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Reducing Wildfire Ignitions from Open Burning

in the Black Hills of South Dakota

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CERTIFICATION STATEMENT

I hereby certify that this paper constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions, or writings of another.

Signed:____

Abstract

The research purpose of this study was to identify and analyze the causal factors of wildfire ignitions from open burning activities in the Black Hills of South Dakota. A descriptive methodology that incorporated a causal-comparative experimental design was used to answer the research questions of the description of the factors and their relationships to wildfire ignitions during the winter burning season. The Mann-Whitney test and classification and regression tree analysis were used as procedures to identify and describe the relationships for the factors of ignition. Results showed that temperature and wind factors were most significant in causing wildfire ignitions. Recommendations are to apply the results within a comprehensive community risk reduction strategy framework in the fire department's service area.

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Introduction

The Black Hills of South Dakota is a forested area of small mountains located in the far western region of the state. This area is internationally known for the attractions of the Mount Rushmore and Crazy Horse rock carvings. This mountainous region contains a complex wildland fire environment that is the product of a densely settled landscape that is adjacent to an overstocked ponderosa pine forest. This situation creates a serious potential for a catastrophic wildland urban-interface fire at any time of the year when a fire is ignited under extreme fire weather conditions. Given the rugged terrain features over the landscape combined with an abundance of available wildland fuels, wildfire burning under these extreme weather conditions can present immediate problems for firefighter and civilian life safety with the potential for significant loss in residential structures and community infrastructure.

Historically the residents of the Black Hills have responded well to interagency efforts put forth by federal, state, and local fire departments and agencies to engage the community in wildfire prevention and risk mitigation efforts in the wildland-urban interface. From the creation of the Black Hills Forest Fire Protection District in 1939, to the national Smokey Bear campaign and the local "Keep South Dakota Green" effort; with recent efforts to adopt the national "Firewise Communities ®" model combined with local jurisdictions adopting zoning regulations and building codes; all point to a progressive trend of a community risk reduction effort targeted at wildland fire.

Despite the best efforts of wildfire prevention and risk reduction activities, there still exists a problem on how the South Dakota Division of Wildland Fire Suppression can reduce the frequency of wildfire ignitions from open burning activities in the Black Hills Forest Fire Protection District. The purpose of this research is to identify those causal factors that determine the occurrence of wildfires ignited from open burning and to develop recommendations for an appropriate risk mitigation strategy that will reduce the rate of occurrence of those ignitions in the Black Hills Forest Fire Protection District.

The descriptive research method utilizing a causal-comparative analysis of data was used for this research project. The research questions deal with analyzing and reducing the rate of wildfire ignitions from open burning in the Black Hills of South Dakota and are summarized in the following two points: (a) the identification of the causal factors that determine the frequency of wildfires ignited from open burning activities; and (b) the analysis of any relationship of these identified factors that cause wildfires to be ignited from open burning activities.

Background and Significance

The problem of reducing wildland fire ignitions from open burning in the Black Hills Forest Fire Protection District (BHFFPD) is an important area of study for the South Dakota Division of Wildland Fire Suppression (SDWFS). Under South Dakota state law, a person wishing to conduct open burning activities such as the burning of tree limbs, branches, twigs and logs in an open fire within the Black Hills must first apply for a burning permit from a SDWFS field office, (South Dakota Codified Law § 34-34-16). Then upon receiving such an application, the local SDWFS fire officer must then take into account the climatic conditions that would allow for the safe use of open fire and either deny the permit or issue one based on restrictions due to forecasted weather. (South Dakota Codified Law § 34-34-17). At times of favorable burning conditions in the winter burning season, SDWFS field offices and the zone dispatch center may issue hundreds of these burning permits on a daily basis to individual citzens to burn debris or "slash" piles in the BHFFPD. The use of open fire and the issuance of burning permits is promoted as public policy by SDWFS in order to encourage residential homeowners in the Wildland Urban Interface (WUI) to clear vegetation and brush from around their residences in order to create defensible space around structures to "Firewise Communities®" standards as a community risk reduction activity. Given the options from hauling vegetative matter to the landfill, chipping, or burning, the use of open fire is the usually the most economical method for landowners to utilize for brush disposal.

Given the fact that the State of South Dakota carries out its jurisdictional responsibility to suppress wildland fire on state and privately owned forested lands in the Black Hills through SDWFS, places the fire department in a unique position of having to advocate the use of fire, albeit in a safe manner, by allowing many simultaneous ignitions across the BHFFPD on any given burning day in the winter season in order to accomplish a community risk reduction activity.

Management issues arise for SDWFS when climatic conditions change suddenly with the advent of fohen or gravity winds that are given the local name of "*Chinooks.*" While not as strong in intensity or temperature as the foehn winds of Southern California that are known as the "*Santa Ana's*" (National Wildfire Coordinating Group, 2003), these Chinook winds will quickly melt snow cover on a winter's night and dry wildland fuels fast enough to allow a previously permitted fire to get out of control. Once the fire escapes the control of the permittee, local fire departments are called in conjunction with SDWFS to staff personnel and equipment to suppress the wildfire. There is an inherent risk in any suppression action in a wildland work setting by exposing the local cooperating fire department and SDWFS personnel to life-safety problems during suppression activities that did not have to happen if the wildfire was not ignited in the first place.

During the winter burning season in the BHFFD when permitted open fires are allowed, daily fire weather forecast products are not available from the local forecast office of the National Weather Service, leaving SDWFS fire officers with a lack of options in dealing with impacts of sudden fire weather changes of relative humidity, dry bulb temperatures, eye-level wind speeds, and wind gust and direction information needed by fire managers in the field to manage the problem of reducing wildfire ignitions from open burning in the BHFFPD.

Another linkage of this applied research project to the field operations of SDWFS is that of incorporating the recent technological advances of Remote Automated Weather Stations (RAWS) in providing real-time fire weather observations across the BHFFPD and using that data to answer the research questions of identification and assessment of those factors that may cause open burning activities to escape control and cause wildfires.

Furthermore, this research project will provide a significant base of scientifically gathered data for support of any prevention and mitigation issue that may arise in the future should the need to restrict open burning in the BHFFPD be necessary due to increased population or climate change. Currently, SDWFS has statutory authority to issue regulations to control open burning in the BHFFPD (South Dakota Codified Law § 34-35-19), but lacks the scientific data to support the rule-making process. Therefore, the data that was gathered and the analysis produced in research project will have a future impact on the organization in supporting its efforts in promulgating rules under the existing statute.

The research purpose of identifying and analyzing the factors that influence wildland fire ignitions from open burning fits well with the second year Strategies for Community Risk Reduction course objectives of application of data analysis and affecting strategic change through models and management. The process of identifying the factors that lead to escaped fires from open burning will lead to a more targeted and effective mitigation effort with the general public that obtains burning permits. In addition, it will provide more managerial expertise to SDWFS firefighters and commanders in possessing more situational awareness of the environmental and weather factors that cause wildfire ignitions to occur from open burning. This increased awareness will happen because local firefighters will be able to better understand the dynamics of how local factors influence wildfire behavior. As Stephens (2005) observed in his national study of forest fire causes on United States Forest Service lands that there was a high geographical diversity of wildfire occurrence across the nation and that local solutions were needed to solve local wildfire management problems.

