWI climatologies are specific to the ERA5 dataset, a 0.25^o x 0.25^o grid cell size, and the locations selected. See Figures 7, 8, and 9 for these climatologies, as well as Table 4 for additional information.

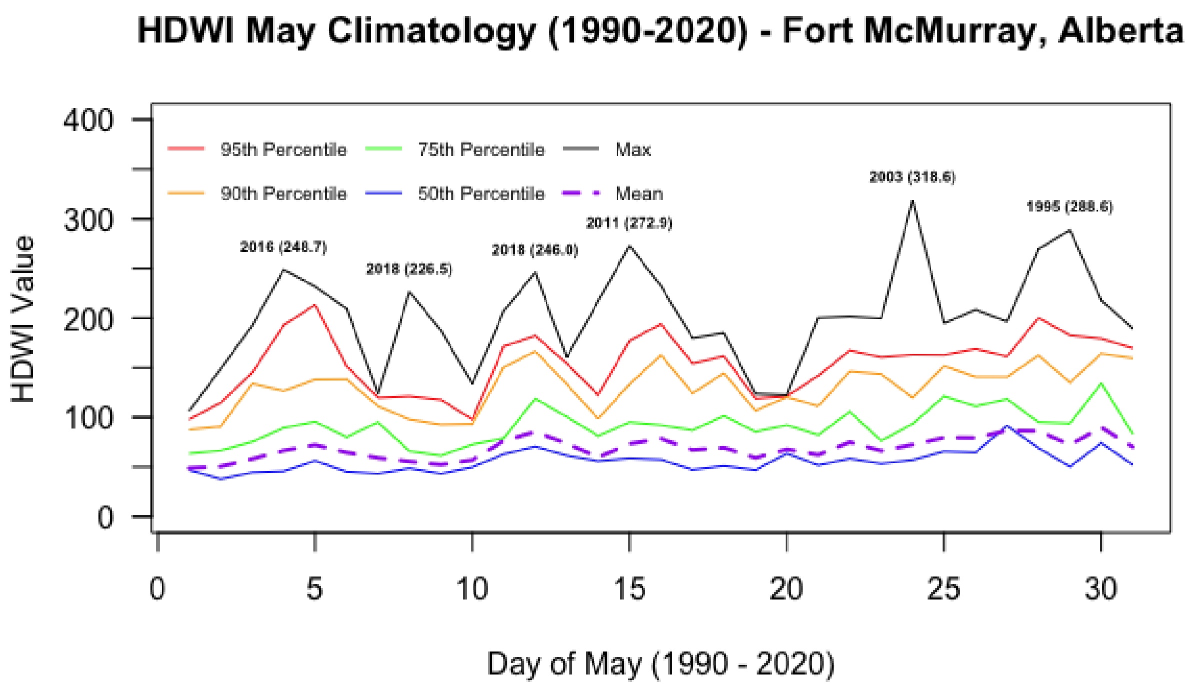

Figure 7. HDWI May Climatology (1990-2020) for Fort McMurray, Alberta (56.75º x 111.50º) with significant HDWI values and year of occurrence.

