UNIVERSITY OF CALGARY

Prototype Development for a Wildfire Modeling and Management System

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOMATICS ENGINEERING

CALGARY, ALBERTA

March, 2005

APPROVAL PAGE

ABSTRACT

The main objective of this research is to investigate the solution to three problems currently existing in wildfire management. The three problems are:

1. Wildfire policy does not adequately outline guidelines that should be followed when conducting prescribed burns
2. Canadian fire modeling programs are sub optimal and should be improved
3. Communications between fire management districts are sub optimal and should be improved with the introduction of an Internet based wildfire management and modeling system.

Solutions to these problems are accomplished through the completion of four sub-objectives. The first sub-objective is to investigate the parameters that influence fire behavior and how wildfires react to various elements in the environment. The three primary influences on fire spread are weather, topography and vegetation type. The second sub-objective of the thesis is to investigate Canadian and American wildfire policies and make recommendations for Alberta's new prescribed burning policy. The outcome of this sub-objective determined that the following items should be implemented when developing a new policy.

1. Descriptions of the methods used to ignite prescribe fires and defined guidelines for choosing the safest ignition method
2. Goals intended by having the prescribed fire
3. Identified ideal and unacceptable weather condition criteria
4. Descriptions of the minimum amount of needed suppression/monitoring forces
5. Weighting systems for risks based on certain weather, topography and fuel type combinations to create a "go"/"no go" criteria for the prescribed burn
6. Pre-created backup plans in case prescribed fires escape

7. Environmental impact assessments
8. Economic advantage of using prescribed burning instead of other forest thinning techniques
9. Procedure to determine what type of fire will be the most beneficial for a certain type of forest

The third sub-objective is to investigate benefits and short comings of six existing fire models. Finding ways to improve existing models helped determine the requirements needed for a new Canadian fire model. Some of these requirements include having spatial modeling capabilities, having flexible resolution abilities that depend on input data and having a methodology based on the algorithms of the Canadian Fire Danger Rating System. Completing this sub-objective offers a solution to the second problem existing in wildfire management.

The fourth sub-objective is to develop a new fire modeling and management system called the WMMS. This includes the development of a new Canadian Wildfire Spread Probability Model (CWSPM) and the development of a web based Wildfire Management and Modeling System (WMMS). The results of the CWSPM are compared to an actual burn perimeter and show good correlation with the true data. At the final stages of this research, a new fire model was developed by Alberta Sustainable Resource Development and it was decided not to include the CWSPM into the web application and instead to use the newly developed Prometheus model. This was done to help the WMMS system gain national acceptance since it uses a model that is to become the Canadian standard modeling system. The WMMS system includes other features such as an innovative hotspot detection system, spotter aircraft tracking tool, distance to nearest lake tool and a historical fire database. It is anticipated that the creation of this web application will inspire fire managers to reassess the way that wildfires are managed and address the need to develop a more robust fire management and modeling system. This last sub-objective will offer a solution to the third problem existing in wildfire management.

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Symbols Used in Fire Behavior Prediction Equations

BE	Buildup effect on Rate of Spread
BUI	Buildup Index
C	Degree of Curing
CBH	Height to live crown base, m
CF	Curing function for grass fuel types
CFB	Crown Fraction Burned
CFC	Crown Fuel Consumption
CFL	Crown Fuel Load, kg/m^2
CSI	Critical surface intensity for crowning
FI	Fire Intensity, kW/m
FFC	Forest Floor Consumption
FFMC	Fine Fuel Moisture Code
FMC	Foliar Moisture Content, %
FME	Foliar Moisture Effect
F(F)	Fine fuel moisture function
F(W)	Wind function
GFL	Grass fuel load, kg/m^2
GS	Percent Ground Slope
H	Fuel low heat of combustion from Byram's Equation, kJ/kg
H	Humidity, %
I	Fire intensity, kW/m
ISF	ISI with slope influence and zero wind
ISI	Initial Spread Index, accounts for slope and wind
M	Moisture content equivalent of the FFMC, %
PC	Percent conifer (for mixedwood fuel types M-1 and M-2)
PDF	Percent dead balsam fir (for mixedwood fuel types M-3 and M-4)
PH	Percent hardwood (for mixedwood fuel types M-1 and M-2)
q	Proportion of maximum rate of spread at a BUI equal to 50
Q	Moisture Equivalent
R	Rate of forward spread, m/sec
RAZ	Net effective wind direction vector
ROS	Final Rate of Spread for both surface or crown fires
RSC	Crown fire spread rate for C-6 fuel type
RSF	Surface Fire Spread Rate
RSI	Initial spread rate without the effects wind
RSO	Critical Rate of Spread
RSS	Surface fire spread rate for C-6 fuel type
RSZ	Surface spread rate with zero wind on level terrain
SAZ	Slope azimuth, upslope
SF	Spread Factor
SFC	Total Surface Fuel Consumption
T	Temperature, °C
TFC	Total Fuel Consumption
w	Weight of fuel consumed in the active fire front, kg/m^2
WAZ	Wind azimuth, degrees

WFC	Woody Fuel Consumption
WS	Observed wind speed, km/h
WSE	Slope equivalent wind speed
WSV	Net wind speed vector
WSX	Net wind speed vector in the x direction
WSY	Net wind speed vector in the y direction

Symbols Used in Developing the CWSPM

α	Direction angle between the directions being considered for fire spread and the direction from which the frictions are acting.
k	Varies directional dependency of the DISPERSE function

Chapter 1: Introduction

1.1 Background

Created by natural or man-made activities, it is estimated that wildfires around the globe burn over 750,000 square kilometers of forest each year (Rothermel, 1993). Canada's forests alone comprise ten percent of the world's forests and feed an annual average of 9,500 wildfires burning roughly three million hectares. These fires can be devastating for both the environment and the economy. Currently, fifty-six percent of Canada's forests are commercially productive and contribute upwards of fifty billion dollars to the national economy each year. On the other hand, the financial loss caused by forest fires average around one billion dollars annually. As a specific example, Canada's boreal forest fires in 2000 took a devastating toll on the environment and resulted in one-billion dollars of lost revenue (State of Canada's Forests, 2000).

There are many causes of wildfires. Many fires are started unintentionally or carelessly. However, the two most frequent natural causes of wildfires are lighting and the friction of wind rubbing dry wood together. The most frequent unnatural causes include campfires, discarded cigarettes, controlled burning, equipment fires, railroad sparks and juvenile stupidity (State of Canada's Forests, 2000).

1.1.1 Benefits and Drawbacks of Wildfires

In some instances wildfires can provide benefits to the forest ecology by burning away dead, decaying debris and initiating new growth. On the other hand, uncontrolled wildfires can be devastating and result in irreversible changes to the environment.

1.1.1.1 Benefits of Wildfires

When managed properly, wildfires clear away the dead, decaying vegetation that accumulates on the forest floor. This promotes new growth and reduces the possibility of potentially larger, more disastrous, uncontrolled fires. In addition, for some tree species, fire is the only way to reproduce. The intense heat of a fire opens the pinecones that protect the tree's seeds. These seeds can take root in the area of the passing fire or can be transported by the strong, turbulent winds from the fire to be planted tens or hundreds of meters away (Rothermel, 1993). Another advantage of wildfires is that they break down organic mater into soil nutrients. In many cases, landscapes once devastated by fire are bursting with new, healthy growth within a few years.

1.1.1.2 Disadvantages of Wildfires

Wildfires can also be devastating by degrading the environment and diminishing natural resources. The burning of tropical forests alone pumps 2.4 gigatonnes of carbon into the atmosphere per year (Rothermel, 1993). This translates to thirty percent of the total carbon dioxide emissions in the world. Wildfires can also kill wildlife, create mudslides/landslides as a result of the absent vegetation, reduce the aesthetics of the environment, threaten families and homes and influence long-term health problems as a result of the increased air pollution.

1.1.2 Potential Fire Hazards for Today's Forests

How to best preserve the world's forests has been a topic of debate since the late 1970's. Before the extensive fire suppression efforts that began thirty years ago, small-scale fires swept through landscapes every five to twenty-five years (Gayton, 1998). However, since the seventies, fire suppression technology has greatly improved and wildfires occurring near communities are not tolerated as a natural phenomenon. Decades of successful fire suppression activity have allowed many forests to grow uninfluenced by fire.

As a result of this, it is not uncommon for some forests to become ingrown and slowly suffocate themselves to death (Parsons, 1978; Gayton, 1998). The amount of dead vegetation in these forests put them at risk of feeding huge fires that could consume valuable lumber resources, devour fire suppression budgets, and threaten the safety of both fire-fighters and nearby communities.

As a result of these increasingly more common, high impact fires it is important to develop accurate fire modeling techniques that can predict fire danger and spread. Accurate fire modeling will give fire management crews more time to prepare fire breaks to help gain control of large fires in addition to providing insight on ways to improve the best possible techniques of suppressing fires of any size.

1.2 Methodology

The background on fire research that was conducted for this thesis involved extensive reading and personal interviews. From the advice of Cordy Tymstra, Fire Science and Technology Supervisor with Alberta Sustainable Resource Development (SRD), three courses were taken by the author to gain the knowledge needed to write this thesis. The first course entitled "Principles of Fire Behavior" (Principles of Fire Behavior, 1993) described the accepted theories of how environmental parameters affect fire behavior. All wildland firefighters working in Alberta must take and pass this course to be granted employment. The focus of the next two courses was on the two completed components of the Canadian Forest Fire Danger Rating System (CFFDRS). One course discussed the general equations of the Fire Behavior Prediction System (Hirsch, K. G., 1998) and the other course described the general equations of the Fire Weather Index System (Understanding the Fire Weather Index System, CD). These systems will be discussed in more detail in the body of the thesis. It is the theories of fire behavior that are presented in these courses that are stated in this thesis. Altering opinions by academia are not explored.

From the information gained on the background reading that was undertaken and interviews with Cordy Tymstra from the SRD office in Edmonton, Alberta and Rick Arthur from the SRD office in Calgary, Alberta, it was learned that there are three main problems in the wildfire management and monitoring industry.

The first problem is that currently Alberta has no prescribed fire policy. This creates inconsistencies between different fire management districts in the province. The second problem is that each fire management district is using different programs for their management systems. This creates sub-optimal communication between different agencies and inconsistent criteria for fire prediction. The third problem is that the current data acquisition system could be improved to include higher accuracy hot spot detection within existing fires.

This research set out to provide solutions to the first problem by investigating the existing Canadian and Albertan policy to identify what is stated about prescribed burning and to locate gaps in the policy. The author made contact with Morgan Kehr who is the Prescribed Fire Operational Coordinator for Alberta SRD and was informed that no documents had yet been drafted to identify the information that should be included in the new Albertan policy. In order to continue the research, existing American prescribed burning policy was investigated to determine how the subject of prescribed burning is approached. Merits and shortcomings of American prescribed fire policy and relevant portions of Canadian fire policy were identified and recommendations were made to the new Albertan prescribed fire policy.

To solve the two remaining problems the author was introduced to two different fire management systems; one used by the SRD department in Edmonton and one used by the department in Calgary. At a subsequent interview with Cordy Tymstra, the author was told that having a unified fire management system to link the different fire management districts in Alberta would be a very beneficial tool to the future development of the wildfire industry. It was decided by the author and after the advice of the author's supervisor to develop an Internet based wildfire management system to accomplish this task. Further research on the requirements of a wildfire management system determined that the most necessary component was a wildfire prediction model. Research on existing models revealed that Canadian prediction modeling software could be improved. It was then decided to build a fire behavior prediction model that overcame some of the shortcomings of the existing models.

Development of the Canadian Wildfire Spread Probability Model (CWSPM) and criteria development for the Web based management system began in January of 2003. To save time, a website programmer was used to implement the requested criteria into the website. The criterion for the website was to implement the following:

- Implement the Data Acquisition System developed by the Mobile Multi-Sensor Systems research group at the University of Calgary (Wright, 2004) for real-time forest fire hotspots detection.
- Add a database containing information on past Albertan fires.
- Include a distance to nearest lake tool to allow fire managers to easily locate the nearest water resources.
- Include a flight trajectory tool to show the observatory path that spotter aircrafts have taken.
- Include the CWSPM as the fire behavior prediction model.

The CWSPM was designed as a probability model that used standard Canadian fuel type data that is accepted by the CFFDRS. The model was developed to have input based on a scheme of weighted parameters. The values for the weighted parameters were chosen by a trial and error method that linked the weighted parameters as closely as possible to the results of the CFFDRS. This will be discussed in more detail in Chapter 4. By spring of 2003 a new model called the Prometheus model was developed by Alberta Sustainable Resource Development. This model is to become the Canadian standard for fire modeling. Even though the CWSPM was being developed it was decided by the author to use the Prometheus model in the website in place of the CWSPM. This choice was made for the following reasons.

- The new Prometheus model has a Microsoft Component Object Model that allows it to be easily programmed into a website.
- The WMMS system will gain more recognition because it is using Prometheus.
- The Prometheus model uses the equations of the CFFDRS
- Prometheus is to become the standard model across Canada.
- The University of Calgary could work with SRD to debug the Prometheus COM which SRD plans to implement into their own future, Internet based, wildfire management system.

Despite the choice to use the Prometheus model in the development of the Web based wildfire management and modeling system, development of the CWSPM was still completed. The intention of the CWSPM shifted from being used as the web based fire modeling system to being a Canadian model that fire managers or the general public could use to get quick, easy to compute, predictions of fire spread probabilities.

1.3 Problem Statement

There are three problems that need to be addressed to improve the efficiency of the wildfire industry. Solutions to these problems will greatly improve communications and make wildfire management more efficient. The three problems are:

1. Wildfire policy does not adequately outline guidelines that should be followed when conducting prescribed burns
2. Canadian fire modeling programs are sub optimal and should be improved
3. Communications between fire management districts are sub optimal and should be improved with the introduction of an Internet based wildfire management and modeling system.

1.4 Research Objectives

The main objective of this research is to find ways to improve the existing practices of managing and modeling wildfires by finding solutions to the three wildfire management problems previously stated. This is accomplished in this thesis by breaking the main objective down into four sub-objectives.

The first sub-objective is to investigate the parameters that influence fire behavior to learn how wildfires react to various elements in the environment. The second sub-objective is to identify fire policy and find the inadequacies so that recommendations can be made to the new Albertan prescribed fire policy. This would solve the first problem existing in wildfire management. The third sub-objective is to investigate benefits and short comings of existing fire models. Finding ways to improve existing models will help determine the requirements needed in a new fire model. This would solve the second problem existing in wildfire management. The fourth sub-objective is to develop a new fire modeling and management system. This includes the development of the new CWSPM and the development of the web based wildfire management and modeling system. It is anticipated that this research will inspire fire managers to reassess the way that wildfires are managed and promote the development of a more robust, complete fire management and modeling. This last sub-objective would offer one solution to the third problem existing in wildfire management.

1.5 Thesis Outline

This thesis is divided into six chapters. The following section breaks down the contents of each remaining chapter.

Chapter 2 will give background information on the importance of wildfire modeling. This chapter will,

- give an overview of the parameters that affect fire spread
- discus the different techniques used in fire monitoring
- discuss the gaps in Albertan prescribed fire policy and make recommendations for future policies

Chapter 3 will discuss in detail the procedures and mathematical equations used by Canadian Fire Managers to predict rate of fire spread and fire intensity. In addition, it will analyze the existing software for performing fire growth predictions and will discuss how the models can be improved.

Chapter 4 will use the information discussed in the first three chapters to discus the design and development of the CWSPM. This model will be compared to the actual final fire perimeter of a historic fire. The intent of developing this model was to design a Canadian fire prediction model that surpassed the functionality of existing models. This model was to be integrated into the Web based wildfire modeling and management system that was designed by the author but instead the recently developed Prometheus fire behavior prediction model is used. The development of the CWSPM is included in this thesis to demonstrate a valuable tool for quick, easy to compute, fire probability predictions.

Chapter 5 will discuss the functionality of an Internet based, real time, Wildfire Modeling and Management System (WMMS), which is the apex of this thesis' research. In this chapter the reader will discover the abilities of the system, how it was developed and how it can be utilized to revolutionize wildfire modeling. This system combines one of the most advanced hotspot detection systems available to date with the most advanced fire behavior prediction model in Canada to create a real time Internet based GIS that could change the way wildfires are managed in Canada.

The WMMS integrates the following features into a real-time data updating system and GIS based web browser:

- Real time airborne thermal infrared and RGB images of current fires
- Real time spotter aircraft flight trajectories
- Active fires reported by management or the general public
- Fire history of each fire management district
- Fire behavior predictions for future fire spread based on algorithms used by the fire behavior prediction software Prometheus (designed by the Alberta Government in 2003)

This system has the potential to greatly improve fire management's abilities to monitor this natural disaster and can be utilized by both fire managers and the general public. It has the potential to have a significant impact on how wildfires are combated resulting in reduced damage to the environment, improved safety of fire crews and appreciable financial savings. Communication techniques between the different facets of fire management personnel also have the potential to improve as this system harnesses some unique ways of displaying data and monitoring fire behavior (Trevis and El-Sheimy, 2004). Some possible improvements to the system and future work will also be discussed.

Chapter 6 will give the final conclusions and recommendations for this research.

Some of the material presented in Chapter 5 has been previously published in papers. In those cases where the candidate has been the author or a co-author of these papers, quotations are not indicated as such, but are simply referenced.

Chapter 2: Background to Fire Modeling

2.1 Parameters that Affect the Behavior of Wildfires

Wildfire behavior is dictated by the elements present in the surrounding environment. There are three broad factors that contribute to the behavior of wildfires. They are (Principles of Fire Behavior, 1993):

1. Fuel
2. Topography
3. Weather

2.1.1 Fuel

Fuel affects fire behavior in a number of ways. The most obvious way is by the type of fuel the fire consumes. Fuel is described as any type of vegetation that can be consumed by a fire. Different types of vegetation will burn at different rates due to their size, shape, compactness, horizontal and vertical continuity, moisture content and chemical composition (Urban-Wild Land Interface Fire: The I-Zone Series).

Fuel size affects how easily new fires can be started by spotting. Spotting occurs when burning fuels are lifted up into the air by the upward drafts of the fire's convection currents and dropped outside the fire line to start new fires (Brown, 1973). These convection currents are created by cold air that is sucked into the fire and forced upwards as the air heats up from the fire. Debris can be carried by these convection currents distances of a few meters to hundreds of meters depending on the strength of the convection currents and the weight and shape of the debris. Small embers can easily be lifted up by the fire's convection currents but cannot maintain long-term combustion. This prevents most small embers from starting long-range spot fires and allows them to ignite fires only a short distance from the main fire. In addition, small embers may not be able to generate enough heat to ignite some vegetation types. Larger embers, on the other hand, have the size needed to provide enough heat to ignite unburned vegetation, provided the convection currents are strong enough to lift them into the air.