This applied research project met two of the United States Fire Administration Operational Objectives: "*To promote within communities a comprehensive, multi-hazard risk reduction plan led by the fire service organization*" and "*To respond appropriately in a timely manner to emerging issues.*" These objectives were met by producing quality data collection and analysis from RAWS stations weather data and application of the findings into informational items that will change firefighter and civilian behavior to a more proactive stance of reducing the frequency of wildfire ignitions from open burning.

Literature Review

The literature review of wildfire behavior is international in scope and is primarily focused in the area of forestry and natural resource management, with contributions from the disciplines of meteorology, physics, and chemistry.

Identification of Causal Factors: Fuel, Weather and Topography

The identification of causal factors that cause wildfires to ignite and spread has been researched throughout the world wherever wildfire is part of the ecosystem and occurs on a recurring basis. The identification of these factors has occurred over the course of the development of fire behavior models and fire danger rating systems.

Research on wildfire behavior in coniferous forest regimes can be found in Canada, USA, and Russia. Wildfire behavior research focused on Mediterranean-type ecosystems is primarily undertaken in Spain, Portugal, Greece, Australia, and the USA. As Pyne (1982) pointed out on the cultural history of fire in America, the United States Forest Service led the way in wildland fire management and research for most of the 20th century after the catastrophic fires of 1910 in the northern Rockies. Research in that coniferous fuel type during the 1920's and 1930's by Gisborne (1948) was incorporated into the basic fire training of United States Forest Service (USFS) firefighters, and the basic tenets of his work dealing with fuel moistures are still taught through the NWCG curriculum to thousands of rookie wildland firefighters every year in the USA. (National Wildfire Coordinating Group, 2003).

Research by a USFS physicist (Byram, 1957) into the ignition and combustion of forest fuels and how the heat transfer of methods of radiation, convection, and conduction allowed wildfire to burn through forest fuels with the three phases of combustion is very important to understand how wildfires start and spread. This research also introduced to the wildland fire service the concept of the “fire triangle” of fuel, heat, and oxygen.

By the middle part of the 20th century, wildland fire science laboratories were established in Canada, Australia, and the USA (Weise & Biging, 1997) and research was underway by physicists, chemists and engineers on how forest fuels ignite and sustain combustion under the physical conditions of weather and topography. Research by Rothermel (1972), Albini (1976), and Anderson (1982) led to the development of predictive models of fire spread through wildland fuels that could be implemented in the field by natural resource managers and firefighters. This research developed coarse models of fire spread from point ignitions into fuels based on mid-flame wind speed, slope characteristics of the topography, ambient air temperature, relative humidity (RH), and the type of fuel bed that was burned. This allowed fire managers to quantify in a real sense, what they already observed in the field, that wildfire will ignite and carry combustion across the landscape with higher rates of spread and intensity during conditions of higher winds, hotter air temperatures, lower RH’s, steeper slopes, and increased fuel availability. With this scientific validation, the metrics of wildland fire ignition and spread were identified and measured for field use. These identified factors which are better described as variables when used as inputs in the Rothermel surface fire spread model, have been used extensively by wildland fire managers for the last 25 years.

Scott and Burgan (2005) developed a dynamic fuel modeling process that provided a more accurate input into the Rothermel surface fire spread model and refined the fuel model selection process into more choices to use for field managers to use with laptop computers. As advances in technology offered more powerful computing systems, software, and field measuring devices, further refinement of these causal factors of fuel, weather, and topography as inputs provided more accurate modeling of wildfire ignition and spread (Andrews, 2008).

A predictive model that predicts the probability of ignition of wildland fuels from a heat source such as open burning is the National Fire Danger Rating System (NFDRS). The current model utilizes a complex set of algorithms and calculations based on daily weather observations and user inputs collected nationwide through the network of RAWS across the USA. The current model today was started in 1968 by the USFS and received major updates in 1978 and 1988 (Burgan, 1988). The current version calculates outputs called indices or components: Burning Index, Ignition Component, Energy Release Component, and Spread Component. These outputs are processed on a daily basis based on the 1300 hrs local time weather observations from the RAWS (Cohen & Deeming, 1985). In turn, these outputs can be applied to the fire history of the local unit to produce fire danger ratings (e.g. Low, Moderate, High, Very High, Extreme), staffing levels, and guide fire prevention efforts. Given the NFDRS model only produces these outputs once a day, and fire weather is a dynamic event that changes constantly in some locations, the applicability of the model to accurately predict fire danger in lighter fuels has been questioned by researchers investigating fuel moisture relationships in Oklahoma (Carlson, Bradshaw, Nelson, Bensch, & Jabrzemski, 2007). In the Oklahoma study, investigators built upon the earlier work of Nelson (2000) in testing the accuracy of his model for predicting the fuel moisture of various sizes of fuel sticks as compared to the NFDRS algorithm and in most cases, the Nelson model performed better than the NFDRS model, with more frequent observations.

Another national fire danger model that utilizes inputs of daily weather observations is the Canadian Forest Fire Danger Rating System (CFFDRS). This system is designed for predicting fire danger in a coniferous forest regime in northern latitudes and is based on a standard pine type fuel model (Lawson & Armitage, 2008). The outputs that the CFFDRS produces are a function of its four daily weather inputs when contrasted to NFDRS also needs user set parameters in addition to its daily weather inputs. (NWCG Fire Danger Working Team, 2002). The daily weather inputs into the CFFDRS-Fire Weather Index System are: rain during the past 24 hours, dry-bulb temperature, RH, and wind speed. The components produced are: Fine Fuel Moisture Code, Duff Moisture Code, Drought Code, Initial Spread Index, Build-up Index, and the Fire Weather Index. These components are then used in the other parts of the CFFDRS, which are the Fire Occurrence Prediction System and the Fire Behavior Prediction System (Lawson & Armitage, 2008). The major differences between the CFFDRS and the NFDRS is the that the CFFDRS requires only four weather inputs and is modeled to focus on the ignitability of the light dead fuels on the forest floor, whereas the NFDRS requires more inputs and daily user monitoring, and takes into account larger dead fuels such as logs and the live fuel moisture of growing vegetation. As of September 2008, the Great Lakes Forest Fire Compact states of Minnesota, Michigan, and Wisconsin have developed in cooperation with the Department of Meteorology at the University of Utah's Mesowest program the added functionality of CFFDRS component and indices reporting along with the NFDRS outputs for those state's RAWS system (University of Utah MesoWest, 2008).

The Relationship of the Causal Factors

The body of research dealing with the interrelationships of the causal factors of wildfire is a complex body of research that covers internationally many areas therefore only those recent research developments that involve fuel, weather, and topographic factors specific to the study area of the BHFFPD was reviewed.