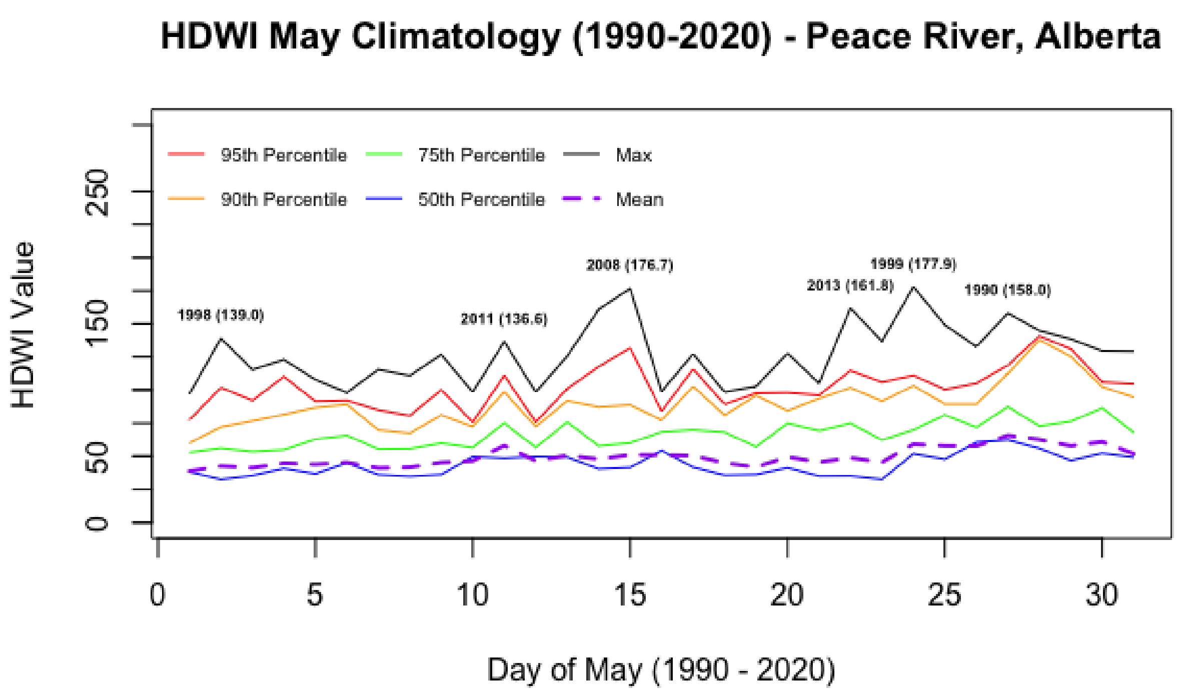

Figure 8. HDWI May Climatology (1990-2020) for Peace River, Alberta (56.25º x 117.25º) with significant HDWI values and year of occurrence.

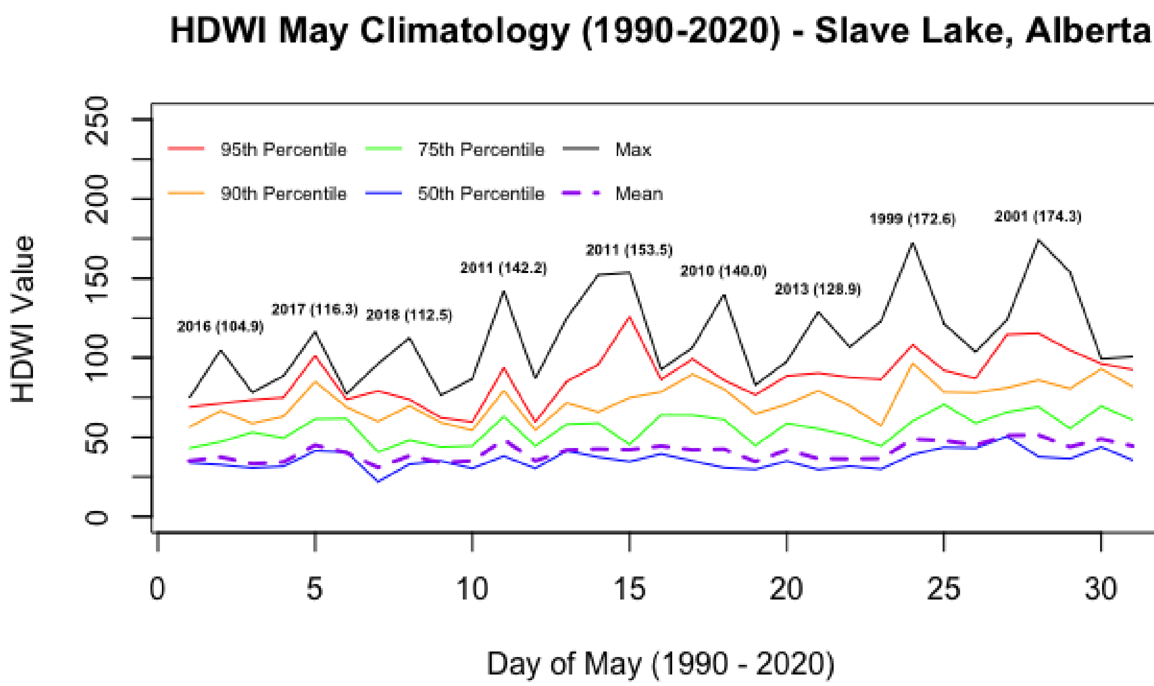

Figure 9. HDWI May Climatology (1990-2020) for Slave Lake, Alberta (55.25º x 114.75º) with significant HDWI values and year of occurrence.

Table 4 summarizes statistics based on climatologies of daily maximum HDWI values for all days in May (1990-2020) for three locations and a combined climatology using all locations. This climatology analysis can help to establish HDWI values significant to, in particular, the 3 locations chosen. The values for Fort McMurray are noticeably greater compared to the other locations. The reason for this is uncertain, other than where Fort McMurray is located may experience elevated HDWI values due to factors such as longitude and more influence from dry artic air masses that provide lower RH values. Additionally, the mean of all 3 locations (100.9) and the 90th percentile value when all three HDWI climatologies were combined (101.9) is very similar to the mean HDWI value on spread days of 102.8 found in the earlier analysis of HDWI over the first 4 days of all fires, as shown in Table 1 and Table 2.