The shape of the fuel also influences its ability to spread or sustain a fire. Round embers can contribute to fire behavior because they have the ability to roll down existing slopes and create new fires in unburned fuels in the valleys below. Flatness and surface area of a burning fuel also influence its ability to start new fires. As the flatness and surface area to volume ratio increases it becomes easier for convection currents to pick up embers and carry them longer distances. These more aerodynamic embers are able to start new fires sometimes hundreds of meters way from the original fire line (Principles of Fire Behavior, 1993).

Fuel compactness will also affect fire behavior. Loosely compacted fuels will allow more complete combustion thereby accelerating the spread of the fire. On the other hand, tightly compacted fuels will slow down combustion, slow down the fires rate of spread but increase the fire’s intensity (Brown, 1973).

Horizontal and vertical continuity of fuels also influence how easy it is for a fire to gain intensity. Fuels that lack horizontal continuity can make a fire loose momentum and put itself out (Carmody, 2001). Similarly, fuels that lack vertical continuity discourage the vertical extent of the fire and hinder the fires progression from surface fires to more intense crown fires.

The moisture content of fuels also greatly affects fire behavior. Moist fuels will be hard to burn because the water in the fuel absorbs the majority of the initial heat. This will hinder fire growth. In comparison, dry fuels act like kindling for the fire and provide extra heat and flame that will help ignite the moister fuels. The increased moisture content in leaves when compared to coniferous tree needles is one reason why fires in deciduous forests are on average less numerous and less violent than fires in coniferous forests (Johnson, 2001).

Chemical content of fuels also influences fire behavior. Some saps, resins and pitch are flammable and can greatly accelerate or intensify the spread of fire. On the other hand cow pies and moist duff act as fire retardants and hamper the rate of spread (Principles of Fire Behavior, 1993).

2.1.1.1 Fuel Type Acting as a Barrier to Fire Spread

When looking at the behavior of wildfire propagation there are a number of parameters that act as natural barriers to fire growth (Principles of Fire Behavior, 1993). Rock, paved roads and bare soil act as unburnable barriers to fire and can halt a fire from crossing over these surfaces. This will, of course, depend on the width and length of the barrier since fires can easily burn around and over small obstacles. If a fire is large enough to spot across a rock or bare soil barrier then the obstacle is not impermeable and will only aid in slowing down the fire's rate of spread. Trails and cut lines also impede the growth of fires. Heavily traveled trails will act as a bare soil barrier and cut lines change the vegetation type from trees to grasses. This fuel type change could take a crown fire down to a surface grass fire. Any change in fuel type can have such an effect on the behavior of wildfires. Depending on the fuel type change the fire could either accelerate or be slowed. Recently burned vegetation also acts as a natural fire barrier by not having much unburned fuel to ignite. Lakes and streams also act as barriers in two ways. The first way is that it is impossible for water to burn so the fire must stop at the lake or riverbank or have enough intensity to jump the river and burn the opposite bank. The second way is that vegetation on the banks of lakes and rivers usually have a higher moisture content, which will make the vegetation harder to ignite. This in itself will aid to slow the fire.

2.1.2 Topography

Topography plays an important role in fire behavior. It can be described by three sub-parameters.

- Slope
- Aspect
- Elevation

Slope affects fire behavior in a number of ways. First, the steeper the slope the faster the fires rate of spread upslope (Brown, 1973). This is due to the higher degree of fuel preheating caused by the smaller angle between the ground and flames. In addition, if there is a great deal of solar radiation on the slope during the day, wind will be created during the night as the land cools and a nighttime inversion develops. This wind can push the fire down slope in unexpected directions. The specific shape of the terrain also affects fire behavior. Ridges can slow a fire because they hinder the preheating of fuels on the other side of the ridge whereas chutes running up the sides of mountains can rapidly speed up the spread of fire by creating steep slopes on three sides of the fire and promoting spread in three different directions. Saddle slopes can be particularly dangerous since fire behavior and spread direction becomes unpredictable, as there are both upward slopes and ridges in the same area. In this case the fire can spread up one slope, up the other, or up both. Areas such as saddle slopes are also often the locations where fire whirls will develop (Principles of Fire Behavior, 1993). Fire whirls or vortexes are comparable to dust devils or even tornadoes but comprised of both wind and fire instead of just wind. These phenomena can accelerate away from the core of the fire leaving trails of fire behind them. They are particularly dangerous both for their unpredictable nature in combination with the high speed of the winds that make them. It has been found that wind speeds in the center of a fire whirl can exceed one-hundred and sixty kilometers per hour. They eventually dissipate as they leave the convection currents and heat of the main fire.

Slopes can also provide shelter for small fires and allow them to grow without being put out by the wind. In this manner, shelter can also allow spotted embers to ignite new vegetation and start a new fire. Local weather patterns can also be affected by slope (Principles of Fire Behavior, 1993).

Aspect affects fire behavior because of the different local climates on slopes facing different directions. North of the equator, south facing slopes will generally be dryer than north facing slopes because they receive more solar radiation (Brown, 1973). This means that there is more potential for a fire to burn on south facing slopes. South facing slopes also promote fire spread by having higher average temperatures.

Elevation is also an influential factor for fire spread. Like aspect, elevation influences the moisture content of fuels. It is indirectly related to curing densities, temperature, snowmelt dates and precipitation (Principles of Fire Behavior, 1993).

2.1.3 Weather

Weather is the most variable and influential component for fire spread. Weather affects temperature, fuel moisture, wind speed and atmospheric stability which all play a role in fire behavior. Temperature is important because the hotter the fuel is, the less preheating needed to ignite it. Fuel moisture, which has already been discussed in the previous section, is related to precipitation and humidity. As the precipitation in a certain area increase, the moisture content in the fuels will also increase and igniting the vegetation will become more difficult.

Wind is perhaps the most influential component of weather when dealing with fire behavior. Wind does many things to influence the propagation speed and direction of an active fire. Wind has the ability to dry fuels thusly making them more susceptible to fire. It also supplies oxygen to feed the fire and can bend fire flames to be more parallel to the ground thereby helping them ignite new vegetation (Principles of Fire Behavior, 1993). A fire can seem unaffected by near zero wind velocities or, in the case of high winds, follow the direction and speed of the wind without any apparent regard for any other parameters such as fuel or topography. Winds such as the Chinook winds of Alberta, Canada are particularly dangerous since they are strong, hot, dry winds that can greatly accelerate the spread of fire (Hirsch, 1998). Fire managers must be very aware of the wind speed and direction because it can vary greatly from hour to hour or even minute to minute. If the wind direction changes suddenly the fire crew could become trapped by the fire or have the fire begin racing towards them. This is why weather observations are so important for fire management and modeling.

Atmospheric stability is also a contributor to fire behavior (Principles of Fire Behavior, 1993). There are two types of atmospheres that one must be aware of when dealing with wildfires: stable and unstable atmospheres. Stable atmospheres occur when there is an inversion and warmer air rises to rest on top of cooler air that is closer to the ground. In this case, air temperature will increase with increased height above the ground. Unstable atmospheres occur when warmer air is closer to the ground and cooler air rests above. In this case air temperature will decrease with increasing height. These two conditions can affect a fire's size and intensity. Stable atmospheres will restrict the vertical development of convection currents and in turn slow growth and intensity. This is because the hot air created from the fire will be unable to rise above the warm air that is in the higher levels of the atmosphere. This prevents strong updrafts that encourage higher fire intensities and long range spotting. Stable atmospheres will also promote milder and steady winds. Unstable atmospheres on the other hand, encourage the vertical development of large convection currents, which will increase the growth, and intensity of the fire. This is because, in unstable atmospheres, the hot air created by the fire is able to rise to incredible heights and this creates strong updrafts and compensating downdrafts. Under these conditions, large wildfires can often create their own local weather patterns which can include local thunderstorms and gusty winds. These winds are particularly hard to incorporate into wildfire models, due to their unpredictability, and have a large influence on fire spread. They also have the capability of uprooting fully grown trees and displacing them outside the most actively burning part of the fire (Brown, 1973).

Cloud cover also indirectly influences fire behavior. Clouds affect the degree of solar radiation that is received by the fuels and can hinder preheating and drying of the fuels (Urban-Wild Land Interface Fire: The I-Zone Series).

2.2 Detecting Wildfires

Today, look-out stations, airborne remote sensing and public sightings are the most common methods used to detect forest fires. In the province of Alberta, Canada, forty percent of all wildfires are detected by sightings from fire lookout stations, twenty percent from aerial sightings and forty percent from public sightings (Wildfire Detection, 2004).

Much research has been conducted on satellite aided wildfire detection, monitoring and modeling. Remote Sensing's ability to cover large areas in a single image makes it an option for wildfire detection and modeling (Sannier, 2002). Some satellites of choice for this procedure are images from the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) series satellites or Moderate Resolution Imaging Spectrometer (MODIS) images. Detection of wildfires using these methods has proven to be successful however; there are a number of drawbacks that do not allow it to be used for high accuracy monitoring or modeling. The first drawback is that the resolutions of many of the satellite images suitable for wildfire detection are very coarse (i.e. NOAA AVHRR has a pixel resolution of 1.1 Km at nadir (Fernandez, 1997)). This means that fires must burn to a considerable size before the satellites can detect them. In addition, it is impossible to differentiate between a single fire and a group of smaller fires (Mahmud, 1999, Knapp, 1996). Predicting the exact perimeter or where the fire is likely to propagate in the future is therefore impossible. Satellites with higher resolution such as IKONOS are possibilities but these have no thermal capabilities to detect the heat of the fire or identify hot spots and obtaining the images is too expensive to have any practical use for this application. The second drawback is that many images taken by these satellites have extensive cloud cover that conceals the evidence of existing wildfires (Mahmud, 1999). Since a single satellite image does not have the spatial resolution, real time capabilities or spectral range needed for high accuracy management and modeling (Knapp, 1996), they will not be discussed further. The application that does have this capability is photogrammetry, which will be discussed next.

Aerial photogrammetry is a common method used to monitor forest fires and it solves many of the problems that occur when using satellite images for this application. To use photogrammetry, a camera is mounted on the bottom of a spotter aircraft and, in combination with GPS positioning and inertial navigation systems, the physical properties and GPS locations of the fire can be determined as the aircraft passes over the area of interest. The images acquired by photogrammetry depend on the type of camera that is used. Video, visual RGB or thermal cameras can be used together or separately to obtain the desired type of information.

One advantage of photogrammetry is that it can be viewed in three dimensions if two images contain the same point of interest. If two such photos exist, these images can be viewed in stereo. A second advantage of photogrammetry is that the resolution of the images can be controlled (within reason) depending upon the flying height of the spotter aircraft (El-Sheimy, 2000). A third advantage of photogrammetry is that the images can be taken when required. One does not have to wait for the satellite's next pass over the area. A fourth advantage of photogrammetry is that the images are taken below the elevation of the clouds; therefore, there are fewer obstructions on the image. Smoke from the fire will still cause obstructions in the images for the visual RGB cameras but thermal cameras are insensitive to smoke and the heat signatures of the fire can still be clearly identified.

Methods used for detecting hotspots and monitoring wildfires are very important to ensure that the fires are detected in the most efficient and cost effective method available.

2.3 Resources Used to Combat Fire

There are many resources used to combat wildfires. These resources include bulldozers to make firebreaks, water/fire-retardant bomber aircrafts and people with hoses, pick axes and shovels doing what they can to douse the fire or create firebreaks. One controversial method of combating fire is by starting new, smaller, controllable fires in the line of the main fire. Setting fires removes the fuel that is needed to feed the main fire and can effectively redirect or halt the advancing fire front (Clugston 2003). Purposely setting a fire with the intention of helping forest health or managing an existing wildfire is called prescribed burning. Although controversial, extensive prescribed burns are what some fire managers believe is the only solution to prevent these large-scale wildfires that have run rampant in many of Canada's forests. To find a solution to the first problem in wildfire management that this thesis is trying to solve, the next section will investigate prescribed burning and related policy. It will pinpoint the weaknesses in Canadian policy and make recommendations for future policies.

2.3.1 Prescribed Burning

Table 2.1 illustrates how prescribed burning contributes to environmental, economical and social issues.

Table 2.1: Possible Benefits of Prescribed Burning

Environmental	***Economical***	***Social***
• Initiates new growth • Clears away dead decaying debris allowing remaining trees	• Saves money by spending smaller amounts	• Attracts the attention of the media to help

to have better access to the sun (Gayton, 1998) • Replenishes the soil with nutrients • Reduces ignition potential • Mitigates the potential for future extreme fires to occur in the area (Gayton, 1998) • Controls insect infestation and disease (Denison, 1997) • Increases water yield for remaining vegetation (Parsons, 1978) • Helps some tree species(i.e. jack pine) that need fire to regenerate or the trees will die (Jack Pine Ecosystem, 2003) • Helps maintain the habitat of some animal species such as the Kirtland warbler who are dependant on the large branches of young jack pine forests (Jack Pine Ecosystem, 2003)	of the budget to control small prescribed fires and not having to fight expensive, extreme fires • More economical than mechanically thinning the trees (Denison, 1997) • Saves residential housing in the case of a larger fire	inform citizens of the hazards of large amounts of fuel build up and how to better protect their homes from fire (Koehler, 1997) • Produces less smoke and ash than the potentially more extreme fires that could sweep through the landscape if no action is taken

Table 2.1 clearly indicates that there are a number of positive environmental, economic and social aspects outlining how prescribed burning aids forests. Despite these sound arguments, there are some arguments that state that prescribed burning is not a solution to forest management. These arguments are stated in the Table 2.2 below:

Table 2.2: Possible Negative Impacts of Prescribed Burning

Environmental	***Economic***	***Social***
• Causes smoke and ash • Releases carbon into the atmosphere • Allows the possibility for a fire to escape and become a large fire (Gayton, 1998) • Lacks proof of effectiveness until an un-prescribed fire sweeps through the landscape.	• Causes skepticism of spending money on a fire if you do not have to • Offers no guarantee that a prescribed burn will save money in the future • Creates high liabilities if personal property is damaged or destroyed	• Causes smoke and ash which could lead to temporary health ailments • Creates public skepticism regarding any forest fire

The main difference between the two schools of thought is that the arguments stating that prescribed burning is not sustainable are intangible and hypothetical "what ifs", whereas the arguments stating that prescribed burning aids forest sustainability are often more tangible and documented from the state of our current forests and results of historical fires.

The advantage of prescribed fires is that they are intensely monitored and only preformed on days where the wind and humidity provide conditions that are adverse to extreme fire behavior. The ferocity of prescribed fires can also be controlled to administer the type of fire that would be most advantageous to a specific forest. Surface fires could be used to control dead vegetation and debris on the forest floor, more intense crown fires could be used to open pinecones and start new forests. Prescribed burning is also favorable to mechanical thinning since the process is less expensive and some of the tree's nutrients are recycled back into the ground. With mechanical thinning these nutrients are removed along with the trees.

2.3.1.1 Prescribed Burning and Policy

Canada has no federal fire policy but instead allows the provinces to develop their own policies. Currently, within each province a limited practice of prescribed burning is used to help forest sustainability. Surprisingly, in the province of Alberta, Canada there is no existing policy that outlines a set of standardized criteria that need to be followed before a prescribed burn can be administered (Kehr, 2004). This task is left up to the manager of each Wildfire Management Area. The policy that exists today, The Forest Protection Policy Manual and Standard Operating Procedures, only states that prescribe burning can be used as a tool for sustainable forest management (Forest Protection policy Manual & Standard Operating Procedures, 2003). No indication of where or when prescribed burning is allowed is outlined in this policy. To remedy this, Morgan Kehr from Alberta Sustainable Development is heading a team who is currently writing an Alberta Prescribed Fire Policy that will outline the standardized criteria for prescribed burns in Alberta (Kehr, 2004). The details of this policy are not yet available.

A policy specifically meant for prescribed burning is important because there are significant differences between general wildfires and prescribed burns. There are at least nine items that should be dealt with in a prescribed burn policy that are not needed in a wildfire policy. These items are listed below:

1. Descriptions of the methods used to ignite prescribe fires and defined guidelines for choosing the safest ignition method
2. Goals intended by having the prescribed fire
3. Identified ideal and unacceptable weather condition criteria
4. Descriptions of the minimum amount of needed suppression/monitoring forces
5. Weighting systems for risks based on certain weather, topography and fuel type combinations to create a “go”/”no go” criteria for the prescribed burn
6. Pre-created backup plans in case prescribed fires escape

7. Environmental impact assessments
8. Economic advantage of using prescribed burning instead of other forest thinning techniques
9. Procedures to determine what type of fire will be the most beneficial for a certain type of forest

Since Alberta has no prescribed fire policy, the United States federal prescribed fire policy will be used to analyze how policy attempts to outline the use of prescribed fires. Recommendations can then be made for Alberta's new policy based on the merits and shortcomings of the American policy. The criteria stated in the American Wildland Prescribed Fire Management Policy include developing a burn plan that specifies the:

- desired fire effects,
- weather conditions that will promote acceptable fire behavior,
- forces needed to ignite, hold, monitor, and extinguish the fire and
- level of risk (low, medium or high) if the burn is conducted (Zimmerman, 1998)

If a prescribed burn is calculated as a high risk then the burn will not be permitted. A go/no-go checklist must also be completed before the burn can be conducted.

Environmental Policy

There is one major problem with the American federal prescribed fire policy that the Alberta government should consider when designing a policy of their own. Strict environmental policies have made it very difficult to meet the criteria needed to perform a prescribed burn and often no burns are permitted because of this. Despite the pressure from environmentalists, President George W. Bush and the US Congress needed to pass the "Healthy Forest Initiative" in 2003, which allows more relaxed restrictions regarding the use of prescribed burning and forest thinning (Healthy Forests, 2002). This initiative no longer restricts the size of trees that can be burned or cut to improve overall forest health and allows more funding for prescribed burns that follow the existing policy. Environmentalists disagree with this initiative because they believe that not enough forests near residences were included in the project and also believe that the project may contain a loophole which will allow an increase in commercial logging (Doering, 2003). This complaint seems unrealistic as fifty percent of the budget for this project is reserved for forests near residential areas. It is true that this initiative may bring more profit to loggers but the existing funds for prescribed burning were too limited and, using Washington, Oregon and California's forests as an example, not adequate enough to effectively promote sustainable forest health.

In Alberta's case, care should be taken to insure that environmental policies meld with the Albertan Prescribed Fire Policy. This may take some pro active effort in developing public awareness to inform the population of the benefits of prescribed burning and how it promotes forest sustainability. Also, ingrown forests near residences should be made a higher priority for burning than remote forests. It would be beneficial for the forest manages to work in a partnership with the insurance companies to initiate programs to identify the potential problem areas and deal with them accordingly.