Forest fuels in the BHFFD tend to be dominated by a long-leaf pine species commonly called ponderosa pine, *pinus ponderosa,* which typical of most members of the pine genus, is a fire-adapted plant species that is dependent on recurrent fire activity to maintain ecosystem health. In the absence of fire due to efficient suppression of small wildfires, duff layers will build up under a continuous cover of unburned pine needle cast litter (National Interagency Fire Center, 2008). It is estimated as of 2004, that the average duff and litter layer in the study area had an estimated M = 3.53 cm and SD = 2.54 cm for average litter depth, and an estimated M = 2.23 cm and SD = 1.75 for average duff depth (Reich, Lundquist, & Bravo, 2004). Most of the study area is considered to be a dry, low elevation ponderosa pine forest that was subject historically to frequent low severity wildfire activity based on the spatial and temporal distribution of fine fuels. (Schoennagel, Veblen, & Romme, 2004). Schoennagel et al. also indicate that fire suppression in this fuel type leads to a buildup of forest fuels available for ignition and combustion that may result in higher intensity fires and that fuel treatments such as thinning and prescribed fire may mitigate the fire risk. Another study of ponderosa pine forests by the Rocky Mountain Research Station (Graham, McCaffery, & Jain, 2004) reviewed over 80 years of fire behavior studies specific to dry coniferous forests and noted that incipient fires may smolder and burn in ground and surface fuels such as duff and litter in these forest types, even under wet fuel conditions, and burn with more intensity once dryer weather conditions affect fuels.

As indentified by the fire behavior and fire danger models, the weather variables of wind, temperature, and relative humidity play important roles as factors of ignition for wildfires. The effect of Chinook winds on wildfire ignition has been studied in the coniferous forests of Alberta, Canada. A study of fire occurrence originating in piled slash from thinning and land clearing operations showed that 74% of wildfire ignitions from open burning during 1995-2000 under conditions of winds > 17.4 km/hr occurred in a region of Alberta that was known for its occurrence of Chinook winds; and 43% of those ignitions occurred in the winter time (Baxter, 2002). Under a controlled laboratory experiment, ponderosa pine wafers (≤ 1.5 gm) that exhibited open flaming properties, would ignite a fuel bed of ponderosa pine needles, (≤ 11% fuel moisture, 21°C dry bulb) under conditions of air flow up to 1 m/s. (Manzello, Cleary, Shields, & Yang, 2006). USFS researchers noted in the early stage of fire behavior research that peak wind speeds (gusts) caused by mechanical and thermal factors in the topography and atmosphere can cause fire spread and intensity to increase at a double or triple rate from those rates that are observed under constant wind flow. These gusts need only to persist for a minimum of one minute for the increase in intensity and spread rate to happen (Crosby & Chandler, 1966).

Relative humidity (RH) relationships and ambient air temperature with regard to forest fuels are a very important concept to understanding fuel moisture and how it affects fire behavior in a ponderosa pine forest. Lighter fuels such as pine needles (litter), duff, cured grass, and dead fuel as small diameter twigs and branch laying on the forest floor in a low elevation ponderosa pine forest such as what is found in the BHFFPD are very sensitive to changes to air temperature and changes in RH (National Wildfire Coordinating Group, 2003), (Schoennagel, et al., 2004), (Graham, et al., 2004). This empirical relationship is best summed in the calculation of the Fine Dead Fuel Moisture (FDFM) input variable of Rothermel's surface fire spread model which takes into relative humidity and the ambient air temperature as part of the calculations for FDFM (Rothermel, 1972, 1983). However, Rothermel's model is a spread model based on the assumption of a steady-state fire that has already originated and does not deal with the probability of ignition. Research into the probability of ignition from a source of open burning into a bed of long-leafed pine needles was first done by Blackmarr (1972). The experiment involved dropping a lighted miniature wooden match, a standard sized match, and three standard sized matches bound together into a bed of slash pine litter that was controlled for various fuel moisture levels and held at a constant 26.7 ° C. The results showed that no fire could be originated with fuel moistures > 50%, and the smaller the heat source (i.e. mini-match) the dryer the needle bed had to be to support ignition. The three bound standard sized matches could ignite wetter needles, all the way to 50% fuel moisture levels, before reaching extinction. Another relative humidity and temperature relationship for fire behavior in a coniferous forest is noted by researchers in Canada. In the "*Weather Guide for the Canadian Forest Fire Danger Rating System*" (2008), Lawson and Armitage note the concept of "cross-over" (p.39) that is held in high regard by Canadian fire managers in planning for fire suppression. "Cross-over" conditions occur when the relative humidity trend line crosses under the air temperature trend line as graphed on an x-y axis. (Appendix A). It is during that condition that field managers feel that fire conditions will produce higher rates of spread and intensity, although the authors provide an example for a large fire in Canada where that was not the case. This same concept is taught in the entry level *"S-190: Introduction to Wildland Fire Behavior"* as entry- level training in the USA wildland fire community but is not given a conceptual term.

For the summary of the literature review, there is a vast body of research on an international scope that deals with the two research questions of the identification of the factors and the relationship of those factors on how wildfires are ignited from open burning activities. Specifically to the Black Hills of South Dakota, there are no specific studies of these factors as they related to the ignitability and spread of fire through the landscape, but work on fire behavior modeling and fire danger rating systems in Canada and the USA in coniferous forest fuel types such as the local fire department's area point to the possible identification of potentially important variables. The literature of the interrelationships of these possible identified variables has been studied specific to coniferous ecosystems was reviewed and some of the interrelationships of weather and fuels were seen to be very important factors in other coniferous ecosystems that exhibit the same characteristics as the study area.

Procedures

The procedural methodology involved the following: (a) delineation of the study area; (b) framing the null (H_0) and alternative hypotheses (H_1) under which to identify the factors or variables of ignition from open burning and their relationships; (c) constructing and validating a database to produce the datasets used for analysis; and (d) conducting the statistical analysis for both research questions.

The general location of the study area is shown on page 40 (figure 1). The study area comprises all of the state and private land within the initial attack area of the Black Hills Forest Fire Protection District which is the jurisdictional area for SDWFS.

The next step of the procedure was to construct the null (H_0) and alternative hypotheses (H_1) under which the first research question of the identification of factors for wildfire ignition was tested by a causal-comparative design (Gay & Airasian, 2003). The H_0 for all testing was that there is no statistically significant difference between the means (M) of any tested factor between two groups: *Fire Occurrence Days* and *Non-Fire Occurrence Days*.

The H_1 was that there exists statistically significant relationship between the means (M) of any tested factor between the two groups of Fire Occurrence Days and Non-Fire Occurrence

Days. The H_0 was the expected outcome for the first research question in this causal-comparative study and the H_0 was only to be rejected in favor of the H_1 when it can be statistically proven that the observed sample mean from a Fire Occurrence group factor was expected to be observed at least 95% of the time, or conversely, the H_1 was accepted when the probability level is less than 5 percent ($\alpha < 5\%$) that the sample mean from a Fire Occurrence group could come from the same distribution of the sample means of the same Non Fire Occurrence group factor . For instance, if the sample mean (X) of the 1300 hourly observed air temperature of the Fire Occurrence group has a > 5% probability of coming from the same population sample of the Non Fire Occurrence group, the H_0 is not rejected.

The second research question of the relationship of any identified factors to the cause of an wildfire ignition from open burning was tested by the use of a binary classification and regression tree analysis program (Breiman, Friedman, Olshen, & Stone, 1984), (De'ath & Fabricius, 2000), (Brosofske, Cleland, & Saunders, 2007). This question tested the ability of the model of indentified factors to accurately predict the positive value of the categorical variable.