Table 4. HDWI Climatology values for all days in May at each of the 3 locations, when all 3 location's values were combined, and means of the 3 locations (1990-2020).

	Min	50p	Mean	75p	90p	95p	Max
Combined	0.6	44.2	53.1	69.6	101.9	127.7	318.6
Fort McMurray	1.4	56.3	68.9	91.2	133.7	164.4	318.6
Peace River	2.1	43.9	49.6	66.5	92.6	108.9	177.9
Slave Lake	0.6	35.0	40.4	56.1	76.5	91.4	174.3
Mean	1.4	45.1	53.0	71.3	100.9	121.6	223.6

HDWI values for the first 4 days of the 2016 Horse River Wildfire were calculated and compared to the HDWI climatology for this location (Table 5). During three of the first 4 days of this fire HDWI values exceeded the daily 95th percentile value of the climatology and exceeded the monthly 95th percentile on 2 of the first 4 days. The observed HDWI values on May 1, 3, 4 (Day 1, 3 and 4, respectively), were the maximum HDWI values recorded in Fort McMurray from 1990-2020 on those specific days of May in 2016. The only day with a HDWI value below the 95th percentile was May 2, 2016 (Day 2), when the calculated HDWI value (112.8) was above the 90th percentile and above the mean spread day value (102.8) identified in the spread day analysis.

Over the first 4 days of the Horse River Wildfire, ISI values were examined. ISI values from FIRES and those calculated by Tymstra et al. (2021) which incorporated wing gusts were in the very high range for all days except on May 2nd when ISI.F was 7.6 (High). The lower HDWI and ISI values on these days were due to slightly lower wind speeds and a slightly greater VPD value. Though these values did not exceed very high ISI values or the 95th Percentile HDWI value, they still represent conditions for increased fire behaviour that will be difficult to manage.

These very high ISI values all exceed the threshold for crown fire development in most conifer fuel types (ISI > 10) and support the fuel moisture complex on this fire in early May, 2016. However, as discussed earlier, ISI was not significant in explaining spread days in our dataset due to consistently elevated values (mean ISI greater than 10.0 in all cases) for spread days and non-spread days.

With respect to HDWI and ISI thresholds to determine spread days, the only spread day observed from May 1st to May 4th, 2016 on the Horse River Fire was on May 2nd. Day 1 (May 1st, 2016) did not experience a spread day on this fire. However, the last size update for the Horse River Fire was reported at 1913hrs (120ha), this may have been an estimation error and one could expect additional growth into the evening beyond 200ha. On Day 2 (May 2nd), even though ISI.F was only in the high range, this fire still experienced 431% of DRG on this day. The HDWI value on May 2nd still exceeded the spread day HDWI threshold found in this spread day analysis of 102.8. Additionally, May 3rd and May 4th could not be analyzed due to only have one fire size update. One would expect significant growth on those days due to the maximum HDWI values experienced for this location (1990-2020) as well as ISI values in the Very High range.

Table 5. Calculated HDWI values on the Horse River Wildfire (MWF-009-2016) over the first 4 days compared to May climatology values (1990-2020), with spread day and daily growth. Daily MWF-009-2016 values indicated under the 2016 column. Pink pertains to observed HDWI value exceeding the 95th Percentile value for that day in May, red pertains to the observed HDWI value exceeding the 90th Percentile but not 95th Percentile. ISI values included for reference.

	2016	MIN	50p	MEAN	75p	90p	95p	MAX	ISI.F	ISI.AR		
May	---	**1.4**	**56.3**	**68.9**	**91.2**	**133.7**	**164.4**	**318.6**	---	---	**SD**	**Growth**
01-May	**106.5**	15.0	46.8	48.9	63.5	87.6	98.1	106.5	14.7	13.1	No**	120ha**
02-May	**112.8**	14.1	37.8	50.5	66.6	90.9	114.8	148.9	7.6	8.8	Yes	431%
03-May	**192.5**	9.0	44.4	58.1	75.4	134.1	145.0	192.5	14.8	12.2	NA	NA
04-May	**248.7**	2.3	45.7	66.5	89.4	126.7	192.8	248.7	11.0	12.6	NA	NA

I believe these May climatologies can assist fire weather forecasters, fire management officials and the people working on the ground by providing additional information regarding HDWI for determining days that may present increased or dangerous spring fire weather in Alberta.

CHAPTER 4 - DISCUSSION

4.1 Spread Days and Fire Growth

HDWI has shown to represent spread day potential for large spring wildland fires in Alberta. Though the fires analyzed here are large fires of note that spread quickly and are difficult to manage, HDWI can be a useful tool for prevention, preparedness and suppression planning, especially since these fires are examples of the large conflagrations in May in Alberta.