Economic Policy

An insertion of the economic advantages or disadvantages of a prescribed burn should also be included in Alberta's new prescribed fire policy. Although it is expected that some cost/benefit analysis be done before prescribed burning is performed, these requirements were not stated in any of the policies that were looked at. A portion of policy should be reserved for addressing the economic topics relating to forest sustainability that were outlined in Tables 2.1 and 2.2.

Health and Safety Policies

The issue of health and safety is very significant when discussing prescribed burning and forest sustainability, since the fires are purposely set. Prescribed burning, in many cases, is both environmentally and economically sustainable; however, this operation must also be considered socially beneficial to be a good technique for improving forest health. A major concern is air pollution caused by prescribed burns. Environmentalists and some members of the general public argue that prescribed burns should not be allowed because they release unnecessary carbon dioxide and ash into the air. Alberta again has no prescribed burning policy and therefore initiates no health or safety standards for this matter. One important recommendation for Alberta, which is currently mandatory in the Unites States, is to only administer a prescribed burn if it can be predicted that the degradation of air quality in any nearby community is still within the guidelines of any clean air policy such as the Clean Air Act (Super, 2002). Before prescribed burns can be conducted in the United States, environmental assessments must be preformed to ensure that the amount of smoke particles in the air will be less than the air quality standards set by the Environment Protection Agency (Glickman, 1995). If the predicted winds or size of the fire have the potential to lower the air quality of nearby residences below the standard, the burn is not permitted.

The other safety policies that are in Alberta’s Standard Operating Procedures are relevant enough to ensure that fire-fighter safety is a top priority. Perhaps one of the most important existing policy inclusions is the right for a worker to refuse work if they feel they are in “imminent danger” (Super, 2002). Also in Alberta, mandatory safety briefings are held for all crew members each day. As another precaution, a Safety Officer is assigned to every fire and reports on any problems, issues, concerns during the fire and makes recommendations on how safety could be improved for the next wildfire suppression activity.

2.3.1.2 Effectiveness of Policy

If Alberta adopts many of the recommendations outlined in this section, prescribed burning could prove to be an effective tool to maintain forest sustainability for issues of environmental, economical and social importance. The only remaining precaution will be to ascertain the effectiveness of the new policy. In the past, the only area where prescribed burning has become an unsustainable tool is when control of the prescribed fire is lost. The following list is a set of three different escaped prescribe burns that have happened in the United States and the damage they caused.

- Cerro-Grand Fire, New Mexico - burned 235 residences in Los Alamos (Cerro Grande Prescribed Fire, 2000)
- Lowden Ranch, California – burned 23 residences (Lowden Ranch Prescribed Fire Review, 1999)
- Sawtooth Mountain, Arizona – 1 Fatality (Sawtooth Mountain Prescribed Fire Burnover Fatality, 2003)

In these three cases, and in most prescribed burn runaways, not following the guidelines of the existing policy was the cause of the loss of control of the fire (Sawtooth Mountain Prescribed Fire Burnover Fatality, 2003; Cerro Grande Prescribed Fire, 2000; Lowden Ranch Prescribed Fire Review, 1999; Conroy, 2003). The reasons for the failure of these three example cases are stated below:

Cerro Grand Fire:

- Pertinent weather information was not collected;
- Did not follow the burn plan procedure that was approved by the state.

Lowden Ranch Fire:

- The required number of crew were not present at the burn site;
- Three of the four men in charge were not adequately briefed and had not reviewed the burn plan.

Sawtooth Mountain Fire:

- Prescribed burn was unapproved;
- Burn preformed in temperatures that were too high and humidity that was too low;
- Killed worker did not follow the safety standards by:
    - failing to follow the burn plan;
    - working alone.

In each of these cases, if the policy had been followed these disasters would probably have been avoided. A quote from the U.S Department of the Interior, Bureau of Land Management who oversees the Fire Incident Reports states:

> *"When agencies do fail, it is generally not because of a lack of adequate policy, standards and guidance, but a result of not following that guidance. Agencies write a plan, but do not live the plan (*Lowden Ranch Prescribed Fire Review, 1999)*."*

There are a number of different ways that policy is reviewed in Canada and the United States. As mentioned earlier, in Alberta, a Safety Officer is assigned to every fire. It is then the safety officer's responsibility to enforce existing policy and to recommend ways that policy can be improved.

Problems arising from using prescribed burning as a tool for sustainable development do not lay in the method or in policy but in human error. It is a proven fact that forests need fires to regenerate and our intense fire suppression activities have not helped sustain our forests but rather helped them slowly suffocate and die. The use of prescribed burning has the potential to improve forest health from an economic viewpoint while producing minimal adverse effects. Prescribed burns will also reduce the future chance that large, uncontrollable fires will ignite in the area.

2.4 Summary

This chapter discussed the following,

- Parameters affecting forest fire behavior;
- Methods used to detect fires;
- Methods used to combat fires;
- Policy weaknesses in regards to wildfire management and recommendations on what should be included in future Albertan policy.

Currently wildfire policy does not outline guidelines that should be followed when conducting prescribed burns. This chapter has provided a solution to this first problem facing wildfire management. The creation of a new Albertan policy for prescribed burning that follows the recommendations in this chapter will help to ensure that prescribed burns are carried out safely and effectively.

The next chapter discusses how to mathematically predict fire spread and introduces some of the fire models that are used in Canada and the United States. Chapter 3 supplies the background information that is needed to solve the second problem regarding suboptimal Canadian fire behavior modeling.

Chapter 3: Fire Prediction and Modeling

3.1 Predicting Fire Behavior

The first attempt at predicting fire spread using a mathematical approach was achieved by W. R. Fons in 1946 (Rothermel, 1972). He focused on the head of the fire and concluded that a fire spread by employing a series of successive ignitions of the fine fuels in the landscape. A certain amount of heat was needed to ignite these fine fuels and fire spread depended on the time period between ignitions and the distance between the particles in the fine fuels.

Since then, two schools of thought have developed in North America and have become the standards that are used when determining how to predict the spread of wildfires in Canada and the United States. Forest fire managers in the United States use equations developed by Richard C. Rothermel in 1972 (Rothermel, 1972). Canadians use equations based on the Fire Intensity Equation developed by Byram in 1956 (Forestry Canada Fire Danger Group, 1992).

3.1.1 The Rothermel Model

In 1972 Richard C. Rothermel, who worked as a Research Engineer at the Northern Forest Fire Laboratory in Missoula, Montana, developed a mathematical model for fire propagation (Rothermel, 1972). This model attempted to integrate all the variables in the fire environment (Bachmann, 2000). It was unique in the fact that it was able to model the relationship between the burning fire front and the energy released to the adjacent fuels (Urban-Wild Land Interface Fire: The I-Zone Series). No other model was able to do this before. Many wildfire models used today employ algorithms that were designed by Rothermel. This model uses seventeen input variables that describe fuel types, moisture content, slope, aspect and wind patterns

(Rothermel, 1972). Since this model is used primarily in the United States the equations that make up the model will not be discussed. For extensive detail about this model and the equations that complete it refer to Rothermel, 1972.

3.1.2 Byram's Fire Intensity Equation

The mathematical model that Canada uses to predict the rate of spread and fire intensity of wildland fires is inspired by Byram's Fire Intensity Equation,

$$I = H\ w\,R \tag{1}$$

Where,

- I is the fire intensity measured in kW/m.
- H is the fuel low heat of combustion measured in kJ/kg.
- w is the weight of fuel consumed per unit area in the active fire front measured in kg/m^2.
- R is the rate of forward spread in m/sec (Forestry Canada Fire Danger Group, 1992).

In the ten years after its development, this equation gained widespread acceptance by Canadian fire managers and researchers. Accordingly, it was decided in the mid 1960's to use a version of Byram's Fire Intensity Equation for Canadian forest fire predictions. As a result, the Canadian Forest Fire Danger Rating System (CFFDRS) was developed to implement this equation.

3.1.3 Predicting Fire Spread Using the Methods of the CFFDRS

The CFFDRS is currently the Canadian standard for predicting wildfires and was initially developed in 1968 (Hirsh, 1996). To enable it to predict fire behavior using Byram's fire intensity equation, two sub-systems have been developed to handle the fuel type, topography and weather input parameters. The two sub-systems that have been developed are called the Fire Behavior Prediction System (FBP) and the Fire Weather Index (FWI) System. They are used to calculate the predicted values for w and R in Byram's Equation. A third sub-system is currently being developed to include risk of lightning and human caused fires.

The FBP system uses fuel types and topography to calculate quantitative predictions for select characteristics of fire behavior (Hirsh, 1996). Fuel types across Canada have been grouped into sixteen standard classes to help model the effects of fuel type on fire spread. Table 3.1 below shows the standard fuel types and their corresponding abbreviations. These abbreviations will be used extensively throughout the remainder of this thesis.

Table 3.1: Canadian Standard FBP Fuel Types (Hirsch, 1996)

Abbreviation	Fuel Type
C-1	Spruce-Lichen Woodland
C-2	Boreal Spruce
C-3	Mature Jack or Lodgepole Pine
C-4	Immature Jack or Lodgepole Pine
C-5	Red and White Pine
C-6	Conifer Plantation
C-7	Ponderosa Pine
D-1	Leafless Aspen
M-1	Boreal Mixedwood – Leafless
M-2	Boreal Mixedwood – Green
M-3	Dead Balsam Fir/ Mixedwood – Leafless
M-4	Dead Balsam Fir/ Mixedwood – Green
S-1	Jack or Lodgepole Pine Slash
S-2	Spruce/Balsam Slash
S-3	Coastal Cedar/Hemlock/Douglas-fir Slash
O-1a	Matted Grass
O-1b	Standing grass

The fuel types listed in Table 3.1 above are not the only fuel types found in Canada's environment. Fuels not listed as a standard fuel type must assume the identity of one of the currently existing standard fuel types to be able to utilize the FBP calculations. The restricted number of available fuel types is a limitation of the system. An example of problems encountered when using limited fuel types arises when wildfires spread through un-modeled agricultural crops. In situations such as this the FBP system may not produce optimal results.

The FWI system is composed of six components that model fire behavior based on fuel moisture and wind dynamics. The first three components deal with the moisture content of fuels on the forest floor. The layers are defined as scattered litter and other fine fuels, loosely compacted organic layers at moderate depth and deep, compacted layers. The three remaining components of the FWI system include predicted rate of fire spread, fuel available for combustion and predicted head fire intensity. These six components are calculated using the equations from Van Wagner, 1987.

The CFFDRS method of predicting fire intensity differs from Byram's equation in a number of ways. First, Byram's equation is meant to use observed input values as parameters in the equation. When using the CFFDRS method, only predicted values are available. Second, the value for H has been changed from a variable into a constant value of 18,000 kJ/kg. This value is the average heat of combustion for the sixteen fuel types outlined in the FBP system. The value of 18,000 was chosen based on results of measurements taken from small scale fires occurring in various fuel types. The CFFDRS version of Byram's Fire Intensity Equation can now be shown. The resulting equation is Equation 2 below:

$$FI = 18000 \times TFC \times ROS \qquad (2)$$

Where,

FI	is the fire intensity measured in kW/m.
TFC	is the predicted total fuel consumption measured in kg/m^2.
ROS	is the predicted Rate of Spread measured in m/min.

An extensive number of equations must be computed before the intensity of a fire can be calculated. The next few pages will illustrate the background for these equations. All equations have been taken from Forestry Canada Fire Danger Group, 1992 unless otherwise stated.

3.1.3.1 Calculating Fine Fuel Moisture Code and Buildup Index

The first set of equations that need to be calculated when determining a fire's Rate of Spread and Fire Intensity are the Surface Fuel Consumption (SFC) equations. To solve the equations for Surface Fuel Consumption, the Fine Fuel Moisture Code (FFMC) and Buildup Index (BUI) must be calculated.

Fine Fuel Moisture Code

The FFMC describes the moisture content of the upper most layer of fuel on the forest floor. This upper most layer is called the surface litter layer and is approximately 1.2 centimeters in depth (Understanding the FWI, CD). This parameter may change hourly and certainly daily and is greatly dependant on temperature (T - in degrees Celsius); humidity (H - in percent); wind speed (W - in kilometers per hour) and rainfall (r_0 - in millimeters). FFMC values can influence the likelihood and speed of surface fire spread, spotting probability and extreme fire behavior. The FFMC is related to ease of ignition because the upper most layer of the forest floor is where most fires ignite. For the FFMC equation and derivation refer to Van Wagner, 1987.

If the FFMC calculations produce values below seventy-four it is unlikely that a fire will be able to ignite in that location (Understanding the FWI, CD). This is because the fuel moisture content is too high to support combustion. Values greater than ninety-two indicate that there is the potential for extreme fire behavior.

Buildup Index

The BUI models the amount of fuel available for burning. It is calculated using two input variables concerning the moisture of the fuels in the two lower layers of the forest floor, namely the Duff Moisture Code and the Drought Code. The Duff Moisture Code (DMC) represents the moisture of the fuel in the forest floor layer that is just below the fine fuel litter layer. Fuels available for burning in the DMC layer are located up to a depth of about seven centimeters under the surface litter layer. The DC represents the Drought Code and corresponds to the moisture of the fuel in the deep layers of the forest floor. These layers reach an approximate depth of about eighteen centimeters (Understanding the FWI, CD).

Calculating the Duff Moisture Code for the BUI

The first BUI parameter that will be discussed is the DMC. The DMC is important for fire modeling because this layer of the forest floor is where the fire front gains most of its energy. DMC is influenced by daily temperature, relative humidity and rainfall. The equation for the DMC (Van Wagner, 1987) was calculated based on four years of empirical observations of the duff layer in red pine and jack pine forest stands in the 1970's. Based on the same observations it was discovered that when the DMC of a duff layer reaches values higher than forty it is able to contribute to Fire Intensity and fire Rate of Spread. At values lower than twenty this layer will not ignite or be involved in the burning of forest fuels (Understanding the FWI, CD). This is because the moisture content of the duff layer is too high for combustion to be able to occur.

Calculating the Drought Code

The second parameter needed for the BUI calculation is the Drought Code. This code is an indicator of smoldering combustion, seasonal drought and total fuel consumption. It is affected by the daily rainfall, noon temperature and month of year (Understanding the FWI, CD). If the value of the DC is very high (i.e., five-hundred) then sustained smoldering combustion will be present and the fire will be very difficult for the mop-up patrols to extinguish. The deep duff layers are not capable of flame but if intense smoldering is present they can greatly damage soil composition and root systems. This can make it impossible for the forest to regenerate quickly after the fire has been extinguished. For further details on this equation refer to Van Wagner, 1987.

3.1.3.2 Calculating Surface Fuel Consumption

The next step in determining the Rate of Spread of a fire and the fire intensity is to calculate the Surface Fuel Consumption (SFC). This parameter is dependant on fuel type. There are two types of SFC calculations. The first type uses the Fine Fuel Moisture Code (FFMC) as an input parameter. The second type uses the Buildup Index (BUI) as an input parameter. The type of equation used is dependant on the main type of fuel available for burning. If the fine fuels on the forest floor are the primary facilitators of fire spread, the FFMC dependant equation is used. If woody fuel consumption is the primary facilitator of fire spread then the BUI dependant equation is used. If both factors are important, such as in the ponderosa pine (C-7) fuel type, then both the BUI and FFMC are used in two separate equations and summed together to calculate the final SFC. All SFC equations were developed from plotted empirical data. Examples of these plots from (Forestry Canada Fire Danger Group, 1992) can be seen in Appendix A. One example equation for the C-1 fuel type is shown below. For the remaining equations refer to Forestry Canada Fire Danger Group, 1992. SFC is measured in units of Kg/m^2.

C-1 fuel type

$$SFC = 1.5 \times \left[1 - e^{(-0.230 \times [FFMC - 81])}\right] \quad \text{If SFC < 0, set SFC = 0} \qquad (3)$$

For all SFC equations, if the SFC value is less than zero the SFC value is set to zero. This is done because it is impossible to consume a negative amount of fuel.

A constant value is used to calculate the SFC for the grass fuel type. This constant value was chosen since there is no organic fine fuel layer in grass fuel types and it is assumed that all the grass is consumed during the passage of the fire front so there is no need to compute a Buildup Index. The SFC for grass is then equal to the grass fuel load (GFL), which has a standard value of 0.3 kg/m^2 (Forestry Canada Fire Danger Group, 1992).

3.1.3.3 Computing Initial Rate of Spread

The next step in fire modeling is to compute the Initial Rate of Spread (RSI). The RSI can be described as the rate of spread of a fire through level terrain under equilibrium conditions (Forestry Canada Fire Danger Group, 1992). Equilibrium conditions mean that the fire is no longer accelerating its burning pattern from a point source fire but that the fire front can be treated as a line fire acting independently from the initial point where the fire ignited. Similarly to surface fuel consumption, the RSI is dependant on fuel type and has therefore been divided into equations (Forestry Canada Fire Danger Group, 1992) that vary slightly depending on the input fuel type. Just as in the equations used for Surface Fuel Consumption the RSI equations have been developed from best fit curves of plotted empirical data. For the examples of these curves please refer to Appendix B. An example equation for RSI that applies to many of the fuel types is shown below. For the equations and details for the remaining fuel types refer to Forestry Canada Fire Danger Group, 1992.

C-1 to C-7, M-3, M-4, S-1 to S-3 and D-1 fuel types

$$RSI = a \times \left[1 - e^{(-b \times ISI)}\right]^c \tag{4}$$

The constants, a, b and c, are Rate of Spread constants and can be obtained from (Forestry Canada Fire Danger Group, 1992). The ISI parameter indicates the Initial Spread Index parameter. This variable indicates the speed that a fire will spread across a terrain with no regard for fuel type.

Grassy fuel types use a different form of equation to calculate Initial Rate of Spread. When looking at fire spread through grasslands it becomes apparent that the degree of curing (C) is very important when determining grass fire spread rates. Curing is described as the percent of grass steams that have dried and are no longer green (Forestry Canada Fire Danger Group, 1992). To incorporate the degree of curing into a rate of spread equation the percentage of curing is turned into a curing coefficient. There was no empirical data to create this equation so Forestry Canada designed this equation to be linear where the fire has no potential to spread if the degree of curing is less than fifty percent. If this occurs CF equals zero. This is done because it is assumed that a grass stand will not burn if green grass makes up at least fifty percent of the stand (Understanding the FWI, CD). It was also desired to keep the curing coefficient values between zero and one. The graph from which this equation was derived is shown in Figure 3.1 below.