Database

The database used for this analysis was gathered from the fire department's initial attack fire records maintained by the Northern Great Plains Interagency Dispatch Center in Rapid City, SD. The set contained fire occurrence data from November 1, 2004 to April 30, 2008, which was inclusive of the four winter burning seasons when burning permits were issued for open burning. The dataset was limited just to those four winter burning seasons from November 1 to April 30 of the next year which totaled N = 725 days, or ≈ 181 days per winter burning season. In that dataset of 725 possible daily fire occurrence days, there were observed 54 records of Fire

Occurrence Days were wildfires were ignited from open burning activities in the BHFFPD, (n = 54 Fire Occurrence Days out of the 725 total days observed). From those 54 Fire Occurrence Days, there existed a subpopulation of escaped wildfires (n = 23) where the final size of the burned area exceeded .04 ha, ≈ 20 m x 20 m square or 400 sq/m. Those escaped wildfires required more than one engine captain and crew to contain fire spread, and were considered multiple alarm fires. The remaining Non-Fire Occurrence days in the dataset were the remainder of the days that wildfire did not occur from open burning ignitions and can be calculated as N= 725 – 54 or N = 671 Non Fire Occurrence days.

For the Non-Fire Occurrence Days, the 671 matching calendar dates were converted to Julian dates and processed through a random generator algorithm (Haahr, 1998) which produced a list of randomly sorted dates. The first 300 Non Fire Occurrence Days were selected from this random list for inclusion in the study dataset, based on minimum sample size of n = 246 with an estimated variance of .36 for a 95 % CI for a one-tailed test of the H_0 at ($\alpha < 5\%$) when N = 671. The sampling was done because of the labor-intensive effort to build the database.

Both record sets of Non-Fire Occurrence Days and Fire Occurrence Days were merged to create a study dataset with n = 354 records of occurrence, with the unique calendar date assigned. Seven independent variables were collected for each record per national standards (National Wildfire Coordinating Group, 2008). The lists of all variables are as follows:

1.FireDay is a categorical variable assigned to a record based on if a wildfire occurred on that date that was ignited from open burning activities issued under a burning permit. Value is “Y” = yes, “N” = no. FireDay is the response or dependent variable for the second research question.

2.1300T is the average ambient air temperature within the study area of the 1300 hours observations recorded in the national fire weather database for that calendar day.

3. 1300RH is the average relative humidity within the study area of the 1300 hours observations recorded in the national fire weather database for that calendar day.

4. 300WS is the average wind speed over the last hour within the study area of the 1300 hours observations recorded in the national fire weather database for that calendar day. Recorded at a height approximately 6 m from ground level and measured in km/hr for this study.

5. 300WD is the average direction that the wind is blowing from and measured in degrees from true North, on a 0 – 360 scale where 180 degrees is South. Recorded from the 1300 hours observations in the national fire weather database.

6. 1300G is the average peak wind measure within the study area of the 1300 hours observations recorded in the national fire weather database for that calendar day. Recorded at a height approximately 6 m from ground level and recorded in km/hr.

7. 1300FT is the average representative fuel temperature reported within 28 cm of the ground surface within the study area. Compiled from the 1300 hours observations recorded in the national fire weather database for that calendar day.

8. 1300FM is the average representative fuel moisture reported from the 10 hr fuel sticks sensors within the study area. Compiled from the 1300 hours observations recorded in the national fire weather database for that calendar day.

The RAWS weather observations for the following independent variables: 1300T, 1300RH, 1300WS, 1300WD, 1300G, 1300FT, and 1300FM were averaged from the actual 1300 hr observations for the Red Canyon, Baker Park, and Nemo RAWS stations that report into the

NFDRS on a daily basis. Given the spatial location of the fire occurrences over an approximate 120 km north to south transect in the study area, and the varying weather conditions that exist in the study area, the average readings were calculated as a control for the causal-comparative study (R. P. Benson, personal communication, January 16, 2009). These RAWS stations are located in the southern, central, and northern part of the study area, respectively. The RAWS data for the 1300 weather observations were obtained from the University of Utah Mesowest interface Real-time Observation Monitor and Analysis Network (ROMAN) on a website hosted by the National Weather Service (2009).

In summary, the database was constructed so it could be analyzed in two different ways to answer both research questions. For the identification of the factors in the causal-comparative design, the database was divided into two groups, Non-Fire Occurrence (n = 300) and Fire Occurrence (n = 54). For the second question of the relationships, the two groups were merged into one dataset, (n = 354) and the categorical variable FireDay was created to control for Non-Fire Occurrence or Fire Occurrence.

Statistical Procedure

The first research question of identifying the factors of ignition from open burning was completed by comparing the means of each factor or independent variable as grouped by the occurrence of the dependent variable, FireDay. The sample distributions were tested for normality, and the proper statistical test (parametric or non-parametric) was chosen to test for the statistical significance of accepting or rejecting the H_0. Any rejection of the H_0 and acceptance of the H_1 makes the assumption that an identified factor should be tested under the second research question.

The second research question of how the identified factors and their relationships can influence the occurrence of ignition of wildfires from open burning was tested by Classification and Regression Tree analysis utilizing a proprietary software package, CART® ver. 5.0, to test and validate a predictive model based on the identified factors.

The classification tree analysis is a non-parametric test that can work with non-normal distributions and avoid any issue of multicollinearity between the independent variables by forward stepping through the classification process. A major limitation of this procedure as designed is that it only tests for weather related variables and does not test for any human factors that may cause fire occurrence days, such as human error by the burn permit holder or lack of timely fire suppression response by the fire department.

The computational analysis for the statistical testing was performed by free statistical calculator websites provided by P. Wessa of the Office for Research Development and Education in Belgium (2009), R. Lowry, Department of Psychology, Vassar College, NY (2009) and T. Kirkman, Department of Physics, College of Saint Benedict and Saint John's University, MN. (1996).

Results

The Kolmogorov-Smirnov Comparison of Two Data Sets showed that low probabilities of < 5 % for the existence of a normal distribution in either the Non-Fire Occurrence or Fire Occurrence groups for any factor except for 1300T in the Fire Occurrence group and 1300FT in both groups. Appendix A contains the summary results from this test for normality.

Therefore, the Mann-Whitney test was used in place of the *t*-test for testing between groups of factors. Table 1 contains the results of the Mann-Whitney test between the factors of

Air Temperature (1300T), Relative Humidity (1300RH), Wind Speed (1300WS), Wind Direction (1300WD), Wind Gust (1300G), Fuel Temperature (1300FT), and Fuel Moisture (1300FM); as grouped between Non-Fire Occurrence and Fire Occurrence.

Table 1

Mann-Whitney Test of Factors Grouped by Occurrence

Factor	Mean Ranks of Factors (Fire, Non-Fire)	z	$p_{(1)}$	$U_{\text{Non-Fire}}$
1300T	225.5, 168.9	-3.74	0.0001*	10,691.5
1300RH	145.5, 183.3	2.49	0.0064*	6,374
1300WS	217.5, 170.3	-3.12	0.0009*	10,621
1300WD	175, 177.9	0.19	0.4247	7,966
1300G	209.8, 171.7	-2.52	0.0059*	9,844
1300FT	224.3, 169.1	-3.65	0.0001*	10,625
1300FM	162.7, 176.6	0.93	0.1762	7,191

Note. * Significant at $p < .05$, where $p_{(1)}$ indicates the directional or one-tailed test.