Of the main contributors to large wildfire growth in the spring, FFMC and wind (Tymstra et al., 2019), I chose to focus on strong winds and dry air to identify days that present dangerous fire weather conditions. Strong, dry winds play a role in increasing fires from large sizes to fires of unusual sizes (Potter and McEvoy, 2021). Though extreme surface winds are not the only prerequisite for large fire growth, these winds increase the likelihood that a fire will escape suppression and grow to large sizes (Beverly, et al., 2011).

Currently, atmospheric indices are not used as indicators of fire spread or fire behaviour potential in Alberta. As outlined in the Flat Top Complex Wildfire Review Committee (2012), the need for improved prediction of high wind and dry air events that result in dangerous fire weather conditions are imperative. HDWI was developed to capture the effect of hot, dry and windy conditions present in the lower levels of the atmosphere and their impact on fire growth. As mentioned earlier, HDWI does not examine the impacts of the fuel complex on fire behaviour or spread as it is a weather-only index. Therefore, HDWI is not linked to the FWI System or the FBP System. Additionally, the incorporation of weather variables from other layers in the atmosphere, and not just at the surface, will assist in enhancing the ability to predict dangerous fire weather conditions. I hypothesized that HDWI could be a successful index for predicting these conditions because it assesses important variables (VPD and WS), at multiple levels. An earlier study by Srock et al. (2018) also showed that HDWI was a good predictor of dangerous fire behaviour days on four historic wildland fires in the United States.

The physical drivers of HDWI (WS and VPD) have profound effects on fire behaviour including increasing the rate at which fuels dry, and the spread rate of an ongoing fire. Local atmospheric levels of stability are also an important factor in wildfire behaviour and spread, including wind speed and atmospheric mixing in response to stability. Mixing is typical in an unstable atmosphere, where there is resistance to mixing under stable conditions. Instability can result in turbulent and gusty wind conditions, causing fires to move, at times, unpredictably and at higher rates of spread. Stable atmospheres provide more consistent wind speeds and, depending on the pressure gradient and the origin of a high-pressure system, provide dry air coupled with strong winds. Strong, dry winds associated with high pressure systems will result in higher rates of spread and higher rates of drying of fuels, resulting in elevated fire behaviour. Stability determines the amount of mixing that occurs. However, it is reasonable to assume that near-surface mixing from late afternoon onward makes it possible that WS and VPD at 500m above the surface or less may affect a fire any point in the day (Srock, et al., 2018). The mesoscale weather systems used to calculate HDWI make it difficult to forecast local occurrences such as local mixing, local wind shifts that are the result of sources such as the indrafts and outdrafts associated with thunderstorm development and frontal passage, or the occurrence of low-level jets that result in elevated wind speeds. Therefore, it is important that if these occurrences are forecasted, they should be incorporated into the calculation of HDWI values.

WS has a large impact on HDWI, and therefore the calculations using ERA5 data may be misrepresented depending on forecasted WS and actual WS. That is, if ERA5 is providing lower than actual wind speeds due to the large grid sizes, HDWI will also be lower due to actual, potentially higher local winds experienced. As a result, the actual HDWI that occurred over our 80 large spring fires may have been greater than calculated in our analysis using ERA5 weather, and therefore, the HDWI thresholds found here may be lower than what will be forecasted when used in a forecasting mode, or lower than what will actually cause spread events.

ISI value distributions did not have a significant difference between spread days and non-spread days in this analysis. As discussed, this may have been due to a number of factors such as the occurrence of elevated ISI values over the first 4 days of each of these 80 large spring wildfires whether they were spread days or not, resulting in little variation of ISI values between spread days and non-spread days. Another factor could have been the effect of suppression on days 2 to 4 of these fires. Though it is assumed that suppression would not have been effective on the head or main areas of growth on these fires, management can still restrict overall growth due to its effect on other sections such as the back and parts of the flanks, even on elevated fire weather days. With that, however, one may expect HDWI to also display these results. However, spread day and non-spread day distributions being significantly different with HDWI values and not ISI values may be the result of analyzing a weather-only index against a fuel moisture index, which was one of the main research objectives of this analysis (Research Objective #2).