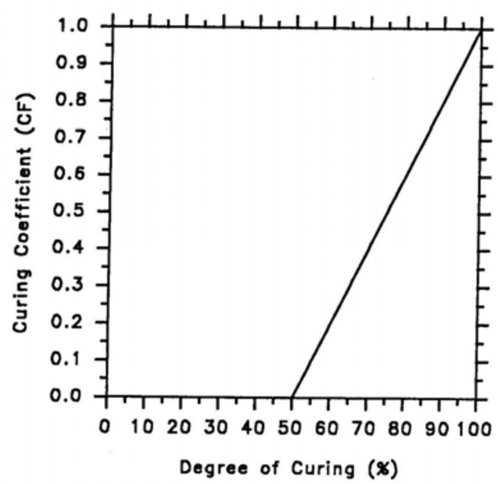

Figure 3.1: Relationship between CF and Degree of Curing for Grass Fuel Types (Van Wagner, 1987)

The equation for Curing Coefficient is shown in Equation 5.

$$CF = 0.02 \times C - 1.0 \qquad C > 50 \qquad (5)$$

CF represents the Curing Coefficient and C is the degree of curing recorded in percent.

The adjusted Final Rate of Spread equation for grass is then the Initial Rate of Spread Equation shown in Equation 4 multiplied by the Curing Coefficient. The equation is shown below,

$$ROS = a \times \left[1 - e^{(-b \times ISI)}\right]^{c} \times CF \qquad (6)$$

Where a, b and c are the rate of spread constants from (Forestry Canada Fire Danger Group, 1992). To view the rate of spread plots that were used to derive Equation 6 please refer to Appendix B. The plots for standing and matted grass have been derived from empirical data collected on grass fires in Australia (Forestry Canada Fire Danger Group, 1992).

3.1.3.4 Calculating Final Surface Rate of Spread

To calculate the Final Rate of Spread, slope must be taken into consideration. One example method of calculating slope is shown below. This equation uses elevation rise divided by horizontal ground distance.

$$GS = \frac{Elevation\_Rise}{Horizontal\_Ground\_Dis\tan ce} \times 100 \qquad (7)$$

Where, GS is the slope of the ground measured in percent.

The Spread Factor (SF) due to slope was calculated from empirical observations of fire behavior on various slopes. It describes how quickly a fire will spread depending on the degree slope of the terrain and is the next parameter that must be identified. The graph is shown below.

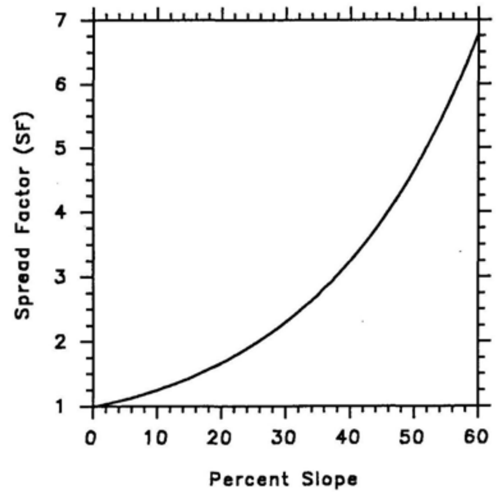

Figure 3.1: Relationship between the Spread Factor and Percent Slope (Forestry Canada Fire Danger Group 1992)

Equation 8 is the equation of the curve depicted in Figure 3.2. It can be used to compute SF as shown below.

$$SF = e^{3.533 \times \left(\frac{GS}{100}\right)^{1.2}} \tag{8}$$

Forestry Canada does not recommend that Equation 8 be used for slopes greater than sixty degrees. This is because the SF increases drastically for slopes greater than sixty degrees and, due to lack of empirical evidence, it is uncertain if Equation 8 remains true for these steep slopes (Forestry Canada Fire Danger Group, 1992).

Using Equation 9 below the Slope Adjusted Zero Wind Rate of Spread (RSF) can be computed. This equation represents the effect of slope on the rate of spread assuming that no wind is present. The SF and a variable called the Zero Wind Rate of Spread (RSZ) are used to compute the RSF parameter.

$$RSF = RSZ \times SF \tag{9}$$

Where the RSZ is calculated using a variation of the appropriate RSI equation, whose example is shown in Equation 4. The difference between the RSZ and RSI equations is that the RSZ equation uses different parameters to calculate the ISI. Instead of calculating ISI to be dependant on all parameters but fuel type the ISI is calculated to be dependant on all parameters but fuel type, wind speed and slope. This simplifies the calculations until it is more convenient to add the combined effects of wind speed and slope. The resulting RSI value is equal to the RSZ since all wind effects have been entered as zero and the RSZ is the Zero Wind Rate of Spread. The RSZ value is now entered into Equation 9 with the previously calculated SF to calculate the resulting RSF.

To include the effects of wind on rate of spread the following equations are used to calculate the Initial Spread Index (ISI) with the influence of slope but still having zero wind. The acronym for this variable is ISF. Equation 10 below will work for all fuel types except mixedwood (M-1 and M-2), and grass (O-1) (Forestry Canada Fire Danger Group, 1992). The remaining equations are slight variations of Equation 10 below. For those equations refer to Forestry Canada Fire Danger Group, 1992. In Equation 10 a, b, and c are the rate of spread constants from Forestry Canada Fire Danger Group, 1992.

$$ISF = \frac{\ln\left[1-\left(\frac{RSF}{a}\right)^{\frac{1}{c}}\right]}{-b} \tag{10}$$

The ISF value can now be plugged into the Wind Speed Equivalent equation (WSE), shown in Equation 11 below. The Wind Speed Equivalent value represents the effect that the terrain’s slope will have on a fire’s rate of spread if it were a wind speed.

$$WSE = \frac{\ln\left[\frac{ISF}{0.208\times f(FFM)}\right]}{0.05039} \tag{11}$$

The *f(FFM)* function is the Fine Fuel Moisture Function which is derived from empirical evidence of how fine fuels absorb and release moisture. It is dependant on the FFMC value discussed earlier. Details about this parameter can be found in Van Wagner, 1987.

Now, the Wind Speed Equivalent (WSE) and the actual wind speed (WS) must be combined to attain the total effect of both parameters. Vector algebra is used to preserve both the magnitude and direction of the force of the wind.

$$WSX = [WS \times \sin(WAZ)] + [WSE \times \sin(SAZ)] \tag{12}$$

$$WSY = [WS \times \cos(WAZ)] + [WSE \times \cos(SAZ)] \tag{13}$$

$$WSV = \sqrt{WSX^2 + WSY^2} \tag{14}$$

$$RAZ = \cos^{-1}\left(\frac{WSY}{WSV}\right) \tag{15}$$

Where WSX is the magnitude of the resulting force in the x direction and WSY is the magnitude of the resulting force in the y direction. WAZ and SAZ are the Wind Azimuth Direction and Uphill Slope Azimuth Direction respectively. WSV is the Net Effective Wind Speed and RAZ is the Net Effective Wind Direction (Forestry Canada Fire Danger Group, 1992).

From this point the WSV is used for all remaining computations involving wind speed. The RAZ is used as the fire spread direction when growing fire perimeters on GIS models as discussed in the next chapter.

The Initial Spread Index value which includes the effects of wind speed can now be calculated. See Van Wagner, 1987 and Forestry Canada Fire Danger Group, 1992 for the full description of the equation. Two forms of this equation exist. The first version is used for wind speeds less than or equal to forty kilometers per hour. In the case of very intense wind speeds (values above forty kilometers per hour) an adjusted wind function parameter in the ISI equation must be used (Forestry Canada Fire Danger Group, 1992).

The next step in the Canadian fire modeling procedure is to calculate the Buildup Effect (BE). This parameter is a function of the BUI discussed earlier.

Its purpose is to give the Initial Spread Index a parameter that accounts for the fuel available for combustion that is not as variable and dependant on fuel moisture as the BUI. The BE has been developed to equal zero when the BUI equals zero and levels off at extreme BUI values. This inverse relationship is accomplished by subtracting the average BUI, BUI_0, from the inverse of the calculated BUI for that fuel type. A value, q, was also introduced to help determine the value of the BE. The value of q will increase or decrease depending on how the increasing depth in the forest floor of each fuel type will influence a fire's rate of spread. The value q represents the proportion of the maximum possible spread rate, without regard for the ISI, determined from a standard BUI value of fifty (Forestry Canada Fire Danger Group, 1992). This constant of fifty was chosen because it was the average BUI calculated for all fires contained within the CFFDRS database. The resulting equation for BE is shown below,

$$BE = e^{\left[50 \times \ln(q) \times \left(\frac{1}{BUI} - \frac{1}{BUI_0}\right)\right]} \tag{16}$$

The BUI_0 and q values are constants and can be obtained from Forestry Canada Fire Danger Group, 1992.

The BE can now be used with the RSI (whose example calculation is shown in Equation 4) to determine the Final Rate of Spread, ROS, measured in meters per minute.

$$ROS = RSI \times BE \tag{17}$$

Equation 17 will not work for the conifer plantation fuel type. Additional information is needed to determine the Final Rate of Spread for this parameter. Reasons for this and the Rate of Spread calculations for the C-6 fuel type will be discussed after the calculations for Crown Fire Rate of Spread.

3.1.3.5 Calculating Crown Fire Rate of Spread

For all coniferous forest fuel types, crown fuel involvement can be quite influential on Fire Intensity and Rate of Spread. To identify when an initial surface fire will gain enough intensity to involve the tree crowns, the Critical Surface Fire Intensity (CSI) equation must be calculated. This equation depends on Crown Base Height (CBH) and the Foliar Moisture Content (FMC).

Calculating Foliar Moisture Content

The Foliar Moisture Content (FMC) describes the amount of moisture content in needles of conifers that are at least one year old. It is an important parameter for coniferous forests because it affects the initiation of crowning and the rate of crown fire spread (Forestry Canada Fire Danger Group, 1992). This parameter varies with location and time of year. The FMC can be calculated in two different ways depending on what initial information is available. Both methods have been derived based on six years of empirical data. One method is used if only latitude and longitude information on the site is available. The second method is used if information on latitude, longitude and elevation of the site are available. For these equations refer to Forestry Canada Fire Danger Group, 1992.

Once the FMC has been determined it can be used in the Critical Surface Fire Intensity (CSI) equation shown below.

$$CSI = 0.001 \times CBH^{1.5} \times (460 + 25.9 \times FMC)^{1.5} \tag{18}$$

The Crown Base Height, CBH, is previously calculated from empirical data and is used as a constant. The values for the CBH for each fuel type can be found in Forestry Canada Fire Danger Group, 1992.

The CSI is used to determine the Critical Surface Fire Spread Rate (RSO). If the Rate of Spread, ROS, is larger than the Critical Surface Fire Spread Rate, RSO, the tree crowns will become involved in the fire and the ROS value must be adjusted to account for this. If the surface fire Rate of Spread exceeds the Critical Surface Fire Spread Rate by ten meters per minute it is assumed that the tree crowns are at least ninety percent involved in the fire (Forestry Canada Fire Danger Group, 1992). This equation is derived from Byram's Fire Intensity Equation shown in Equation 2.

$$RSO = \frac{CSI}{300 \times SFC} \tag{19}$$

If the ROS computed in Equation 19 exceeds the RSO and crown involvement is assumed, the crown fraction burned (CFB) can be computed using the following equation,

$$CFB = 1 - e^{-0.23 \times (ROS - RSO)} \tag{20}$$

3.1.3.6 Rate of Spread for Coniferous Plantations

The Final Rate of Spread for the coniferous plantation is treated differently from any other fuel type because these plantations tend to be more uniform than most natural forest stands and therefore have a different influence on fire behavior. Because of their structure, this fuel type is more easily modeled when separated into surface and crown fire rates of spread. One of the parameters needed to compute the Rate of Spread for the C-6 fuel type is different than the parameters used for the other fuel types and will be discussed here. This parameter is called the Foliar Moisture Effect (FME). It is an adjusted version of the FMC that accounts for the increased spacing between the trees of the coniferous plantation fuel type. This increased spacing allows for more oxygen to access the fire and aids more complete combustion and higher fire intensities. It is assumed that the oxygen supply is doubled in C-6 stands (Forestry Canada Fire Danger Group, 1992). The FME equation is found in Forestry Canada Fire Danger Group, 1992.

And the Crown Fire Spread Rate is,

$$RSC = 60 \times \left(1 - e^{-0.0497 \times ISI}\right)^{1.0} \times \frac{FME}{FME_{avg}} \tag{21}$$

Where the average FME (FME_{avg}) is equal to 0.778 and is chosen by empirical methods (Forestry Canada Fire Danger Group, 1992).

Now, using the RSI from example Equation 4 and the BE from Equation 16 the Surface Fire Spread Rate is,

$$RSS = RSI \times BE \tag{22}$$

The equation for the Final Rate of Spread in a coniferous plantation fuel type is shown in Equation 23.

$$ROS = RSS + CFB \times (RSC - RSS) \tag{23}$$

Where

RSS	is the Surfaced Fire Spread Rate in m/min
CFB	is the Crown Fraction Burned
RSC	is the Crown Fire Spread Rate in m/min

3.1.3.7 Calculation of Fire Intensity

To calculate Fire Intensity the Total Fuel Consumption (TFC) must be computed first. The equation to compute Total Fuel Consumption is comprised of variables for the Surface Fuel Consumption (SFC) and the Crown Fuel Consumption (CFC). The Surface Fuel Consumption equation has already been described in example Equation 3. The Crown Fuel Consumption Equation can be computed by multiplying the Crown Fuel Load (CFL) by the Crown Fraction Burned (CFB).

$$CFC = CFL \times CFB \tag{24}$$

Where CFL a constant found in Forestry Canada Fire Danger Group, 1992.

The Total Fuel Consumption is the result of a simple addition between the Crown Fuel Consumption and the Surface Fuel Consumption.

$$TFC = SFC + CFC \tag{25}$$

Finally, Fire Intensity can be calculated using the variation of Byram's Fire Intensity Equation from Equation 2.

$$FI = 18000 \times TFC \times ROS$$

TFC is the Surface Fuel Consumption (SFC) in the case of the S, D and O class fuel types or the TFC in the case of coniferous forest fuel types. The Fire Intensity is calculated in units of kW/m.

There are many steps that are employed to calculate the final Rate of Spread and Fire Intensity of a wildfire. This process is very tedious but very necessary when trying to predict wildfire propagation. Regardless of the mathematical model used, there are three reasons why the results of the mathematical model may not parallel what is observed in reality (Urban-Wild Land Interface Fire: The I-Zone Series). These reasons include:

1. Model not applicable to the fire scenario
2. Model has errors inherent in its design
3. Data used in the model is either too generalized, not accurate or out of date

Many fire modeling software programs have been developed in Canada and the United States. Most Canadian models use equations from the CFFDRS just described; however, there are some other sets of equations such as Rothermel's equations which are used for many American models. Different models use different methods for displaying their information and use different parameters depending upon the country or specific site they were developed for. Some of the techniques used to design these models and an overview of the more popular models will be discussed next.

3.2 Background to Existing Fire Prediction Models

3.2.1 Spatial vs. Non-spatial Models

In the realm of fire propagation models there are two categories that models can be placed in regarding the way that they display their results: spatial models and non-spatial models. Spatial models allow the user to see a pictorial representation of how the fire is propagating through the terrain. Non-spatial models do not give pictorial representations but rather display the fire propagation information in the form of graphs and charts.

Each model has a number of advantages and disadvantages. Non-spatial models are easier to develop and require less sophisticated computer hardware to display the results. They are however, less intuitive and more cumbersome to use because they require the interpretation of numerical values. Spatial models on the other hand require less interpretation and the user can visualize the predicted fire propagation patterns on the computer screen in the form of an image. The drawback of spatial models is that they require more computer memory and are more difficult to develop. In addition to the mathematical equations used to calculate a fire's rate of spread and intensity, a spatial model requires a method of representing how these parameters can be accurately displayed on the computer screen. There are two different base techniques that can be employed to do this when designing spatial models. The two techniques are The Cellular (Point) Propagation Technique and The Wave (Vector, Curve) Propagation Technique (Tymstra, 1999). These techniques will be discussed in the next sections.

3.2.2 Fire Propagation Techniques for Spatial Models

3.2.2.1 The Cellular Technique

The Cellular or Point Propagation Technique is a common method used in fire growth models (Tymstra, 1999). This technique uses raster grids of regular cells both as data input layers and as the template for propagating the fire. If a cell is determined to be a “fire” cell, then, the fire from that cell is able to propagate to any of the eight neighboring cells in the next iteration. Successive fire predictions are then performed on the neighboring cell that has the soonest arrival time.

There are two major drawbacks associated with the Cellular Propagation Technique. The first is that fires in reality do not naturally propagate in patterns of regular grids. Because of this regular gird and restricted possible fire spread direction, the predicted size and shape of fires are often unrealistic when using the Cellular Model (Finney, 1998). The second drawback is that this model struggles when neighboring cells are not homogeneous. When encountering cells with different wind speeds, wind directions or fuel types the accuracy of the model diminishes (Finney, 1998). The Wave Propagation Technique attempts to resolve these inefficiencies.

3.2.2.2 The Wave Technique

The concept of Wave Propagation was initially developed by Dutch mathematician, Christian Huygens in 1678 to explain the behavior of traveling light waves (Finney, 1997). In 1975 Gywn Richards from Brandon University adopted this principle to describe fire growth behavior (Urban-Wild Land Interface Fire: The I-Zone Series). He analytically derived a differential equation that determines a fire’s propagation from a single point. This theory is actualized in fire modeling by defining a fire ignition point or perimeter using a vertex or vertices. Each vertex is given x and y coordinates. Expansion of the fire perimeter is then determined by calculating the Rate of Spread (ROS) and zero-wind-slope direction vector (RSF) using the equations discussed in the previous section. Time is introduced into the model by multiplying the Rate of Spread by a chosen time-step. Since the ROS equation is only useful for the head fire spread rate, a fire shape must be introduced to determine the spread rate in the directions other than exactly perpendicular to the fire perimeter. Ellipses are the most common and widely accepted shape used when trying to mimic a fire's spread. However, ellipses are not the only relevant shapes as shown by the research done by Byram in 1959 on fan shapes (Finney, 1998) and by Richards in 1990 on lemniscate shapes (Finney, 1998). For the purposes of this research only the most common shape, the ellipse, will be discussed. To spread the fire from each vertex along the fire perimeter an ellipse is drawn in an orientation coincident with the no-wind-slope direction vector. The vertex is often situated on the rear end of the semi major axis as shown in diagram A of Figure 3.3. In the case of no-wind, a circle is drawn with the vertex located at the center of the circle. The ratio between the semi minor and semi major axis of the ellipse is dependant on the fire behavior parameters of that vertex. As each time step is completed the fire polygon will enlarge, the number of vertices will increase and new ellipses will be computed for the subsequent iterations (Finney, 1998).