The Mann-Whitney test cannot directly compare the sample means of the factors for significance differences as does the *t*-test. But the Mann-Whitney procedure can still test the null hypotheses of no significant difference between factors by the use of an ordinal scale of measurement (e. g. greater than, less than, or equal to) on a directional test of the H_0 by the observed standardized *z* value. In this case, a negative *z* value infers that the factor in the non-fire occurrence group contains a significant sample of smaller values as converted to rankings of the raw measures as compared to the fire occurrence group for that particular factor. The computed $U_{Non\text{-}Fire}$ statistic shows a higher number correlated with smaller ranking values given that the statistic is calculated as the difference between the total maximum sum of all rankings and the sum of the actual observed rankings. A positive value of the *z* score and a lower computed $U_{Non\text{-}Fire}$ statistic infers the opposite situation, a sample of smaller cumulative rankings for the fire occurrence group.

The probabilities associated with the *z* values show the chance that if the H_0 was true, the probability of that calculating that particular *z* value within that sampling distribution would be equal to or less than the $p_{(1)}$ value displayed in the chart.

For this analysis the results showed that the factors of wind direction and fuel moisture as observed at 1300 hours on the fire occurrence day were not significantly different than those same factors observed at the same time on a non-fire occurrence day. However the H_1 was accepted that there were significant differences between the remaining factors because air temperature, wind speed, wind gusts, and fuel temperature observations were sampled and found to occur at higher rankings on fire occurrence days. The factor of relative humidity was observed to be statistically significant at a lower ranking on fire occurrence day.

The results for the second research question of the relationships between the identified factors were calculated from the classification tree analysis. The significant factors of Air Temperature (1300T), Relative Humidity (1300RH), Wind Speed (1300WS), Wind Gust (1300G), and Fuel Temperature (1300FT) were used as predictor variables to predict the occurrence of the binominal dependent variable of fire occurrence (FireDay) in the classification tree analysis.

The results of the classification tree analysis are displayed as decision trees in Appendix B. The best set of predictors for a fire occurrence day for Model A (N = 354 days, n = 54 fire occurrence days) were fuel temperatures and wind gusts. The best set of predictors for Model B described as the subset of fire occurrence days (N = 354 days, n = 23 fire occurrence days) that resulted in escaped wildfire with ha burned > .04 were air temperature and wind speed. A summary of both models are displayed in Table 2.

Table 2

Summary Statistics for the Classification Tree Analysis

Model	Primary Splitter	Secondary Splitter	Misclassified Fire Occurrence Days	Relative Cost
A	1300 FT ≥ 8° C	1300G ≥ 16.36 km/hr	7	0.788
B	1300T ≥ 5.4° C	1300WS ≥ 7.24 km/hr	0	0.403

When calculating the decision trees for both models, trees were produced that contained anywhere from 15 to 40 classification nodes on a single tree based on many more split levels. However, pruning these over-fit models resulted in the optimal trees as displayed in Table 2 and produced models with lowest relative cost, or overall prediction error. It must be pointed out that model A misclassified 154 non-fire occurrence days as fire-occurrence days, and model B misclassified 110 non-fire occurrence days as fire-occurrence days. These optimal models only had a primary splitter and one secondary splitter and in both models the independent variable

1300RH had relatively low importance as a factor in developing the decision tree. Both optimal models determined that a temperature signal served as the best primary splitter (1300FT and 1300T) and a wind speed signal in either 1300G or 1300WS observations served as the best secondary splitter for both models.

Discussion

The major purpose of this study was to identify the factors and their relationships with regards to the frequency of ignitions of wildfire from open burning activities in the BHFFPD. The first research question of the identification of those factors by the use of casual-comparative design method led to results comparable to other research findings of wildfire occurrence in coniferous forest types with the exception of fuel moisture. The results of this applied research project showing the significance of the factors of wind speed, wind gusts, relative humidity, fuel temperature and air temperature with regards to the ignition and spread of wildfire has been documented by researchers for many years.

The NFDRS incorporates wind speed as a factor in calculating the Spread Component and indirectly into the calculation of the Burning Index (NWCG Fire Danger Working Team, 2002). The CFFDRS incorporates wind speed into the calculation of its Initial Spread Index and Fine Fuel Moisture Code (Lawson & Armitage, 2008). The significance of the factor of wind speed is also incorporated in the modeling of fire behavior in forest fuels (Rothermel, 1972, 1983) and (Albini, 1976). Wiese and Biging (1997) also point to other fire behavior models that incorporate wind speed as an input factor.

However the factor of wind gusts are not as well documented in the literature except for the work of Crosby and Chandler in their report to firefighters in the field on how to document wind speeds (1966). However, implicit in the Rothermel surface fire spread model is the concept that the effect of wind as factor for fire spread is small at lower wind speeds in fine fuels, but increases at a rapid rate as wind speeds increase in intensity (Albini, 1976). Furthermore, work over the last 25 years to develop the software for operational deployment for field use of the Rothermel model has not seen a major adjustment to the use of wind speed as input variable (Andrews, 2008). The results of this applied research project with regards to the factors of wind speed and wind gusts show the significance of these variables on fire occurrence days during the winter burning season, as would be expected.

The factors of air temperature, fuel temperature, and relative humidity in this study show significance as both temperature factors were sampled at higher values on fire occurrence days than on non-fire occurrence days and the opposite finding was noted for relative humidity. Comparing these findings with the research in the field supports the results of applied research project. Air temperature is used as a key factor along with relative humidity to determine the Equilibrium Moisture Content which is the basis of all fuel moisture equations in the NFDRS model (Cohen & Deeming, 1985). Air temperature and relative humidity are also used as a direct inputs for determining the fine dead fuel moisture in the Rothermel surface spread model (Rothermel, 1983) and as a direct inputs to determine the Fine Fuel Moisture Code and the Duff Moisture Code in the CFFDRS (Lawson & Armitage, 2008). To further show the strength of both air and fuel temperature as a factor, Byram's work (1957) laid the foundation on how both air temperature and fuel temperature enhance combustion in forest fuels by applying mechanical engineering studies on combustion processes to forest fires. As fuels get warmer by both hotter air temperature and or flame impingement, fuel moisture is driven off from the fuel, increasing its availability for burning. The Rothermel model and the NFDRS also account for fuel temperature by utilizing model inputs that vary the amount of solar radiation on the fuels (NWCG Fire Danger Working Team, 2002), (Rothermel, 1983). As expected by a review of the research, air temperature, fuel temperature, and relative humidity are significant factors on fire occurrence days in the BHFFPD when open burning activities cause wildfire ignitions, when temperature factors have higher values at the 1300 observation while relative humidity values are lower.