Though it was determined in this analysis that ISI was not effective at determining spread days, I still believe that this FWI System value provides valuable information pertaining to spring fire growth. The mean ISI value for non-spread days from FIRES (ISI.F) for all 4 days (Case 9), day 1 separate (Case 11) and days 2-4 separate (Case 12) were in the very high ranges (12.3, 10.6 and 14.5, respectively). One would expect these ISI values to result in significant fire growth which did not occur on the non-spread days in this study. Therefore, I recommend HDWI be used as an indicator of spring fire growth in conjunction with ISI. Of the cases I examined in this study (Appendix B), I recommend using the case of HDWI over all 4 days (Case 4) in combination with an ISI threshold (Case 9). For example, a spread day may be expected for a new start (e.g. Grow to 200ha+ on the day of ignition) when the HDWI exceeds the mean spread day HDWI value of 102.8, and ISI is 8.7 or greater as in Podur and Wotton (2011), ISI is 9.0 or greater as in Tymstra et al. (2021) or, though not statistically significant, the mean ISI.F value on spread days found here of 12.0 (Case 9 – Appendix B, Table 1 and Table 3).

There are potential sources of error in this study, namely the sources discussed in "2.4 Assumptions". Situations may have also occurred on these 80 large spring wildfires where suppression was successful on the head due to assistance from barriers to fire spread. These barriers can include anthropogenic features such as roads or natural features such as bodies of water, exposed rock, or less volatile fuels. Additionally, fuel moisture (except for ISI) and fuel type inputs for fire growth were excluded from this study. Fuel type and fuel moisture content are driving factors in fire behaviour, but I wanted to address weather alone due to a lack of knowledge of atmospheric influences alone on spring wildland fire growth.

The fire size data used in this analysis of HDWI on spring fire growth is that of ocular estimations of size. Other sources of fire size data have become available later in this 31-year study period such as Landsat or MODIS hotspot determination. Methods such as this may be more accurate but have limitations such as being inhibited by cloud or smoke, satellite parallax, and cell size resulting in diminished accuracy. These methods were not used due to their availability over the entire study period of 1990-2019. Additionally, I believe the categorical nature of spread days used in this analysis can alleviate discrepancies that are the result of estimation error.

4.2 Application of HDWI

I recommend the primary function for the application of HDWI be to support decision making in the wildland fire prevention, preparedness and suppression planning processes. Forecasting extreme fire weather is the first step in preventing the potential impacts a human-caused fire could have on the public. Wildfire prevention measures need to be implemented during extreme wildfire weather and wildfire behaviour conditions (Flat Top Complex Wildfire Review Committee, 2012) for the purpose of mitigating human-caused fires. Even if very severe fire weather is forecasted or experienced, there will be no area burned if there is no ignition (Flannigan et al., 2005). If HDWI (and ISI combined) thresholds for spread days are reached, prevention methods should be employed. Though the prevention system can take time to be implemented, fire prevention methods "need to be strategically applied and removed quickly" (Tymstra et al., 2021, Pg. 833), therefore, the implementation of these methods also need to be improved.

May fires that grew to 1,000ha (1990-2019) accounted for 97.7% of total area burned by fires that started in May, and nearly 50% of the total area burned in all months (Government of Alberta, 2019). That is, the fires analyzed in this study represent the extreme events that the province of Alberta has experienced in the last 30 years. Though these fires are the ones that get up and go, and are very difficult to manage, I believe the results of the analysis of HDWI can support prevention planning more than preparedness and suppression planning.

Though the mean peak HDWI time of occurrence was found to be approximately 1700h MDT, the range of 1600-1900h MDT is the recommended daily forecast period due to the pronounced peak of HDWI maxima observed for the month of May (1990-2020). Forecasting HDWI over a period of core hours, such as 1600-1900h MDT, will ensure the occurrence of changes in weather such as wind events be captured, rather than only forecasting a one-hour timestamp. To provide a suitable tool for the operational forecasting of HDWI, I examined the Windy application (windy.com). This application is an ECMWF product that provides 3-hour forecasts of temperature, wind speed and relative humidity at the surface and 950 hPa level. Hourly HDWI was forecasted for all days in May 2022 (the day prior) and compared to observed ERA5 HDWI values. A preliminary examination of the Windy application forecasts and values observed in ERA5 weather suggest the Windy application may be a viable forecasting tool. If using the Windy application, this results in 2 HDWI calculations from the three-hour forecasts of 1400-1600h and 1700-1900h MDT.

Forecasting HDWI will provide hourly values over the course of the following hours or following day. If HDWI can be forecasted for multiple days in advance it will assist in identifying dangerous fire weather conditions beyond a 24-hour timeframe (e.g. up to 2 to 5 days in advance). Due to the nature of weather forecasting, it may be difficult to accurately forecast HDWI beyond, for example, a 48-hour timeframe. However, especially with significant wind events, these dangerous conditions may still be captured when forecasting more than 24 hours in advance. If apparent spikes in HDWI values are forecasted, fire management officials should consult fire weather meteorologists to gain a better understanding of the cause for these occurrences (Killough, 2021).