The new fire perimeter is then determined by adding new vertices at the head of each ellipse and joining the vertices together by a line. This is the method shown in Figure 3.3, Diagram B. The second method uses the boundaries of the ellipses as the new fire perimeters. If the ellipses calculated for two neighboring vertices overlap, the overlapping boarders are dissolved and the resulting irregular shape takes the place of the two ellipses. New vertices are then created along the new perimeter and the process is repeated for the next time step. This process is performed for all ellipses around the fire perimeter.

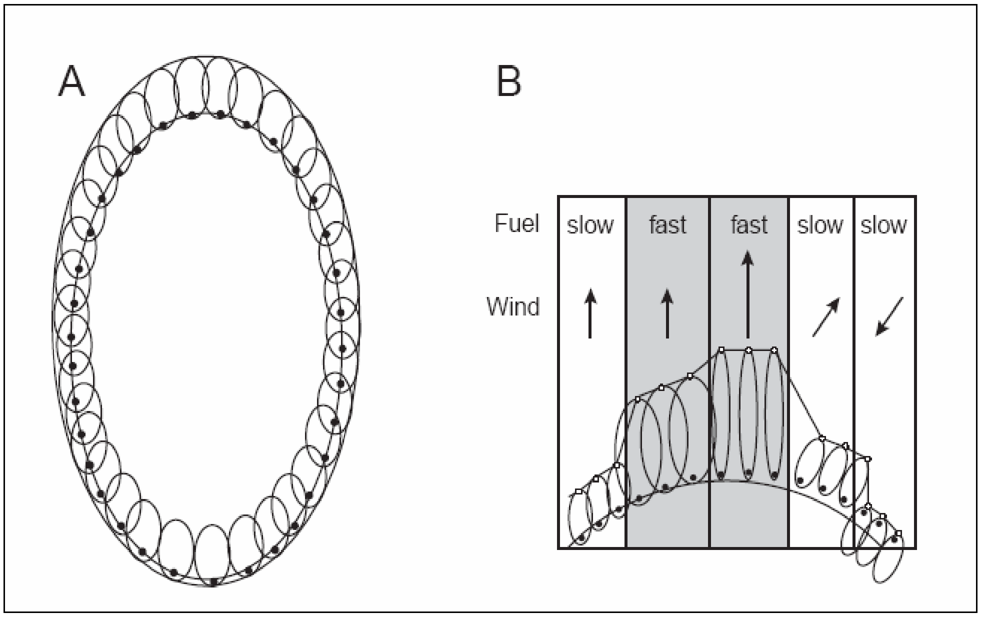

Figure 3.2: Diagrams of the Elliptical Fire Growth Technique (Finney, 1998)

Diagram A in Figure 3.3 above depicts the elliptical fire spread under uniform conditions. There is a small constant effective wind in this diagram, which accounts for the slightly elongated ellipse. Diagram B depicts the elliptical fire spread under non-uniform conditions of both fuel type and effective wind speed. From this diagram it can be seen how the fire perimeter can become irregular.

The Wave Propagation Technique avoids some of the problems encountered when using the Cellular Propagation Technique. Problems such as geometric distortion, under estimation of size and incorrect location of fire perimeters are reduced with the use of this second model (Finney, 1998). This model also has faster computational speeds. The drawback of this technique is that the coding is more in depth.

Now that the basic elements of fire propagation models have been discussed this chapter will delve into analyzing the positives and negatives of the different fire propagation models that are currently available. The section below does not give a complete list of all the possible fire models but rather discusses the models that are most commonly utilized within Canada and the United States.

3.3 Evaluation of Existing Fire Propagation Models

The purpose of investigating existing fire models is to determine what features should be included in a new model that will be implemented on an Internet based wildfire management and modeling site. Six models will be investigated in this section.

3.3.1 BehavePlus Version 2.0

The first model that will be discussed is called BehavePlus which replaces its prior edition named BEHAVE. BEHAVE was developed in the early 1980's by the U.S. Forest Service (Grabner, 1999). This model is a non-spatial model whose output is displayed through the use of graphs, charts and simple diagrams. The system was designed to be both a fire modeling tool and a learning guide for new fire management trainees. BehavePlus and accompanying tutorials are available for download, free of charge, at: http://fire.org.

BehavePlus has many abilities as a fire modeling tool. A basic, but very important, ability is that it is able to run on most IBM compatible machines. As for its modeling abilities, it uses wind speed and direction, percent slope, fuel moisture content and fuel model number as input variables. The first three parameters are self explanatory however, the last parameter, the fuel model number, describes the fuel type used by the surface fire spread model. The fuel model number is the American version of the sixteen standard fuel types that Canadians use. BehavePlus has thirteen different fuel models that can be used to approximate the vegetation type of a particular landscape. All input variables are used in equations outlined by Rothermel's Model described earlier. (As each fire model is explored in this section it will become increasingly apparent that many models use the algorithms proposed by Rothermel.) Using these input parameters and the Rothermel model, BehavePlus is able to output the following parameters (Hunter, 2004):

- Surface fire rate-of-spread and intensity
- Heat per unit area
- Safety zone size
- Size of a point source fire
- Fire containment
- Spotting distance
- Crown scorch height
- Tree mortality

Despite the abundance of information this model provides, there are a number of limitations that hinder its success. The first is that this model is capable of modeling only surface fires. Fires of a larger intensity, such as crown fires, cannot be modeled using this program. The second limitation is that the fuel type is assumed to be continuous, uniform, homogeneous and contiguous to the surface. This means that variations in the ground cover are not taken into consideration. The third limitation is that the conditions of the fire environment are assumed to be constant. This includes slope, aspect and weather parameters which are simplified into uniform constants. Simplifying these three parameters could greatly affect the results of the model. The wind condition would be especially affected since wind speed and direction can change so rapidly and have such a large effect on fire behavior. The fourth and final limitation is that the model does not have spatial capabilities so the output parameters must be interpreted from various tables. This is perhaps the most important limitation since it is very difficult to relate a numerical value of rate of spread to actual area covered on the ground on all sides of the fire front.

3.3.2 FireLib

FireLib is derived directly from the model Behave and, like Behave, this model is capable of evaluating the spread rate and intensity of wildfires. Improving on Behave, FireLib performs all the same functionalities as Behave but also provides spatial data results. This model is written in ANSI standard C computer code and uses the Rothermel model to calculate fire behavior (Bevins, 1996). In addition, when calculating its visual output depicting fire spread it uses the Wave Propagation Technique to display the fire propagation patterns on the screen. FireLib is available free of charge from www.montana.com/sem. The site also offers the source code and the user manual for the program.

There are four inputs that are needed for this model to run properly. They include fuel model number, moisture content and effective wind speed and direction.

Since FireLib was derived from Behave the two modeling programs have all the same capabilities and limitations. The only difference is that FireLib goes one step beyond the capabilities of Behave and can give a spatial diagram of how the fire will spread through the landscape.

3.3.3 EMBYR: Ecological Model for Burning the Yellowstone Region

This model is a less popular model developed by Robert Gardner at the University of Maryland to help model the forest fires that plague Yellowstone National Park in Wyoming USA (Hargrove, 2000). Its focus was to create a tool that could evaluate the risk of the fire spreading through areas in the park. Although this model is site specific it can be used in other landscapes if additional fuel type parameters for the different landscapes are created (Hargrove, 2000). The documentation, source code, executables and example simulations are available over the Internet at the following site: http://www.al.umces.edu/faculty/bobgardner.html.

There are four non-standard pieces of software that are needed to run EMBYR. They are:

1. Unix/LINUX environment

2. XPM extension installed into X windows
3. C compiler
4. FORTRAN compiler

The mandatory parameters that are used as input into the EMBYR system are coordinates of ignited areas, fuel type and locations of each fuel type, fuel moisture, wind speed, wind direction and height of wind speed measurement. Like the previous two models EMBYR has spatial modeling capabilities. Some of the advantages of the EMBYR model are:

- Accepts and produces data files compatible with a variety of GIS software.
- Handles the possibility of having multiple fuel types in one cell.
- Outputs parameters such as:
    - Four gradients of potential to burn (i.e., not likely to burn - very likely to burn
    - Burned areas
    - Burning areas.
- Includes the probability for spotting to occur.

In addition to EMBYR's advantages it does possess three major limitations. Since EMBYR is only able to execute in UNIX/LINUX environments many potential users may not be able to run this program. The second limitation is that this system employs the Cellular Propagation Technique to display fire spread, which has some inherent disadvantages that have been discussed earlier. The third limitation is that the model is only capable of fifty meter cell resolution. This limits the model to being able to predict only the future spread of larger fires.

3.3.4 Farsite (Fire Area Simulator)

Farsite is a vector propagation fire growth model that is currently the fire growth model of choice in the United States. Running on a Windows platform, this model is a newer model than BehavePlus and was developed by Mark

Finney in 1995 with support from Systems for Environmental Management and the USDA Forest Service (Finney, 1997). Copies of Farsite can be downloaded free of charge from the Internet site http://www.farsite.net. Also available at this site are files containing tutorials, help files, user guides and reference guides. Like the first two models discussed in this chapter, this system uses the well known Rothermel model to determine the local maximum fire spread rate from a point as a function of the input parameters (Fujioka, 2001). The six parameters that are used as input into the Farsite model are shown below. The first five parameters should be in the form of raster maps (Finney, 1997):

1. Fuel model
2. Canopy cover
3. Elevation
4. Slope
5. Aspect
6. Weather information

Additional parameters are necessary if modeling crown fires. These additional parameters are tree height, height-to-live crown base and canopy bulk density (Urban-Wild Land Interface Fire: The I-Zone). If any of the parameters are not known the model has default layers that can be used instead of the more ideal application specific data. If any default layers are used the reliability of the system is decreased.

The Farsite model has a number of abilities. Some of the model's abilities are listed below:

- Spatial modeling capabilities (Output can be numerical, graphical or pictorial)
- Spatial database capabilities of a GIS
- Spotting and crowning included in the model
- Huygen's principle of Wave Propagation for simulating the growth of a fire front (Finney, 1997; Finney, 1998)

- Automated, fast
- General weather logged on a daily basis
    - Maximum and minimum temperature
    - Relative humidity
    - Recorded precipitation
    - Wind speed and direction are usually logged on an hourly basis for more accurate results

Despite all the abilities of this model it does not come without limitations. The two limitations of this model are that the fuel bed, terrain and weather parameters are assumed to be homogeneous and the interface for the system is not user friendly.

3.3.5 FIRE!

FIRE! is one of the more sophisticated fire models available today. This model successfully links fire behavior modeling into the ArcInfo GIS environment (Weinstein, 1995). FIRE! also has spatial modeling capabilities where one can see the detailed fire simulation propagate through the landscape on the computer screen. Although this model is the property of the popular GIS company, “ESRI”, the computation engine of the model is actually Farsite. Farsite interacts seamlessly within the ArcInfo environment and the combination of the two programs (ArcInfo and Farsite) result in a very advanced fire modeling GIS system. To acquire the model, FIRE! must be purchased from ESRI and added to the Arc Tool Box in ArcInfo.

This model was developed to improve on two crippling limitations that most previously developed fire models possessed (Weinstein, 1995).

1. Non-spatial capabilities
2. Raster based systems that limited the accuracy and functionality of the visual displays

This model again uses Rothermel's algorithms to do its propagation predictions. It also uses the Wave Propagation Technique to display the fire's growth on the screen.

There is some preliminary information that needs to be collected before the model can be run. The necessary preliminary information is shown below (Weinstein, 1995):

- Satellite imagery corrected to UTM coordinates
- Thermal Photogrammetric imagery corrected to UTM coordinates
- ArcInfo GIS coverages representing past and present land-use and land-cover characteristics (used in the calibration of the model).
    - Fuel layer (from land use map)
    - Canopy density layer
    - Slope layer (from DTM)
    - Elevation layer (from DTM)
    - Aspect layer (from DTM)
- Field data (used as training sites for image classification and model calibration)

FIRE! provides a spatial map delineating the propagation of the fire, plus, additional information located in image attribute tables. These additional output parameters are shown below:

- Fire's perimeter at user-specified time intervals
- Flame length
- Fire-line intensity
- Time of arrival
- Heat per unit area
- Rate of spread for every pixel within the burned perimeter

There are a number of advantages to be gained when using FIRE! over other wildfire modeling programs. One advantage is that FIRE! enables Farsite to work seamlessly within the ArcInfo environment. Because of this FIRE! has all of the advantages of Farsite plus the additional advantages gained by using ArcInfo as a platform for the model. Another advantage is that FIRE! has vector capabilities instead of the more limiting raster capabilities and it is capable of utilizing satellite or airborne images as background maps.

Despite all of its advantages this model is not without limitations. The torching and spotting algorithms are reported to be not very reliable (Weinstein, 1995) and the model cannot perform real time updates for developing wind and weather patterns. In addition, this model does not permit methods for performing interactive simulations of containment efforts by allowing the user to create fire-lines and backfires during a burn. It must also be calibrated for every study area.

3.3.6 NFDRS (National Fire Danger Rating System)

NFDRS was developed in 1972 by the United States Government to establish the probability of fire outbreak (Wearth, 2004). It is not a site specific prediction system like the ones previously discussed, but rather fire probability prediction model for the United States. NFDRS is a compilation of different computer programs and algorithms put together by a number of cooperating companies to create a national fire danger rating system. The basic mathematical model that this system uses is Rothermel's mathematical fire propagation model (Urban-Wild Land Interface Fire: The I-Zone). NFDRS calculates worst case fire scenarios using mid-day weather inputs and idealized fuel characterizations over typical areas of 10,000 acres and larger (Wearth, 2004). The results of this program can be viewed over the Internet from the following Internet site: http://www.seawfo.noaa.gov/fire/olm/nfdrs.htm

Some of the advantages of this fire propagation modeling system are:

1. Accounts for area encompassed by the United States
2. Uses Huygen's principle of wave propagation for simulating the growth of a fire front.

The main limitation of the NFDRS system is that the resolution of the system is very coarse. The resolution of NFDRS is 1km square, (Wearth, 2004). This prevents it form being useful in precise fire behavior predictions. It also means that only large fires are visible on the maps.

3.4 Optimal Model Features

There are a number of features that optimize the functionality of a wildfire model. Such features include spatial modeling capabilities and using Huygen's principle of Wave Propagation for simulating the growth of a fire front. For models used in Canada it is important to implement the algorithms of the CFFDRS. The model must also be user-friendly and applicable for a wide range of areas. Resolution is also an important factor and it would be beneficial to have the flexibility to change the resolution of the model depending on the input data that is available.

There are some improvements that could be made to any of the models previously discussed to greatly benefit their functionality. The first improvement is that high-resolution images could be added to a spatial model's map background. Instead of using land use maps as background images one could use thermal or RGB images. The thermal images would be a beneficial edition since the locations of the hot spots are easier to identify (Wright and El-Sheimy, 2003). Another addition is that the fire models could be Internet accessible. This would allow fire predictions to be made in the field. Data regarding people and resources could also be connected to the model. This would enable information on the number and location of trucks, planes and fire fighters to be easily estimated for fast handling of resources. It would also be beneficial to attach images of the surrounding lakes and rivers so that fire managers can plan the shortest route to appropriate water resources. The last improvement is to adjust the zooming tool so that subsequent zoom-in's result in more detailed images on the screen.

3.5 Summary

This chapter has investigated methodologies used in Canada for predicting fire behavior. It has also looked at six of the most popular wildfire models available in Canada and the United States today. The abilities and limitations of each model were discussed and some recommendations have been listed that could improve their functionality.

The following chapter will describe the development of a new Canadian fire model that strives to improve upon some of the weaknesses of the models already discussed.

Chapter 4: Building a Fire Model

A new fire model has been created with the intent to include it as the fire modeling program on the Internet based wildfire management and modeling system discussed in the Chapter 5. After the release of the Prometheus fire growth model by Alberta Sustainable Resource Development it was decided to refrain from using the new CWSPM and instead to implement the Prometheus model into the system. Despite this, the development of the new CWSPM was completed and its focus shifted from becoming the Internet wildfire modeling tool to becoming a quick, easy to use fire model that fire managers can use to get an estimate of fire spread probabilities. Prometheus differs from this model since it provides fire perimeter predictions and not fire spread probabilities.

The software that was chosen to create the model is called Idrisi. Idrisi is a raster based GIS software program that allows the user to build an automated model that permits frequent changes to the input parameters without having to make any changes to the model itself. ArcGIS software was also investigated to determine its usefulness in the development of this model but was not chosen due to the author's astute knowledge of Idrisi and the ideal raster modeling capabilities that the software possessed.

4.1 Input Data

The data used to develop the CWSPM is from the Dogrib Fire incident that took place between the dates of September 25th and October 21st, 2001. This fire was located near Nordegg in central Alberta, Canada and burnt an approximate area of 9898 hectares (Prometheus Help files). The majority of burning happened on October 15th when heavy winds (up to forty kilometers per hour) sent the fire burning at an average speed of thirty kilometers per hour. These high wind speeds produced a fire run which burnt 9070 hectares in only 13.5 hours. This accounted for almost ninety-two percent of the total burned area.

The information that will be used to develop the CWSPM includes,

- An ASCII grid of the Digital Elevations for the test area
- An ASCII grid representing the fuel types in the test area (distinguishing the locations and types of both the vegetative and non-vegetative features)
- A text file linking the numbers given to the fuel types in the ASCII Fuel Type file to the actual names of the different feature types
- A file indicating the projections of the images
- Hourly weather information updates for the fire site

The methodology used to design this model included creating a set of weighted values for the parameters that influence a wildfire's behavior. These weights are then combined to produce an image indicating the most probable path that a fire would take through the landscape. The CWSPM takes a simpler approach than the extensive equations used to develop the Prometheus model. The most prominent disadvantage found in the development of the CWSPM is that it does not have a temporal component.

4.2 Developing the Model

The ASCII DEM, ASCII Fuel Type and corresponding projection file were available for download off of the Prometheus website. Both the DEM and Fuel Type files contained header information stating the number of rows and columns in the data grids. To import these files into Idrisi and use them as raster images the header information had to be deleted, leaving the file with only the pixel values for the image. The projection and extents information, found in the header information and projection file had to be entered as image parameters.

Once all appropriate information had been obtained the DEM and Fuel Type files were converted from ASCII text files to raster images and loaded into Idrisi. A screen shot of the resulting DEM raster map is shown in Figure 4.1 below.