However, the non-significance of the fuel moisture factor on fire occurrence days in the winter burning season within the BHFFPD was notable, in that as dead fuel moistures show dryer or lower values in the NFDRS model, the overall fire danger will exhibit an upward trend (NWCG Fire Danger Working Team, 2002). Although the CFFDRS model does not directly sample dead fuel moisture value for its components, implicit in the Canadian model is the fact that as the inputs of rain and relative humidity decrease in value, overall fire danger indices and ratings will show an upward trend as fuels dry out (Lawson & Armitage, 2008). The basic premise of the Rothermel surface fire spread model as combined with fuel model inputs by Anderson (1982) and Scott and Burgan (2005) is based on the fact that lower fuel moisture values contribute to a higher rate of spread and increased fire intensity. A possible explanation as to why the observed 1300 fuel moisture value is not a significant factor in this study is that the mathematical equation that determines the value of the observation may need improvement as to its predictive ability. The Oklahoma study of fuel moisture relationships by Carlson et al. (2007) showed that the application of Nelson's algorithms of fuel moisture had better predictive capability than the current algorithm used by the NFDRS and that the Nelson model for determining dead fuel moisture is slated for use in the next generation of the NFDRS. Nelson's work in the late 1990's recognized a fact that the current fuel moisture observation from RAWS did not model very well model the actual 10 hour fuel moistures as reported in the late afternoon, the critical part of the burning day (Nelson, 2000). It appears that the results of this study support Nelson's results, in that during the winter season, there is even a shorter afternoon time period, and the 10 hour fuel moisture observation from the RAWS does not accurately reflect the lower fuel moistures that must be present on the fire occurrence day for fire spread to occur.

The final factor of wind direction was not seen significant in this study, nor has it been studied as a possible factor in other research. It was included in this study design to test to see if the H_1 would point to a certain wind direction signal in the BHFFPD as to when wildfire occurrence could be expected in the winter time, as the Chinook winds during the winter come out of the westerly direction in the BHFFPD.

The results of the applied research project as to the second research question of the relationships of the factors were not at odds with any general research findings of wildland fire behavior given that the classification tree analysis of the significant factors showed that temperature values of fuel and air were more important than values of wind speed and gusts. However, the fact that relative humidity was subordinate to the temperature and wind factors in the classification tree analysis and was not a major splitter in either model needs to be examined as relative humidity was shown to be a significant factor with lower values on fire occurrence days. This is because relative humidity plays an important role in both determining rate of spread in the Rothermel model and in the calculation of the fire danger ratings in both the NFDRS and the CFFDRS.

There is an abundant source of available light fuels in the BHFFPD as typical of a low-elevation ponderosa pine forest and this fuel is increasing in availability and loading every season that it is not burned (Graham, et al., 2004), (Reich, et al., 2004). Given that relative humidity plays such an important role in determining the fuel moisture content of light fuels (Cohen & Deeming, 1985), a possible explanation for why temperature and wind factors are better classifiers than humidity for the prediction of a fire occurrence day is because of the inverse relationship of air temperature and relative humidity. As air temperature increases, relative humidity decreases as noted in the "*crossover*" by Canadian firefighters (Lawson & Armitage, 2008), and the classification tree analysis considers fuel temperature to be a good surrogate variable for relative humidity on the fire occurrence day by recognizing this relationship in the process of building the classification tree. This same relationship could also explain why air temperature is the primary splitter for fire occurrence days where fires escape initial attack control in that fuels are warmer and dryer and more available for combustion.

The factors of wind measurements as expressed in wind speed and wind gusts as secondary splitters in both models was not unexpected given the importance that the both the NFDRS and CFFDRS models place on wind speed variables for computation of fire danger and the significance that wind speed plays in the Rothermel model of fire spread. But the result that wind gusts were not the secondary splitter on fire occurrence days where fires escape initial attack control was not expected, given that firefighters are trained in entry level courses that on unstable atmospheric days where wind gusts predominate, extreme and dangerous fire behavior may be occurring. (National Wildfire Coordinating Group, 2003).

Comparing the secondary wind gust splitter value of $\geq$ 16.36 km/hr for Model A (N = 354, n = 54) to the Alberta study (Baxter, 2002) of wildfires started from open burning of slash piles where the average wind speed was 17.4 km/hr at the time of initial attack indicates a possible threshold where the factor of wind speed or wind gusts are an important factor for ignition of wildfires from open burning.

Where model B (N = 300, n =23) for fires that escaped initial attack and burned > .04 ha, the secondary splitter was not wind gusts as expected, but instead wind speeds ≥ 7.2 km/hr. Two explanations are offered here for this finding. First, that given that model B was a subset of model A, the classification tree analysis had already accounted for the variability of the wind gust factor in the larger dataset and used the wind speed factor as the next best splitter under air temperature for model B. A second explanation is that recent research by Manzello et al. (2006) has shown that just one flaming firebrand of ponderosa pine material can ignite a fuel bed of ponderosa pine litter (fuel moisture ≈ 11%) under steady wind speed conditions up to 3.6 km/hr. And as Blackmarr (1972) pointed out in research on the ignition of pine needle beds with flaming matches, as the fuel moisture pine needles decreases, less flame intensity is required for ignition. Therefore if the ignition of a steady-state fire is conducive under those conditions of constant wind speeds, then it would follow that a surface fire would continue to spread under Rothermel's model, and increase in intensity as increasing values of wind or slope factors are present in the area of the spreading fire. (Rothermel, 1972).

In summary of the discussion, it appears that within the BHFFPD during the winter burning season, the measurement values of temperature in the form of fuel and air temperatures, combined with wind speed and wind gust measurements, can provide a workable model for the coarse scale prediction of ignition of wildfires from open burning. This will hold true even in the absence of accurate fuel moisture observations, and may prove to be more reliable indicator until at that time better fuel moisture measurements in the form of Nelson's model can be utilized in the NFDRS. Hopefully, some time in the future, accurate fuel moisture measurements will be able to be used in this classification tree analysis to provide for a more robust model of prediction of a fire occurrence day.

Organizational Impact

The results of this study will provide important information for immediate application in the operational, administrative, and fire prevention sections of the South Dakota Division of Wildland Fire Suppression. Agency personnel will be able to: (a) target prevention efforts; (b) understand when to ramp up fire detection and prevention patrols at the most effective times; (c) better detect the signals of the significant factors when observing real-time weather data; (d) create a field expedient fire danger rating system when certain NFDRS indices and components are not produced in the winter burning season; (e) communicate more effective means of simple fire prevention concepts dealing with weather factors to burn permit holders; and (f) use the data from the results to create a database for a science-based approach to the rule-making process under South Dakota State Law.

Recommendations

This study identified the factors that influenced wildfire ignitions from open burning and described the relationships between those factors in order to gain understanding on how to reduce the rate of wildfire ignitions. It is recommended that the South Dakota Division of Wildland Fire Suppression start on risk mitigation strategy to reduce the rate of occurrence of wildfire ignitions from open burning for the 2009-2010 winter burning season. A guiding coalition can be created from existing organizations that are already involved in wildfire risk mitigation in the BHFFPD such as the South Dakota Fire Safe Council, Keep South Dakota Green, local Firewise Communities® subdivisions/communities along with local agency and volunteer fire departments. This network of organizations can deliver a vision and communicate a message to homeowners in the wildland urban interface that clearing defensible space around a structure, and using open fire to burn the residue is an accepted practice to be encouraged, but it must be done more safely than what has been done in the past. Using research from this applied research project, a sense of urgency can be imparted to the message. Residents that live in the WUI need to understand that in a low elevation ponderosa pine forest, such as the Black Hills, wildfires are a natural occurrence and part of the ecosystem, and fire is needed to maintain a healthy ecosystem. These residents also need to understand that recent studies from the USFS Rocky Mountain Experiment Station, as reported by Graham et al. (2004) that wildland fuels are building up around their housing areas on an annual basis, and there is good scientific basis for knowing that the buildup of light flammable fuels is very prevalent across the BHFFPD, as Reich et al. (2004) have pointed out.