Forecasted HDWI values should be evaluated in reference to the spring Spread Day threshold found in this analysis (102.8) or the May climatologies in section 3.3. Nonetheless, since there is no way to tie higher index numbers to quantitative fire behaviour outputs, to add context to the idea that higher HDWI values result in increased fire behaviour (Killough, 2021), forecasted HDWI values should be evaluated in reference to local long-term trends. Additionally, HDWI values should be analyzed in terms of complementing the outputs of the daily FWI and FBP System outputs. HDWI will aid in capturing strong dry wind occurrences, including weather in the lower levels of the atmosphere that quickly affect the surface conditions on a wildfire. Since HDWI is a weather-only index, values are not linked to the FWI or FBP Systems. If thresholds for HDWI are met, they should be considered when FWI or FBP System outputs also present dangerous spring wildland fire conditions. HDWI should be analyzed hourly to identify days and periods of days where fire weather conditions may present dangerous fire behaviour conditions. These HDWI values should be examined with respect to trends (as in the climatologies) and should be considered a complementary tool to the FWI system and outputs of the FBP system for predicting spring wildland fire spread events in Alberta.

As mentioned, HDWI could assist in wildland fire prevention, pre-suppression and suppression planning. In the case of applying HDWI to May wildland fire prevention in Alberta, when forecasted HDWI thresholds are expected to be met, in combination with elevated ISI values, prevention measures should be put in place. For example, the Fire Ban Matrix in Alberta could include HDWI value thresholds, so when these are expected to be met or exceeded, aspects of the Fire Ban Matrix are initiated – whether that be Fire Advisories, Fire Restrictions, Fire Bans or Forest Closures. These prevention measures can help mitigate human-caused wildfires on public lands in Alberta. That being said, lightning caused wildfires are not preventable and can still cause great challenges if ignited under similar conditions to those examined in this analysis.

To supplement current available fire weather forecasting tools, such as the FWI and FBP Systems, when used as an additional tool in the toolbox HDWI has shown to be a valuable addition to predicting elevated levels of fire weather conditions and subsequent fire growth with respect to spring spread days. However, with each of the assumptions in mind, there are obvious shortfalls of the data provided and analyzed. I believe HDWI can be a useful tool in forecasting extreme fire weather and provide valuable information to wildland fire prevention, preparedness and suppression planning during the critical month of May in Alberta.

4.3 Future Research

Future research is required into HDWI, including examination of HDWI throughout the rest of the fire season. Though this analysis only examines wildland fires that started in May, spring conditions are still prevalent in the early portion of June leading to green-up. Additionally, spring is not the only season that large fires can ignite. In Alberta, there have been 112 fires >1,000ha in final size that started in June (Government of Alberta, 2019). 33 of these started between June 1 and June 15, with the remaining 79 starting after June 16. Of these 112 fires, only 2 were caused by humans (June 9th and June 26th). The absence of large human-caused fires in June does not preclude further research into HDWI in this month, especially since lightning ignited fires are still very prevalent in Alberta and can grow to large sizes. Therefore, further research of HDWI throughout the remainder of fire season in Alberta is necessary. Further research is also required to assess HDWI across Canada. With respect to the depth of the atmosphere that VPD and WS are collected for the calculation of HDWI, these variables could be collected even further above the surface than 500m. This would potentially aid in capturing upper-level winds that can impact the surface through mixing, such as up to the 850 hPa level, rather than just 500m above the surface.

CHAPTER 5 - CONCLUSION

Wildland fire occurrence and fire behaviour are determined by three broad components: fuel, weather and topography. Currently, wildland fire prevention, preparedness and suppression planning in Alberta are focused around the FWI and FBP Systems. Both systems, the two main components of the CFFDRS, have been used and implemented successfully for decades. However, these systems do have limitations and only account for noon surface weather conditions and noon surface weather forecasts. Other than the application of local knowledge and the broad understanding of mesoscale weather systems in certain circumstances, weather variables and fire weather indices in the lower levels of the atmosphere beyond the surface are not used. Additionally, it has been identified by sources including reviews such as the Flat Top Complex Wildfire Review Committee (2012) (Slave Lake wildfires in 2011) that the need for improved prediction of significant wind events and dry air events that have profound impacts on fire behaviour is of great need.

In this study I examined the Hot-Dry-Windy Index (HDWI) on spring wildland fire spread events in Alberta, Canada, as well as provided forecast options for application of daily fire spread prediction, and 3 climatologies for northern boreal regions for context. To achieve this, I used historical wildland fire data in Alberta (1990-2019) and ERA5 reanalysis weather to calculate historical HDWI values.

Higher HDWI values were observed for the first four days of 80 large spring wildland fires in Alberta that occurred from 1990-2019. When examining the first four days, a spread day is likely when HDWI is 102.8 or greater. Higher HDWI values were also observed on day 1 with a threshold of 110.0. HDWI was not significant when days 2-4 were isolated.