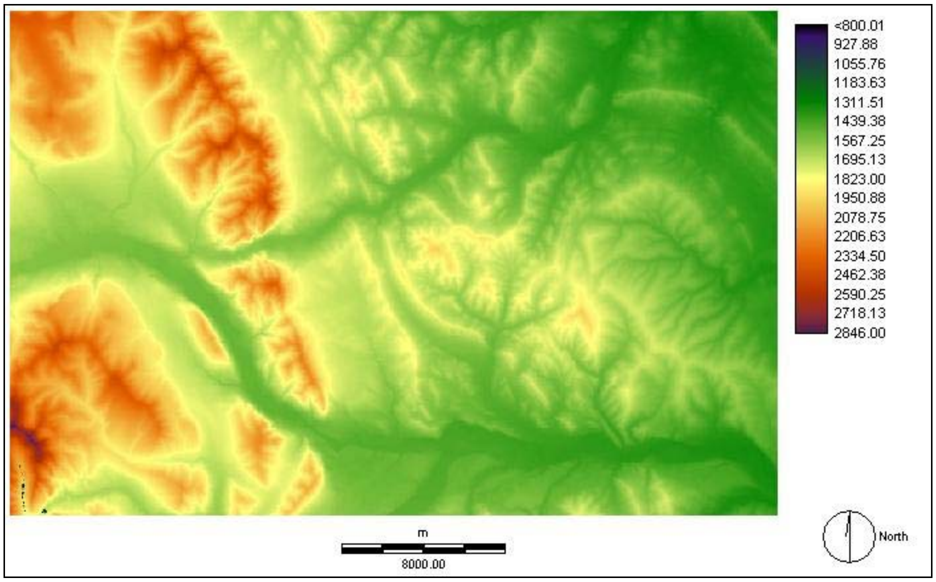

Figure 3.1: DEM for the Dogrib Fire Area

This test area is located on the eastern slopes of the Canadian Rockies, which can be identified on the left hand side of the image. There are also two main river valleys that cut through the site in an approximate east/west direction.

To use the information contained in the DEM image for forest fire modeling, Idrisi's SURFACE function was employed to compute two separate maps from the original DEM. A slope map and an aspect map. The resulting maps are shown in Figures 4.2 and 4.3 below.

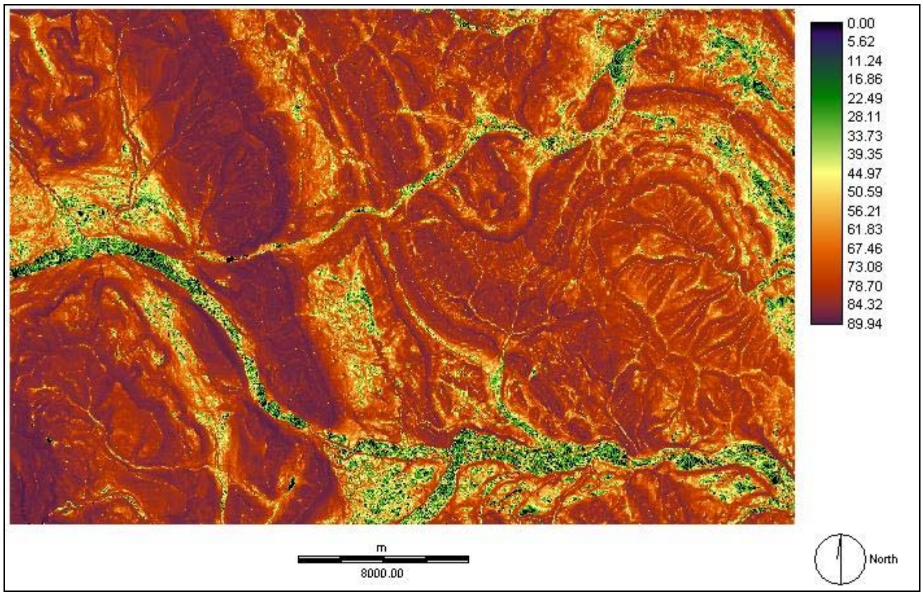

Figure 4.2: Slope Map of Dogrib Fire Area

Idrisi calculates the slope of a pixel based on the elevation of neighboring cells and the pixel resolution of the image. It is computed by calculating the resultant vector of the slope in the x and y directions (Monmonier, 1982).

The aspect map is shown in Figure 4.3 below.

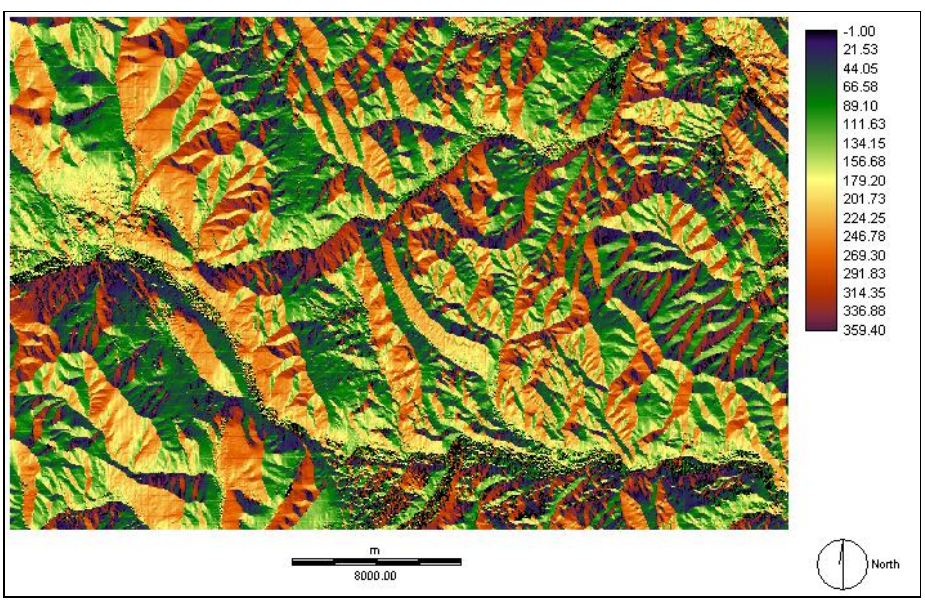

Figure 4.3: Aspect Map for the Dogrib Fire Area

From the slope map shown in Figure 4.2 above it can be seen that there are extensive variations in the terrain. These slopes will play an influential role in the way that the fire spreads through this landscape. As mentioned before, the CWSPM is based on a set of weighted parameters. Each parameter that influences fire spread is given a weight that represents how quickly or slowly a fire would spread through a cell containing only that parameter. When the model is run the different weights assigned to each parameter are combined into a final weight. In this manner the fire is accelerated or decelerated as it travels from cell to cell throughout the entire test image. This type of propagation uses the Cellular Propagation Technique to display the spread probabilities on the computer screen. In Idrisi, implementing a Wave Propagation Technique is not possible.

Turning the slope map into a weighted image requires a number of steps. First, it is known that a fire will travel upslope faster than it will travel down slope and as percent slope increases the greater the effect slope will have on rate of spread. With this fact in mind, the slope map was converted into a weighted image with the values indicating the degree of influence on fire spread. This was done using the RECLASS function in Idrisi. Table 4.1 shows the weights that the slopes were assigned.

Table 4.1: Weighting Scheme for Slope Parameters

Degree Slope (degrees)	Weight
No Data	1
0-5	1
5-20	1.5
20-40	2.2
40-60	4.4
60-90	7.0

The weight values for the slope parameters were estimated based on data from the CFFDRS (see Figure 3.2) and extensive reading and fire research (Hirsch, 1996; Hirsch, 1998; Van Wagner, 1987; Principles of Fire Behavior, 1993; Understanding the FWI, CD). Figure 3.2 in this thesis depicts the CFFDRS table that relates percent slope to the spread factor. The weights assigned to the range of slopes listed in Table 4.1 were based on the graph shown in Figure 3.2. Flat slopes were given a weight of 1.0 because they have little effect on a fires rate of spread. A fire traveling through these slopes would not experience any acceleration or deceleration due to slope. In the case of gentle slopes (zero to twenty degrees) the weight was assigned a value of 1.5. This means that it is approximately fifty percent harder for a fire to travel down a gentle slope or fifty percent easier to travel up a gentle slope. The more substantial slopes of twenty to forty percent are given a weight of 2.2 which means that these slopes are one-hundred and twenty percent as hard or easy for a fire to travel on. The steep slopes of sixty to ninety percent are given a weight of 7.0 because slopes of this steepness will have a very high influence on a fires rate of spread.

The aspect map is used to account for the direction of fire travel and the instances when the fire is traveling up or down the slopes. In Idrisi Aspect maps are created with the direction vector pointing down the slope. This is opposite to direction that fires will spread on slopes. To have this direction vector positioned in the correct direction, the values in the aspect map needed to be reversed. This was accomplished in two steps. The first step used the RECLASS function to assign,

- all aspect values between 0 and 180 to a value of 180;
- all aspect values between 180 and 360 to a value of -180;
- all aspect values between -1 and 0 to a value of zero. (This accounts for flat terrain.)

The second step used the OVERLAY function which adds the reverse image to the original aspect image to attain a reverse aspect image. A flow chart outlining the steps undergone so far in this model's development is shown in Figure 4.4 below.

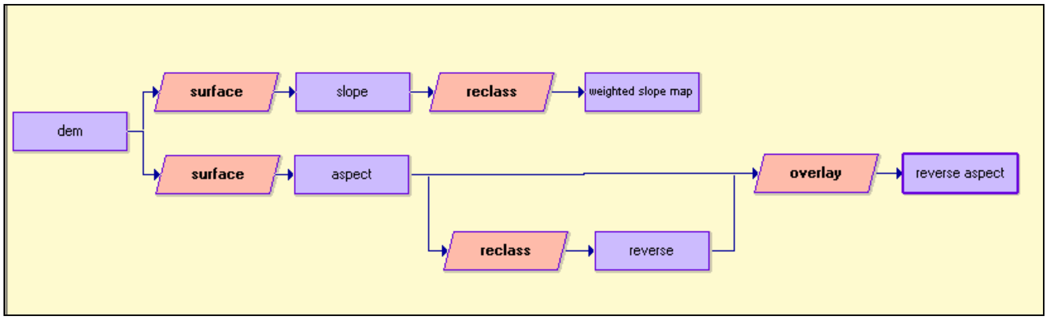

Figure 4.4: Flowchart of Slope and Aspect Map Development

The next input parameters which are included in the CWSPM are contained in the Fuel Type file. When analyzing the Fuel Type file, there were 995 different classes of feature types. Since it would be impractical to classify each of these types individually, they were grouped into twenty-five different types as listed in Table 4.2. Using Idrisi's RECLASS function, different weights were assigned to the feature types based on the speed that a fire could burn through that feature type. Again, a value of one is associated with the base spread rate. A cell with a weight equal to two will be twice as hard to burn through as a cell with a weight equal to one.

Table 4.2: Weighting Scheme for Fuel Type Parameters

Vegetation Type	Weight
No Data	1
C-1	9.0
C-2	1.6
C-3	4
C-4	1.5
C-5	14
C-6	3.4
C-7	3.8
D-1	4.1
S-1	1.25
S-2	2.0
S-3	2.2
O-1a	1

Vegetation Type	Weight
O-1b	1
M-1(5-50 pc)	2.5
M-1(50-100 pc)	1.75
M-2(5-50 pc)	2.3
M-2 (50-100pdf)	1.8
M-3 (5-50pdf)	4.5
M-3 (50-100pdf)	0.8
M-3/M-4 (5-50pdf)	8
M-3/M4 (50-100pdf)	1.7
Minor Roads	200
Lakes or Rivers	100
Barren Rock	999
Bog	5

The original Fuel Type ASCII file had the vegetation classes based on the sixteen standard fuel types outlined in the CFFDRS. The reason why the original file had so many classes was because the M class fuel types were broken down into finer classes based on the percentage of coniferous trees in the forest stand M-1 and M-2 and the percentages of dead balsam fir (pdf) in the forest stands M-3 and M-4. For the purposes of the CWSPM, these classes were broadened and grouped into only two sub classes for each M class fuel type. For the M-1 and M-2 class fuel types the two subclasses indicated forests stands that contained less than fifty percent coniferous trees (pc) and forest stands that contained at least fifty percent coniferous trees. The M-3 and M-4 fuel types were sub classed into forest stands with less than fifty percent dead balsam fir and forest stands with at least fifty percent dead balsam fir. For the M-1 and M-2 fuel types it is expected that the higher the percentage of coniferous trees, the faster the fire spreads through that area. For the M-3 and M-4 fuel types, the higher the percentage of dead Balsam fir, the faster the fire spreads through that area. The weights given to these fuel types and all others are shown in Table 4.2. The grass fuel type has the base spread rate equal to one.

Weights listed in Table 4.2 were assigned based on results computed from the FBP calculator, which is made available in the CD ROM course “Principles of Fire Behavior”, 1993. The rate of spread for the different fuel types was calculated for eleven different scenarios. Various FFMC and BUI values were used and all other values were held constant. The excel spread sheet used to record the parameters of each run is shown in Appendix C, Table C1. The spread sheet showing the rates of spread for each fuel type in each run is shown in Appendix C, Table C2. The fuel types were then ordered based on the number of times each fuel type achieved the fastest rate of spread, spread, second fastest rate of spread etc. The number of times or frequency that a fuel type ranked in each of the spread rate categories was recorded for the twenty-one different fuel type classifications for all eleven scenarios. This meant that there were twenty-one different spread rate categories. The resulting frequency values for each fuel type were then multiplied by a factor depending on their placement in the frequency table. A value of twenty-one was multiplied with the frequency that a specific fuel type would achieve the fastest rate of spread for any of the eleven runs. A value of twenty was multiplied with the frequency that a specific fuel type would achieve the second fastest rate of spread for any of the eleven runs The multiplication factor continues to decrease by one until a value of one is multiplied with the frequency that a specific fuel type would achieve the slowest rate of spread for any of the eleven runs. The resulting, weighted, frequency values for each fuel type were then summed to give one numerical value for each fuel type. The value for the grass fuel types were forced to equal one and all other values were scaled accordingly. The weights for the vegetative fuel types are shown in Table 4.2.

The non vegetative fuel types were given much higher weights than any of the vegetation classes. This is because neither roads, lakes, rivers nor barren rock are capable of supporting fire. They were not however, given the weights of complete barriers to fire spread. In Idrisi this would be a weight value of -1. Assigning high weights was done because in practice fires that possess enough intensity can jump roads and rivers and still continue burning. With the weights that are assigned to the non vegetative parameters, the CWSPM will try to mimic this behavior. For example, if an approaching fire line cell has enough momentum to burn through cells with weights equal to 100, then that fire would probably have enough intensity to be able to heat the fuels on the other side of the river bank and ignite them by intense convective heating or spotting. Barren rock was given the highest weight because this fuel type was mainly found on the mountain peaks where there is little nearby vegetation to sustain a fire.

The flow chart displaying the step undergone in Idrisi to assign the weights for the fuel types is shown below.

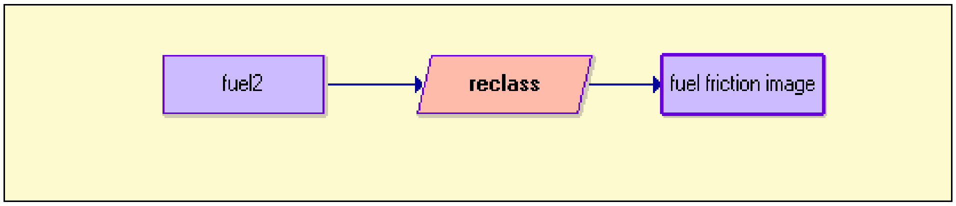

Figure 4.5: Flow Chart of Fuel Friction Image Development

The next parameters that will be discussed are the weather parameters, namely wind speed and direction. These values were obtained from the Prometheus website and were available for three different locations in the test area. The three sites and corresponding wind speeds and directions are shown on the map in Figure 4.6 below. These three weather site locations will also be used as the three ignition sites from where three test fires will be grown using the final CWSPM.

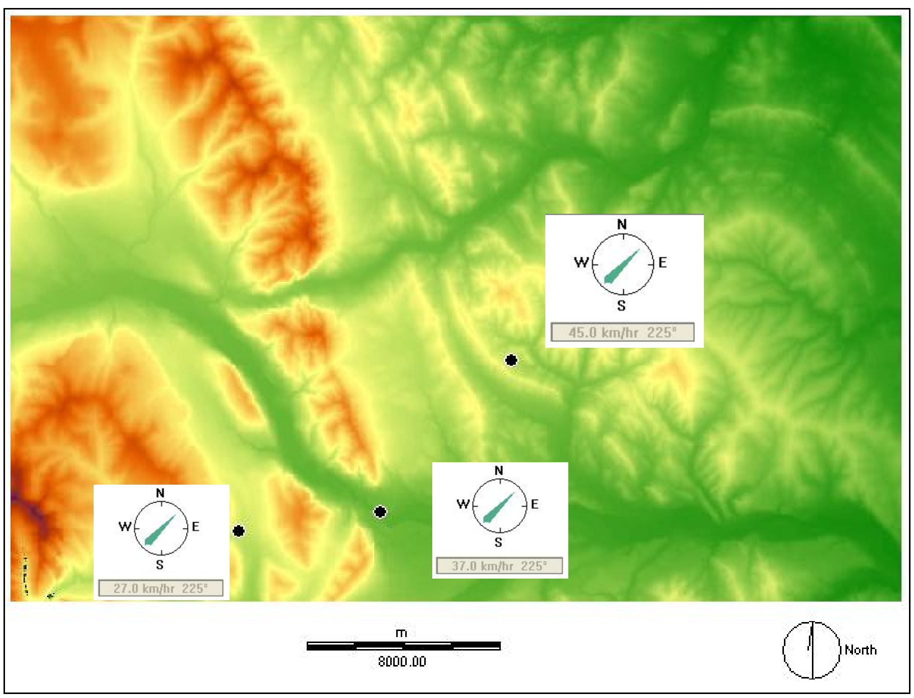

Figure 4.6: Ignition Points and Corresponding Weather Information

To model the wind speed and direction parameters, raster images were created for each ignition point. In one image every cell was given the numerical value of the wind speed. In the other image every cell value was given the numerical value of the wind direction. The creation of these two maps broke the weather information down into magnitude and direction parameters. The magnitude and directions for the wind information can be seen for the three ignition points in Figure 4.6. The weighted slope map and aspect map are also magnitude and direction maps. The slope map indicates the magnitude of force required to propagate up the slope and the aspect map indicates the direction of the slope. A function in Idrisi called RESULTANT can be used to combine the weighted slope map, the aspect map and the weather maps together to get a fire spread probability map based on the magnitude forces of the slope and wind speed maps and the direction forces of the aspect and wind direction maps. Using vector algebra on each cell to get the resulting magnitude and direction does this. All the magnitude vectors are then stored in one file and the direction vectors are stored in the other.

The flow chart for the procedures in the model that have been completed so far is shown in Figure 4.7 below.