Simple techniques such as reminding burn permit holders to watch wind speeds and increasing air temperatures when they are burning can be communicated via the internet based burn permit system and through face to face contact when units are on patrol. One barrier that can be removed is to allow firefighter staffing on the weekend, during the winter burn permit season, firefighters can be seen on patrol in housing areas where open burning is taking place, meet face to face with the actual person doing the burning, and remind them to extinguish the fire, and double check when winds start to increase and the air temperature gets warmer. Also encouraging the local volunteer fire department to perform that patrol, would even lend better credibility to the message delivery.

Short term successes can be followed by keeping track of the rate of occurrence of the ignitions during the burning season, and quickly acting to see if the new strategy is working. The gains realized by this strategy can be consolidated by enacting new rules under the existing authority of state law to shorten the window of the burn permit season in the BHFFPD. Data from this study showed that wildfire ignition from open burning by permit holders is more likely to result when fuel temperatures as reported by RAWS stations are > 8° C or 46.5° F. Therefore the winter burning season can be set by rule making authority to capture that timeframe in the winter months when a high probability exists that fuel temperatures will be < 8°C, which would allow for only a December through February burning season, instead of the traditional season of November 1st through April 30th.

In summary, the data and research in this study show a path for comprehensive community risk reduction strategy that can allow for the general public to use fire as a tool to mitigate risk in their housing areas from catastrophic wildfire in the summer season, by creating defensible space around structures, while at the same time, reduce the risk of accidently starting a wildfire in the winter when performing those risk reduction activities of tree clearing and pile burning.

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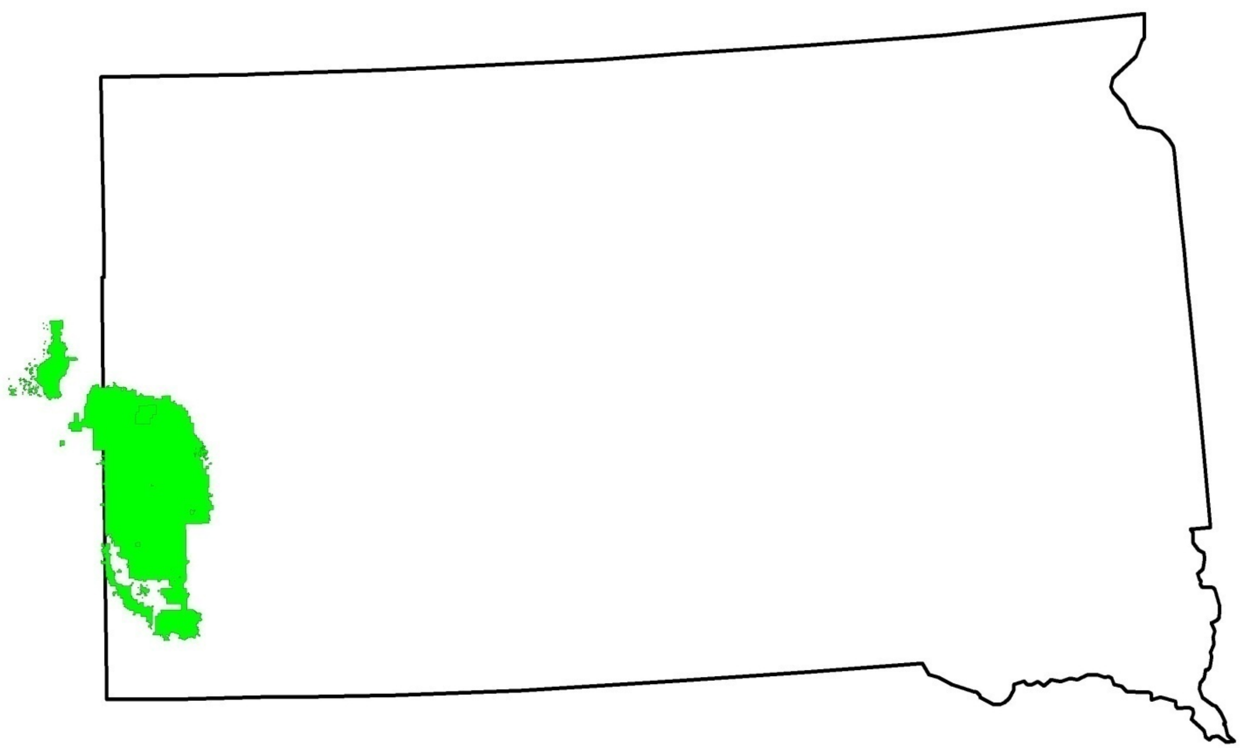
Figure Caption

Figure 1. Outlined border of the State of South Dakota, with the general location of the study area displayed in the left-hand side of the figure. The shaded area is the Black Hills National Forest (BHNF) that is located in both SD and WY. The study area comprises those private and state-owned lands adjacent to and within the BHNF in SD (Marchand, 2008).



Appendix A

Table A1 displays the results of tests of the normal sample distribution for the variables representing the factors of air temperature (1300T), relative humidity (1300RH), wind speed (1300WS), wind direction (1300WD), wind gust (1300G), fuel temperature (1300FT), and fuel moisture (1300FM); as grouped between Non-Fire Occurrence (*n* = 300) and Fire Occurrence (*n* = 54.) The Kolmogorov-Smirnov calculator was provided by the Physics Department at the College of St. Benedict and St. John's University in Minnesota (Kirkman, 1996).