Previous research does not include fire weather indices that isolate weather from fuel moisture, fuel composition or topographical components of the fire environment. The need for improved understanding of other layers of the atmosphere as they pertain to wildland fire weather forecasting is imperative. HDWI will aid in wildland fire preparedness and suppression planning, as well as provide an additional index for assisting in the implementation of wildland fire prevention strategies to mitigate the ignition of human-caused fires, especially in the vulnerable spring fire season in Alberta.

Throughout this analysis I also examined ISI values as this index is an important piece of the FWI System and is the primary FWI System value during spring fire season. ISI value distributions were not significantly different between spread days and non-spread days in my analysis under the methods employed. This was presumably due to the consistently elevated ISI values over these 80 large spring wildfires which resulted in little variation between spread days and non-spread days. Though ISI was not significant, I believe this index is still a very successful and imperative for spring fire spread and fire growth, and should be kept as a main consideration in wildland fire decision making in the spring in Alberta.

In this study I also developed May HDWI climatologies for 3 locations in Alberta – Fort McMurray, Slave Lake and Peace River. I believe these climatologies will provide valuable information to fire management staff on conditions for elevated fire spread potential during the month of May in Alberta. A standard forecasting time-period of 1600-1900h was also identified through the identification of daily maximum HDWI occurrence across Alberta in May from 1990-2020.

Recommendations for future work include the expansion of the spring study period into June, as well as throughout the entirety of fire season and across Canada. HDWI values that determine fire spread may differ throughout the summer months and across the country. Future work should also include the application of more accurate fire size data, which includes the examination of HDWI on current methods for determining fire size such as MODIS/VIIRS. To potentially increase the effectiveness of HDWI at capturing the influence of winds aloft on surface winds, HDWI could include the expansion of the atmospheric level deeper than 500m above the surface.

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APPENDIX A
Wildland Fires Examined

		Assessment Date						Assessment Date			
	Fire	Year	Month	Day	Ex Size (ha)		Fire	Year	Month	Day	Ex Size (ha)
1	DF1013-1995	1995	5	28	129,408.9	41	LWF119-2018	2018	5	23	5,436.3
2	DF1014-1995	1995	5	28	5,692.1	42	LWF122-2015	2015	5	22	31,997.0
3	DF2011-1995	1995	5	27	33,558.0	43	LWF126-2015	2015	5	25	2,130.8
4	DF3011-1995	1995	5	28	2,920.1	44	MWF007-2011	2011	5	14	577,646.8
5	DF3012-1995	1995	5	28	3,448.6	45	MWF009-2016	2016	5	1	485,123.6
6	DL1009-1995	1995	5	28	132,678.7	46	MWF010-2011	2011	5	15	1,474.0
7	DL2061-1995	1995	5	23	13,850.2	47	MWF015-2016	2016	5	5	11,604.0
8	DND002-1993	1993	5	15	4,876.1	48	MWF016-2018	2018	5	26	2,290.3
9	DND007-1991	1991	5	31	1,559.1	49	N02021-1998	1998	5	3	10,886.3
10	DP1017-1995	1995	5	27	7,035.6	50	N03018-1998	1998	5	2	163,138.1
11	E01020-1999	1999	5	25	5,132.3	51	N03022-1998	1998	5	2	5,830.0
12	E01025-1998	1998	5	23	51,250.0	52	N03024-1998	1998	5	2	2,029.0
13	E01027-1998	1998	5	21	3,850.0	53	N03052-1998	1998	5	24	4,875.3
14	E01028-1998	1998	5	21	8,353.0	54	PWF019-2008	2008	5	15	1,307.0
15	E02038-1999	1999	5	25	7,206.9	55	PWF034-2018	2018	5	22	1,168.2
16	E02043-1999	1999	5	25	1,291.1	56	PWF047-2018	2018	5	28	3,992.0
17	E02044-1999	1999	5	25	8,316.1	57	PWF052-2015	2015	5	25	1,202.0
18	E02046-1999	1999	5	26	1,491.2	58	PWF052-2019	2019	5	11	55,179.0
19	E02070-1998	1998	5	24	10,330.0	59	RWF020-2013	2013	5	12	1,303.0
20	E02076-1998	1998	5	27	9,263.0	60	SWF049-2019	2019	5	18	273,045.0
21	E02077-1998	1998	5	28	3,790.0	61	SWF050-2001	2001	5	13	1,270.0
22	E04026-1999	1999	5	25	1,952.2	62	SWF050-2019	2019	5	18	1,456.4
23	HWF020-2001	2001	5	24	8,000.0	63	SWF056-2011	2011	5	14	16,011.2
24	HWF042-2019	2019	5	12	331,946.0	64	SWF057-2011	2011	5	14	87,659.4
25	HWF066-2019	2019	5	27	74,332.0	65	SWF060-2011	2011	5	14	5,453.4
26	HWF070-2012	2012	5	26	1,689.0	66	SWF065-2011	2011	5	14	3,973.5
27	HWF083-2018	2018	5	24	4,754.0	67	SWF069-2019	2019	5	26	58,578.9
28	HWF089-2012	2012	5	31	1,622.2	68	SWF079-2019	2019	5	30	1,001.3
29	HWF104-2005	2005	5	8	7,010.3	69	SWF080-2011	2011	5	15	1,862.2
30	HWF111-2015	2015	5	23	3,521.3	70	SWF087-2001	2001	5	25	2,049.1
31	HWF124-2005	2005	5	14	3,563.0	71	SWF088-2011	2011	5	16	17,472.9
32	HWF127-2015	2015	5	25	3,852.1	72	SWF090-2001	2001	5	25	9,682.0
33	HWF132-2015	2015	5	25	1,261.6	73	W02011-1998	1998	5	20	1,933.8
34	LWF026-2003	2003	5	25	1,310.0	74	W03018-1999	1999	5	24	6,118.8
35	LWF031-2002	2002	5	17	238,866.8	75	W05015-1998	1998	5	2	49,670.0
36	LWF058-2012	2012	5	13	1,037.4	76	W05040-1998	1998	5	20	12,096.0
37	LWF063-2001	2001	5	23	104,534.3	77	W05047-1998	1998	5	24	2,362.6
38	LWF073-2001	2001	5	28	11,520.0	78	W06020-1998	1998	5	21	3,408.0
39	LWF099-2018	2018	5	21	8,647.6	79	WWF020-2006	2006	5	19	1,786.0
40	LWF116-2018	2018	5	22	1,775.7	80	WWF022-2011	2011	5	14	4,213.8