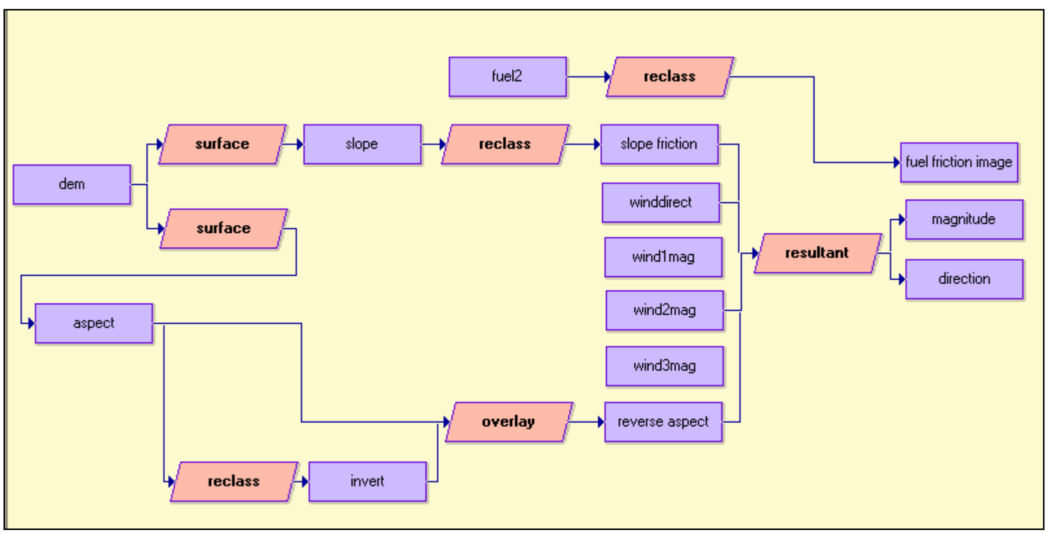

Figure 4.7: Flow Chart Showing Model Progress up to the Resultant Function

From Figure 4.7 above it can be seen that there are three different wind magnitude maps that can be used in the model and only one direction map. This is because the wind direction is the same for the three ignition points in the test area but there are three different wind speeds; one for each ignition point.

The last step in computing the CWSPM involved creating three raster images indicating the locations of the fire ignition points and combining all the data to get the predicted fire growth behavior from those three points. Using the DIGITIZE function in Idrisi, the three ignition points were digitized using on-screen digitizing and saved in three separate raster image files. The coordinates for the points were obtained from the Prometheus demo in the software's help files (Prometheus Help Files). These maps were then saved and used individually as input into Idrisi's DISPERSE function.

The DISPERSE function operates by calculating the probable direction of fire spread based on the directions which forces will act the most strongly (Eastman, 1999). It uses the Equation 98 to calculate its results.

$$Friction = stated\_friction \times \left(\frac{1}{\cos^k \alpha} \right) \tag{98}$$

In this equation α is the angle between the directions being considered for fire spread and the direction from which the frictions are acting. The variable k makes the function increasingly dependent on the direction being considered for fire spread. Using this function, friction forces will have their full effect at hindering fire spread if the fire spread direction is attempting to travel in the same direction as the friction force. As the angle between the fire's spread direction and friction force direction increases to ninety degrees, the friction force will have progressively less influence on the fire's rate of spread. At angles of ninety degrees to the direction of the friction force, the fire-spread direction will cease to be influenced by the friction force at all. At this angle, the friction will be equal to zero. From angles of ninety to one-hundred-eighty degrees the friction force will become an acceleration force and will increase from a magnitude of zero at ninety degrees to full magnitude at an angle of one-hundred-eighty degrees to the direction of the original friction force. In this manner, traveling directions at angles of one-hundred-eighty degrees to the original friction are no longer being acted on by frictions, hindering fire spread, but are instead being acted on by acceleration forces, accelerating fire spread. A k value equal to two gives the function a nearly linear dependency on direction. A k value equal to one-hundred makes the frictions forces being considered degrade less rapidly as α increases to ninety degrees. The higher the value of k, the more difficult it will be for the fire to spread in directions other than zero degrees from the direction of the acting force. For the purposes of the CWSPM that is being explained, the k value was given a value of six. A value of six was chosen because direction of fire travel plays an important roll when dealing with both slopes and wind speeds. This chosen value was the smallest value that was capable of producing fire probabilities where the influence of wind speed and direction could be visually discernable. Wind speed and direction are two factors that will always have a large influence on fire spread regardless of what direction the fire is traveling (Principles of Fire Behavior, 1993).

To perform the DISPERSE calculation a number of raster maps are needed. The raster maps that are used in the DISPERSE function include:

1. One of the three ignition source maps
2. The Force Magnitude map for the combined effects of slope and wind speed
3. The Force Direction map for the combined effects of the aspect and wind direction
4. The Fuel Friction Image map for the friction forces due to fuel type.

The flow chart indicating all the steps needed to produce a fire propagation probability map is shown in Figure 4.8 below. The spread probability map is shown as the last box on the far right end of the flow chart. This entire process is run three separate times; once for each ignition point. The flow chart below shows the set up to run the model for Ignition Point 2.

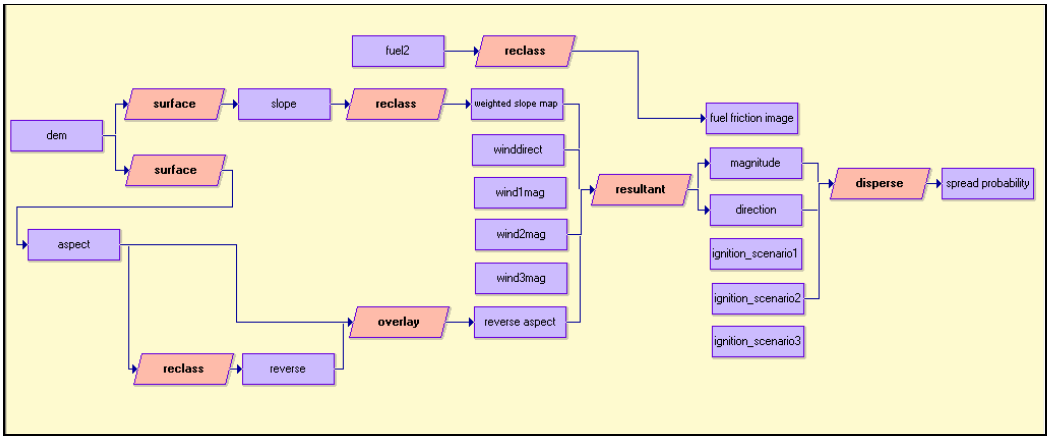

Figure 4.8: Final Flowchart Showing the Methodology of the CWSPM

4.3 Results of the CWSPM

Three different fire spread probability maps have been created from the CWSPM. To help determine their accuracy three probability predictions will be compared to an image of the actual burn perimeter, see Figure 4.9, which was obtained from the Dogrib fire incident. This image was created on October 21 after the fire had been extinguished.

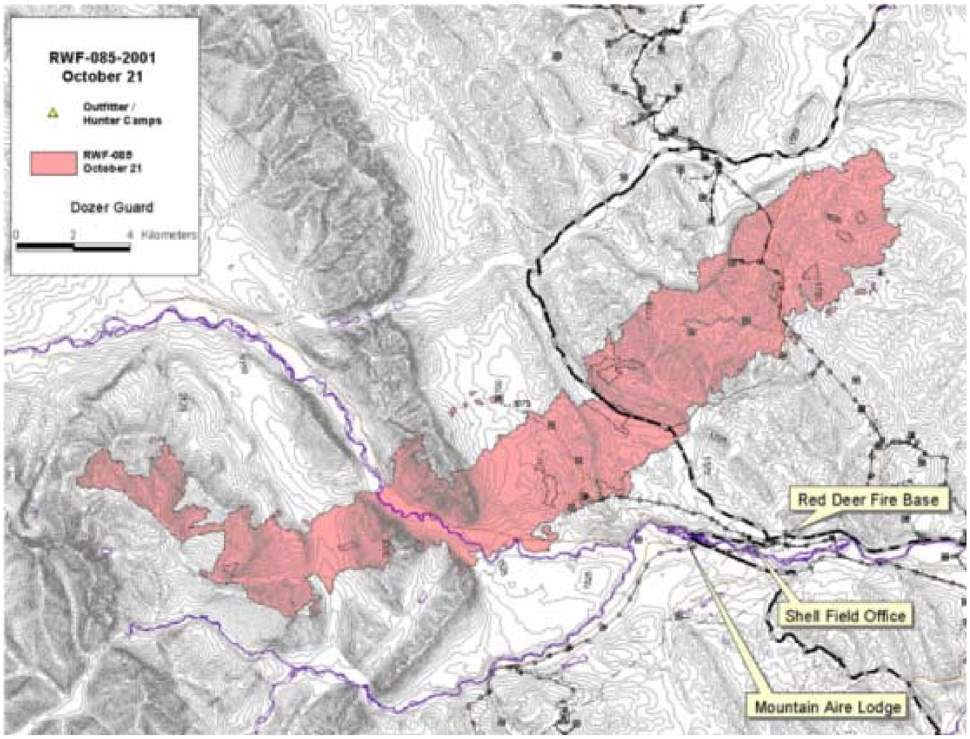

Figure 4.9: Dogrib Fire Burn Perimeter (Prometheus, 2003)

The locations of the ignition points for the three CWSPM predictions are shown in Figure 4.10 below. The area shown in both Figure 4.9 and Figure 4.10 are identical. The mountain ranges and valleys can be used to compare the two images.

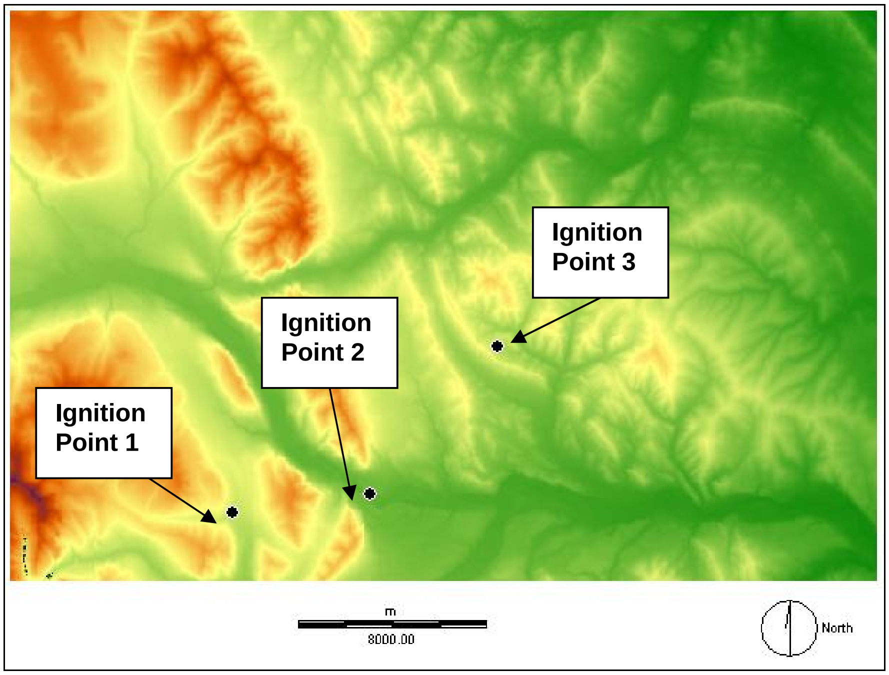

Figure 4.10: Locations of Ignition Points

Ignition Point 1 is located in a valley amidst a Spruce-Lichen Woodland, C-1 fuel type. The wind is traveling at an average speed of thirty kilometers per hour and blowing from the southwest at an angle of 225 degrees. Since no model is available to predict winds created by topography, it is anticipated that the fire will travel in the same direction as the wind and spread towards the river valley that lies to the north east of the ignition point. The result from the CWSPM for the first ignition point is shown below with the DEM map set as the background for the image.

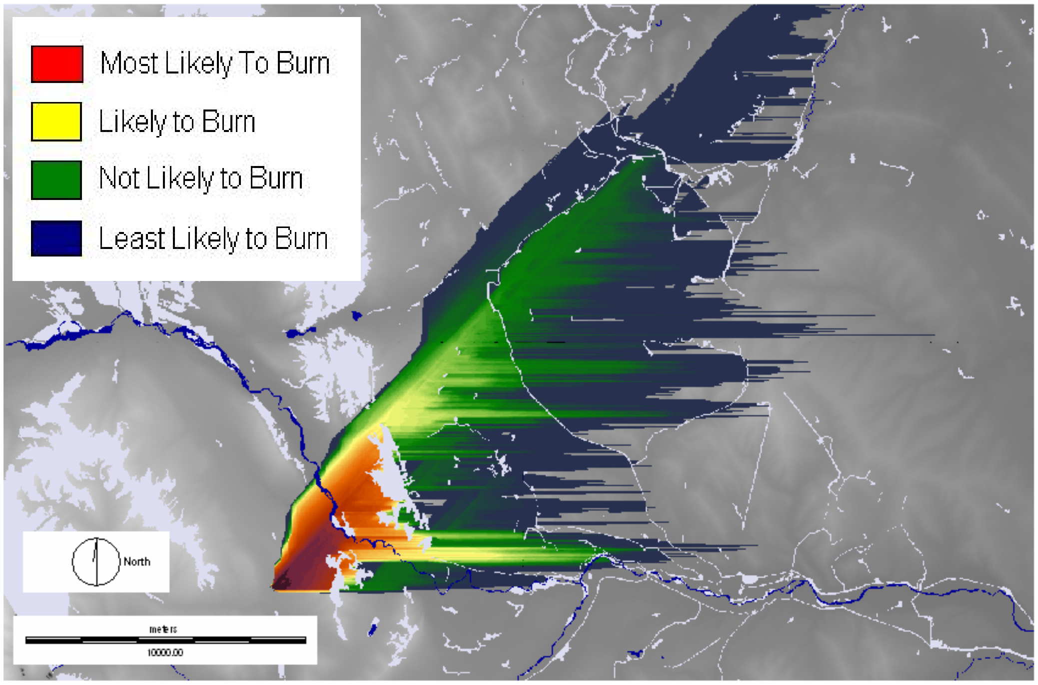

Figure 4.11: Idrisi Probability Prediction (Ignition 1)

Since a time component was not incorporated into the CWSPM, the stopping criterion for the burn prediction was based on a maximum distance. The maximum spread distance was determined by trial and error to be the distance between the ignition point and the furthest outer boarder of the test area. It was imperative that this stopping distance be entered otherwise the fire spread probabilities would have been calculated until the entire screen turned black and no gradients could be seen.

A distinguishing feature that can be seen in this image is the river that runs diagonally from the top left corner of the map down to the bottom right corner. Comparing Figure 4.9 and Figure 4.11 it can be seen that the fire perimeters meet the river at approximately the same location. The two results are not identical however and some differences are apparent when taking a closer look at the images. The CWSPM begins to differ from the actual burn perimeter image after the fire reaches the river. At this point the fire perimeter shown in Figure 4.9 displays unusual behavior. As seen in Figure 4.9, the fire bends south at the river and then bends north east and continues traveling in its expected north easterly direction. This southern shift at the river valley could be due to the winds created by the mountainous terrain. Winds funneling through the valley could have forced the fire to travel south east until it reached the gap in the mountains and could then burn across the foothills in the same direction as the wind. The CWSPM also differs from the original perimeter by displaying a definite pull in the easterly direction. The bias could be the result of distortions appearing in the spread perimeter due to the use of the Cellular Propagation Technique instead of the Wave Propagation Technique. More examples involving comparisons between the two models must be conducted before any firm conclusions can be made.

The second ignition point that will be used for comparison is located on the north east bank of the same river reached by the fire perimeter created by Ignition Point 1. This second fire test example uses a line ignition instead of a point ignition to simulate a fire that has gained intensity, jumped the river and is expanding up the far bank. Line ignitions are often used in fire behavior predictions when an existing fire has been burning for a period of time and the fire manager wishes to predict where the fire will travel in the future (Prometheus, 2004). The same weights are used in this example except the location of the fire line ignition is to the north east of the river and the wind speed has increased from thirty kilometers per hour to forty-five kilometers per hour. The wind direction remains constant. The relative location of this ignition scenario can be compared to the actual burn perimeter by referring to Figure 4.9. The fire probability prediction can be compared to the actual burn perimeter using the river running just south of the fire as a reference.

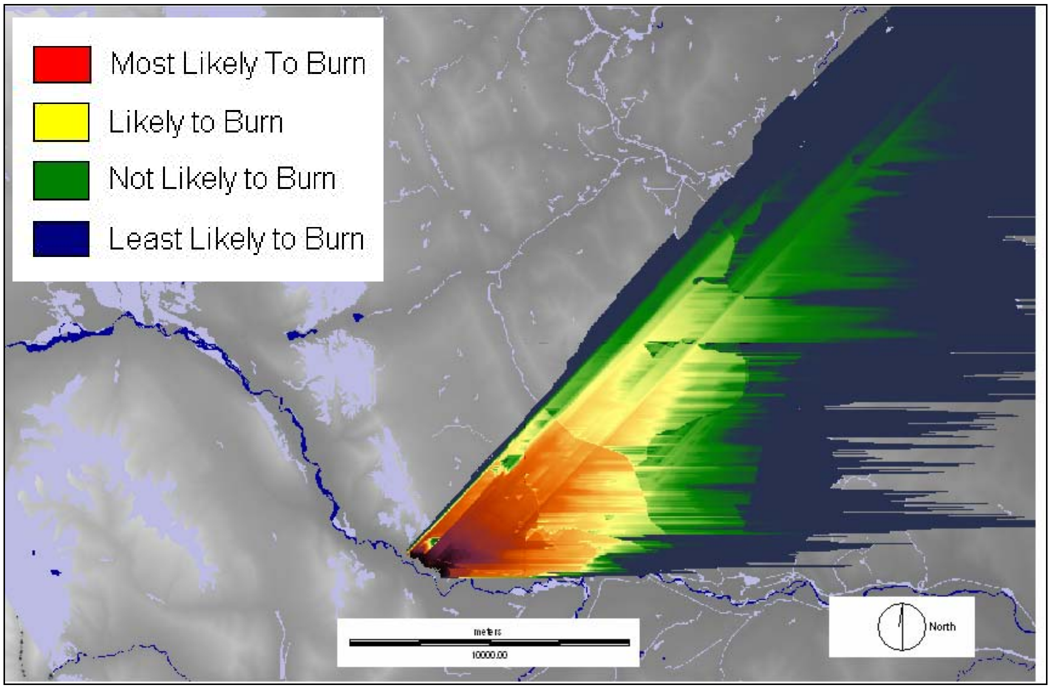

Figure 4.12: Idrisi Probability Prediction (Ignition 2)

When comparing Figure 4.9 and Figure 4.12, it can be seen that both the CWSPM and actual burn perimeter model produce similar outputs. By visual inspection it is apparent that the two are traveling in relatively the same direction. This example provides more consistent prediction results between the actual burn perimeter and the CWSPM, however; the easterly bias is still present.