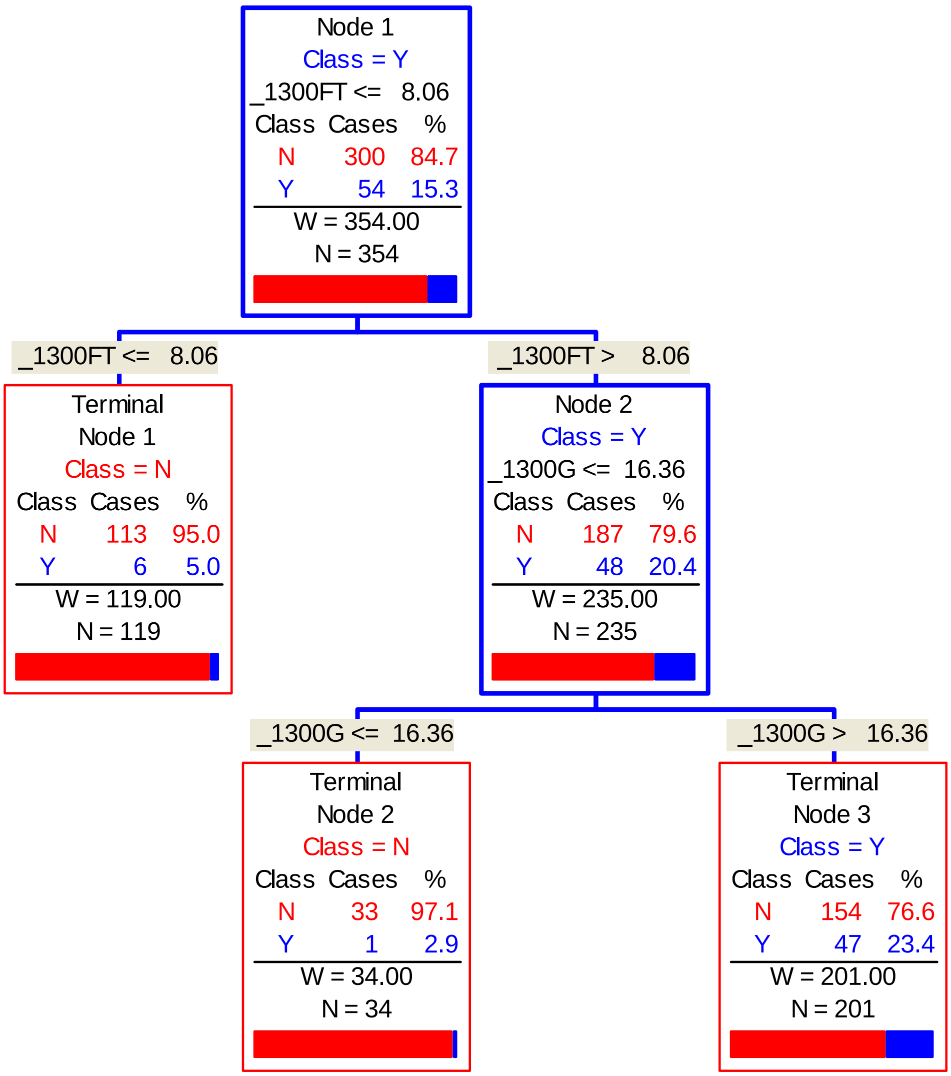
Table A1

Analysis of Sample Distribution

Variable	*X*	*SD*	$X_{\text{normal dist.}}$	$SD_{\text{normal dist.}}$	*p* of norm. dist.
$1300T_{non\text{-}fire}$	6.32	8.05	5.49	8.65	0.04
$1300T_{fire}$	10.63	6.49	10.93	6.82	0.95
$1300RH_{non\text{-}fire}$	38.02	18.2	44.12	17.22	0.00
$1300RH_{fire}$	32.65	18.2	39.52	20.32	0.00
$1300WS_{non\text{-}fire}$	9.21	3.94	10.5	3.75	0.00
$1300WS_{fire}$	11.13	4.00	11.19	4.22	0.00
$1300WD_{non\text{-}fire}$	248.8	73.7	231.8	72.85	0.00
$1300WD_{fire}$	248.5	67.1	247.7	62.37	0.13
$1300G_{non\text{-}fire}$	25.19	10.5	28.53	10.43	0.00
$1300G_{fire}$	29.26	11.4	32.28	12.05	0.00
$1300FT_{non\text{-}fire}$	10.64	8.61	10.38	9.10	0.25
$1300FT_{fire}$	15.04	7.08	15.39	7.65	0.52
$1300FM_{non\text{-}fire}$	10.81	5.31	15.78	8.62	0.00
$1300FM_{fire}$	10.77	6.77	16.47	12.04	0.00

Appendix B

Figure B1. Model A (N=354, $n = 54_{\textit{fire occurrence days}}$).



Appendix B, cont.

Figure B2. Model B (N=354, $n = 23_{fire\ occurrence\ days}$)

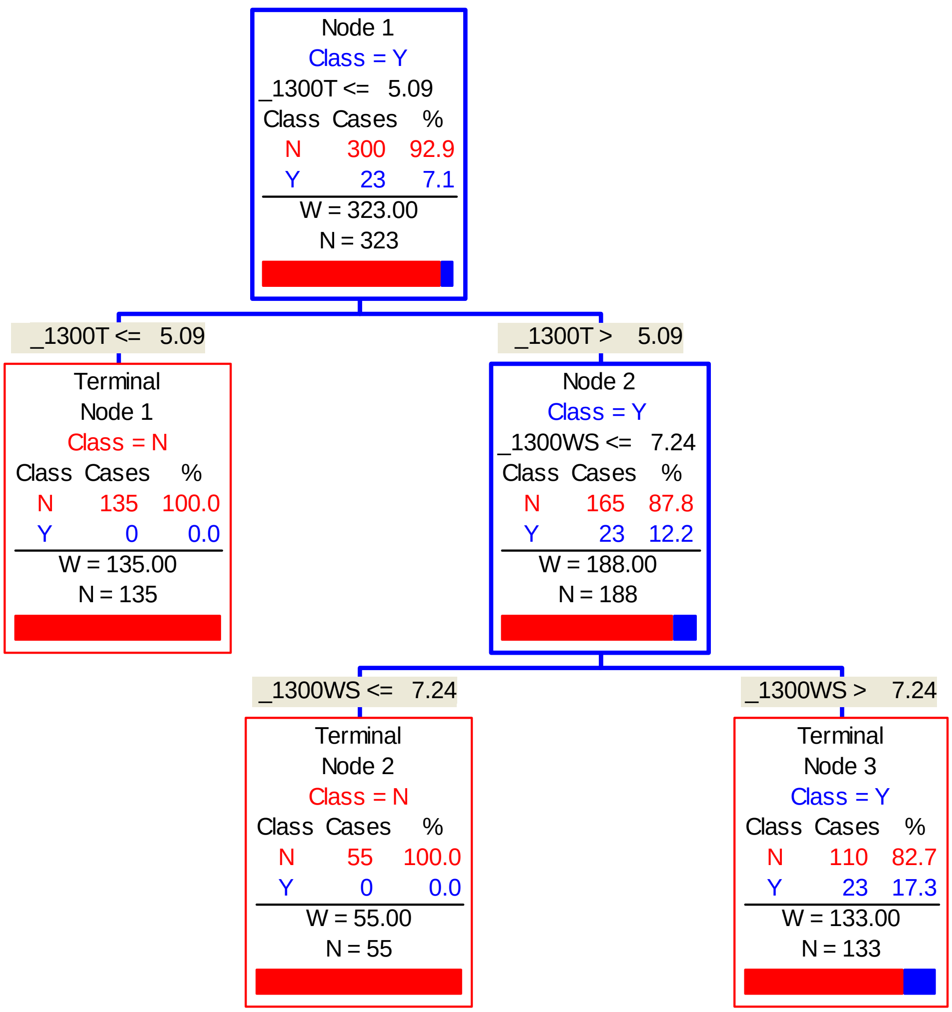


Figure Captions

Figure 1. Outlined border of the State of South Dakota, with the general location of the study area displayed in the left-hand side of the figure. The shaded area is the Black Hills National Forest (BHNF) that is located in both SD and WY. The study area comprises those private and state-owned lands adjacent to and within the BHNF in SD (Marchand, 2008)

Figure B1. Model A (N=354, $n = 54_{fire\ occurrence\ days}$).

Figure B2. Model B (N=354, $n = 23_{fire\ occurrence\ days}$).

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Any errors or omissions in this article are mine alone.

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