APPENDIX B
Cases for Spread Day Analysis

Case	Description	Spread Day Option	Observations		Mean		Permutation Test
			Spread Day	Non-Spread Day	Spread Day	Non-Spread Day	p-value
1	Timeline HDWI All 4 Days	1	89	25	98.1	77.2	0.03
2	Case 2 with IQR3 Outliers Removed	1	88	24	95.8	67.6	<0.01
3	Timeline HDWI Day 1 Only	1	65	4	101.0	35.5	<0.01
4	Timeline HDWI All 4 Days	2	66	48	102.8	81.0	0.02
5	Case 4 with IQR3 Outliers Removed	2	63	47	95.0	76.0	0.01
6	Timeline HDWI Day 1 Only	2	42	27	110.0	77.8	0.01
7	Daily Max HDWI All 4 Days	2	66	48	106.6	93.9	0.22
8	Case 4 with <1hr Elapsed Time Removed	2	66	38	102.8	80.0	0.03
9	ISI.F All 4 Days	2	66	48	12.0	12.3	0.83
10	ISI.AR All 4 Days	2	66	48	17.0	17.1	0.98
11	ISI.F Day 1 Only	2	42	27	13.1	10.6	0.24
12	ISI.F Days 2-4	2	24	21	10.0	14.5	0.07
13	Case 9 with <1hr Elapsed Time Removed	2	66	38	12.0	12.6	0.73
14	Timeline HDWI Days 2-4	2	24	21	90.3	85.2	0.75
15	Timeline HDWI with Surface All 4 Days	2	66	48	124.4	107.4	0.14
16	WMB Noon SurfaceHDWI.F Day 1 Only	2	42	26	96.0	83.4	0.25
17	WMB Noon SurfaceHDWI.R Day 1 Only	2	42	27	97.7	78.3	0.07
18	WMB Noon SurfaceHDWI.ARF Day 1 Only	2	42	26	117.8	102.9	0.33
19	WMB and ERA5 Noon HDWI Day 1 Only	2	42	27	144.0	124.5	0.21
20	ISI.AR Day 1 Only	2	42	27	17.3	15.1	0.49
21	ISI.AR Days 2-4	2	24	21	16.4	19.6	0.38
22	HDWI All 4 Days 1990-2004	2	28	22	91.9	73.6	0.07
23	HDWI All 4 Days 2005-2019	2	38	26	110.8	87.0	0.12
24	ISI.F All 4 Days 1990-2004	2	28	22	10.1	11.0	0.54
25	ISI.F All 4 Days 2005-2019	2	38	26	13.3	13.4	0.97

Spread Day Option 1: DRG>100% for all 4 days
Spread Day Option 2: Day 1 >200ha, Days 2-4 DRG>100%