The third test fire lies to the northeast of the second fire ignition scenario. Figure 4.10 can be referenced again to determine the relative location of this ignition in relation to the previous two. Another line ignition scenario was utilized for this test fire spread probability prediction. For this example the wind speed remains at forty-five kilometers per hour and the direction of the wind continues to blow to the northeast. The results of the CWSPM can be seen in Figure 4.13.

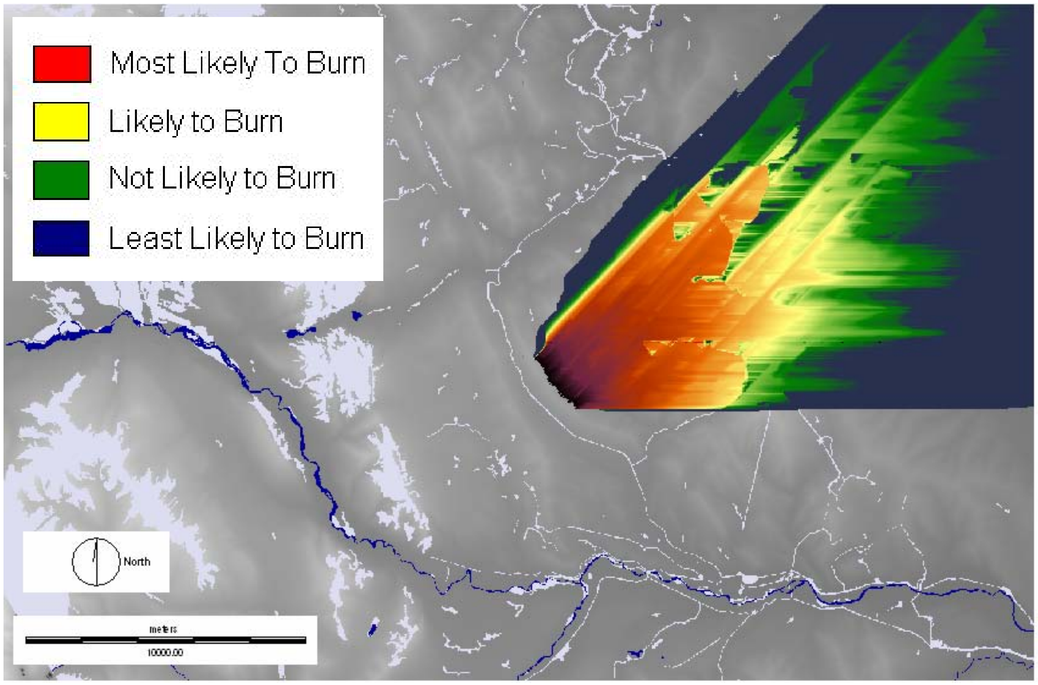

Figure 4.13: Idrisi Probability Prediction (Ignition 3)

This image can be compared to the last area that burned in the actual burn perimeter shown in Figure 4.9. Again the fire probability prediction shows similar behavior to the actual burnt area. The distinguishing features in Figure 4.13 above are the river to the south of the fire and the road that encircles the fire. One difference between the probability prediction and the actual fire is that the flanks of the fire spread prediction created by the CWSPM show more extensive burning than the flanks of the actual fire.

4.4 Summary

For the three example cases that were investigated the results from the CWSPM showed that the model was capable of predicting reasonable fire spread predictions for non-mountainous terrain. To use the model in mountainous terrain wind data would be needed that indicated the direction and speed of wind through valleys. With this information more accurate results could be obtained. The second and third fire spread probability predictions overlapped the area of the actual burn perimeter. This chapter has successfully found a solution to the second problem in wildfire management. The development of the CWSPM fulfils the need for a Canadian fire modeling program that improves upon the features of existing models. The advantages of the CWSPM over the models discussed in Chapter 3 are as follows:

- The model bases its calculations on information obtained from the CFFDRS system. It uses Canadian standard fuel types and weights for slope and fuel type based on calculations from the CFFDRS.
- The model can simultaneously compute a number of burn perimeter predictions for different locations.
- Different backgrounds can be displayed behind the burn perimeter predictions such as fuel type maps or digital elevation models.
- The model is capable of computing single burn perimeter predictions quickly. (Less than one minute per prediction)
- The model produces successful results of predicting fire spread for moderately flat terrain and the model's results could be easily improved for mountainous terrain by acquiring wind data collected in the mountain valleys.
- The resolution of the model is dependant on the resolution of the DEM and fuel type grids. It can therefore be altered.

Many wildfire modeling programs exist today (refer to Chapter 3) to help managers prepare for wildfire events and create mitigation techniques to combat wildfires. Each of these programs has varying degrees of accuracy and, because of the limitless complexities of the environment none are one-hundred percent accurate. Currently, Canada lacks a standard fire modeling software program. Each fire agency in each Canadian province, and even districts within provinces, use different programs to predict wildfire behavior and plan suppression attacks (Trevis and El-Sheimy, 2004). The next chapter will discuss the development of a Real-time, Internet based, wildfire monitoring and modeling system that could be used as a prototype to develop a Canadian standard fire modeling system.

It was intended for the CWSPM to be used as the fire modeling program in this application but the development of a new standard Canadian model dissolved this initial plan. The CWSPM can now be used as a quick, general fire prediction model that gives the user a general idea where a fire will likely spread to. Fire perimeter prediction models such as the new Prometheus model can be used to more time consuming and more detailed fire predictions. This model will be discussed in the next chapter.

Chapter 5: Creating an Internet Based Fire Management System

5.1 Introduction

Wildfire management agencies have a need for a system that can estimate, as accurately as possible, the propagation direction and intensity of spreading wildfires. Understanding behavioral characteristics of wildfires and the way they spread through various vegetation types and terrain is a major concern for environmental agencies, government officials and the general public. If unmonitored or poorly modeled, manageable fires can grow out of control and potentially,

- Gain the intensity and heat capable of devastating entire ecosystems.
- Change local weather patterns (Principles of Fire Behavior, 1993).
- Destroy millions of dollars of prime lumber resources that are essential to the economies of some countries (Johnson, 2001).
- Rage near cities and towns consuming the homes and assets of the citizens (O'Brian, 2003).

Understanding wildfire behavior is critical for maintaining the safety of fire-fighting crews and can also result in significant fiscal savings through improved planning and resource allocation. Currently, wildfire monitoring techniques are neither accurate nor efficient enough to optimally monitor this natural disaster.

Accurate map information is crucial to assist ground crews, helicopters and water bombers in mounting effective initial attacks. Airborne surveillance, involving a spotter aircraft, a Global Positioning System (GPS) receiver and a navigator that looks for smoke, is an invaluable tool that collects and relays fire information to the fire managers (Rothermel, 1993). Timely communication connecting the availability and deployment of bulldozers, planes, crew and other resources is also imperative.

Currently all these facets are performed using suboptimal detection and communication systems. Detection techniques are lacking the ability to optimally detect hotspots that remain after the fire has been suppressed. This creates the potential for the hotspots to re-ignite and start the fire rolling once more. Currently in Alberta, communication is conducted using radios, which in times of heavy fire activity become overloaded and inefficient (Wright and El-Sheimy, 2003). It is also difficult to interpret, through verbal communication, the exact size of the fire and the way it is expanding. Images from spotter aircrafts are used in fire modeling but currently, these images cannot be obtained until after the spotter aircraft has returned to the ground base station and the fire crews have downloaded the images. To add to this inefficiency, resource management, fire risk predictions and fire propagation predictions are all preformed using different computer programs. Combining an optimized fire detection system, fire resource allocation system and fire prediction system that works in real time and links communications between the different agencies, managers and crew would be an invaluable tool to the future of wildfire management.

To help remedy these inefficiencies a real-time, Internet based wildfire monitoring and modeling system has been designed to meet the fire modeling standards of the fire agencies within Canada. This system has the potential to impact the process of predicting wildfire propagation, resulting in reduced damage to the environment, enhanced safety and appreciable financial savings (Trevis and El-Sheimy, 2004). This chapter explores the design and implementation of the Wildfire Management and Modeling System (WMMS). It also discusses how this system could be used province-wide to help different agencies and districts communicate more efficiently with each other and also allow the public to view current provincial fire situations from their personal computers.

As mentioned in Chapter 1 the WMMS system integrates five features into a data acquisition/processing system and accompanying GIS based web browser. The five features are:

1. Real time reporting of current fires,
2. Real time reporting of the spotter aircraft flight trajectories,
3. Active fires spotted by fire crews or general public
4. Fire history of each fire management district and
5. Prometheus fire behavior predictions

Combining these features, the final system is able to locate hotspots of fires within three meters of accuracy, predict where a fire will most likely propagate with time, detect smoldering fires under light surface vegetation, and detect fires through smoke, haze and darkness (Wright and El-Sheimy, 2003).

Three members of the Mobile multi-sensor research group, the University of Calgary, were actively involved in the development of this system. Bruce Wright, a former graduate from the University of Calgary developed the Data Acquisition System that is a component of one of the tools in the WMMS site. For further details see (Wright, 2004). Chuanyun Fei, a former graduate from the University of Calgary, was the site programmer. The author's contribution to the system involved:

- Designing the site features, general functionality, tools, and specifications
- Designing the site's fire modeling system (CWSPM discussed in Chapter 4) which was later replaced with the Prometheus COM
- Testing and validating the site and Prometheus COM
- Editing and making corrections to the website interface
- Designing and programming the current form of the interface for the entry and login screens

- Liaison between Alberta Sustainable Resources and the University of Calgary. Collected and presented recommendations for the future development of the Prometheus COM
- Determining what features Alberta Sustainable Resource Development would like to see in an Internet based wildfire monitoring and molding system through interviews with fire managers and fire scientists

5.2 System Architecture Design

The WMMS can be broken down into three main sub-systems. These sub-systems can be identified as the Data Acquisition System, Control Center System and Response System. The functionalities of each sub-system are shown in Figure 5.1.

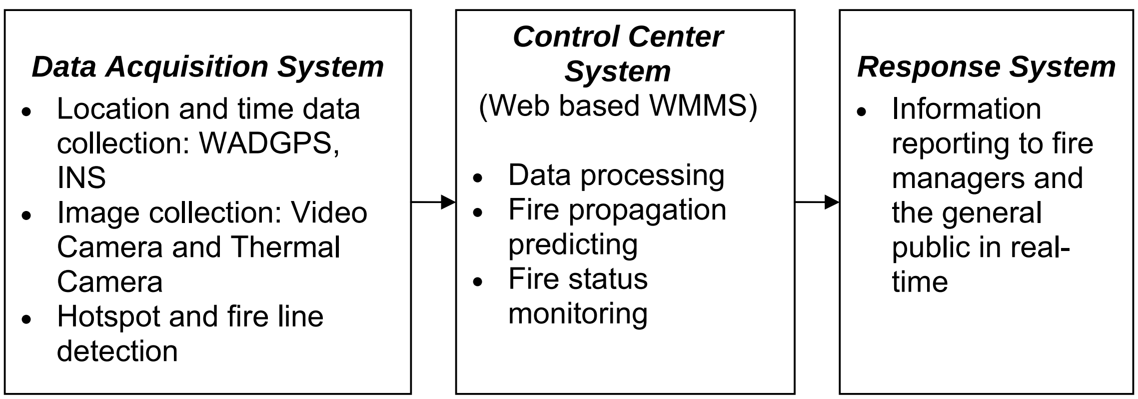

Figure 5.1: Three Sub-Systems of the WMMS

For the purposes of this research, an overview of the data acquisition system will be given to inform the reader of the basics of major functionality. This system is responsible for acquiring, controlling and storing the Wide Area Differential Global Positioning System (WADGPS) data, Inertial Navigation System (INS) data and the thermal camera images collected by the spotter aircrafts during the preliminary search for new wildfires. The data collected by this system is synchronized to a unified time frame by precisely time-tagging all data streams using the WADGPS receiver generated Pulse per Second (PPS) signal (Wright and El-Sheimy, 2003). These time tags can then be used with the WADGPS and IMU data to georeference the images. The three-dimensional coordinates of fires and hotspots are then determined using photogrammetric techniques after calculating the position vectors and orientations of a pair of overlapping images.

The use of a thermal infrared camera is important for this procedure because it senses heat emitted from objects in the form of infrared radiation and thereby enables early detection and location of small fires that can not be sensed by traditional cameras or the human eye. The thermal infrared camera is also immune to factors such as haze, smoke or darkness which, in this application, render traditional cameras useless. The process of uploading, georeferencing and obtaining the three-dimensional coordinates of any identified hotspots in the images occurs in real-time. At this point the coordinate information and any corresponding images can be uploaded to an Internet site via a telecommunications satellite.

It is anticipated that this process will allow fire managers to increase their ability to quickly detect where hidden, smoldering fires are located. The accuracy obtained by this system in real-time is dependant on flying height but is generally less than five meters flying at a height of four-hundred meters and facilitates the acquisition of accurate reports on fire position, size and direction. For further information about this Data Acquisition System, see Wright, 2004.

The Control Center System hosts the webpage. It has many responsibilities. The first of three main responsibilities is archiving all information collected by the Data Acquisition System. The second responsibility is performing the fire behavioral modeling functions. The last major responsibility is displaying the fire status monitoring information. More detailed information about these processes and functions will be given in the next sections.

The last sub-system, the Response System, enables the results of the Control Center System to be displayed to the user. This sub-system allows the remote system user to view the results processed by the Control Center System.

All three sub-systems are linked through the Web based WMMS which organizes all functions of the Control Center System for use by the operator. A flow chart outlining the structure of the WMMS is shown in Figure 5.2.

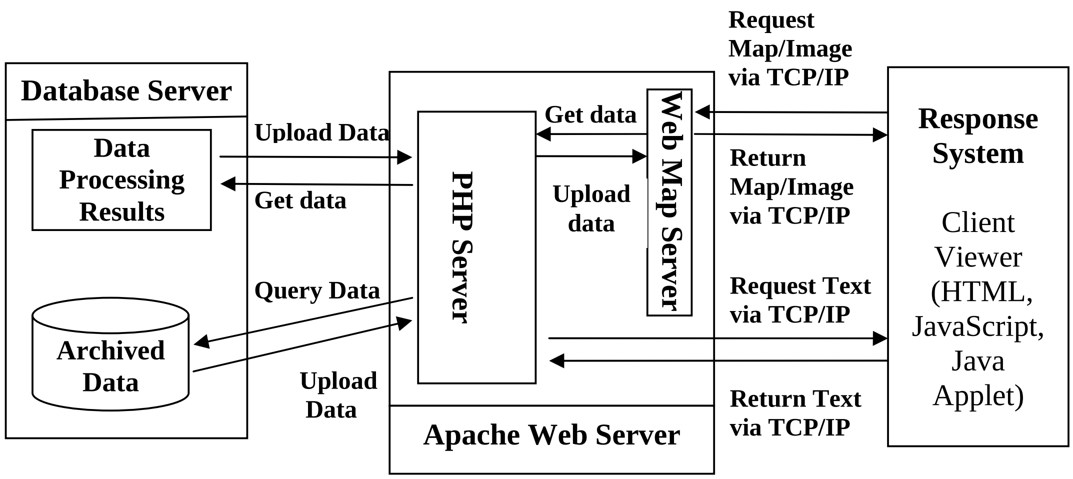

Figure 5.2: Flow Chart Outlining the Functions of the Control Center System

The Database Server obtains the data from the Data Acquisition System and all data processed in the Control Center System can be viewed by the client through the Response System. The WMMS has five main components, as shown in Figure 5.2 that allow the three main sub-systems to communicate seamlessly. These components are listed below:

1. Apache Web Server
2. Web MapServer
3. Hypertext Preprocessor Server (PHP)
4. Database Server
5. Transmission Control Protocol and Internet Protocol (TCP/IP)

5.2.1 Apache Web Server

The Apache Web Server is a computer platform that hosts the Web MapServer and the PHP server. The role of the Apache Server is to connect the client's personal computer to the stored wildfire data on the server via the MapServer and PHP servers.

5.2.2 Web MapServer

The Web MapServer is a public domain development environment from the University of Minnesota that is primarily used when building spatially enabled Internet applications. This software works on any Linux, UNIX and Windows platform and has many GIS features that make it an attractive option for the WMMS Webpage. MapServer also allows the clients to browse GIS data and to create geographic maps (Lime, 2003). It is responsible for all spatial data operations and publications created within this system (Trevis and El-Sheimy, 2004).

MapServer works by configuring each application using a text file called a "mapfile". Anything associated with a particular application is defined in the mapfile as an object. In a single file there can be many objects used to build an entire interface, or just a single object used to build a simple legend or scale bar. To add to the functionality of the system, one can use and modify these objects through an HTML form. The program results are then run through a series of templates depending on the application (i.e. data browse or feature queries) and the results are displayed to the user.

5.2.3 PHP Server

PHP is a general purpose scripting language that is particularly useful in Web development and can be easily embedded into HTML. The PHP server facilitates the transfer of image and textual data between the server and the client. It performs the searching techniques of the spatial and textual data. The user can thus access the newly published data processed by the control center through the Apache Web Server. However, since this web based fire modeling system is capable of publishing information in real time, the data server must be accessed frequently. If textual, real time data is transmitted the PHP server can directly transfer the data from the database to the client via the TCP/IP protocol, which is explained later. If the data is a general image such as fire photos, the PHP server can automatically retrieve it from the database and pass it to the client.

5.2.4 Database Server

Multiple types of data sets are utilized in this application such as text, spreadsheets, general and georeferenced images, GIS data and GPS coordinates. This application uses the Standard Query Language (SQL) to organize the database. The flexibility of the SQL language makes it easy to separate the logical layer and data layer thus increasing its flexibility. This database was also chosen because it can easily be transferred to a more powerful database when extra functionality is required.

5.2.5 TCP/IP Protocol

The TCP/IP protocol is the communication protocol standard that is used in the system to transmit data between the server computer and any number of client computers over an Internet connection. The TCP portion of the protocol establishes the connection between computers and exchanges streams of data. The IP portion of the protocol addresses the packages of data and drops them into the system so that they can be delivered to the appropriate computer.

5.3 Interfaces for the Internet User

5.3.1 User Access and Main Page Layout

The webpage has been designed so that the first page available to the user is a login screen that asks the users to either register or enter their user name and password. At the time of initial registration every user is assigned a user class of "general public". This status can be upgraded to "manager" by an existing manager who has access to the database of the system. Users with managerial status differ from the status of general public users in the fact that they have the ability to control, update and monitor the system. Public users can only view, but not change, the information available in the database. To make the webpage easily handle two classes of users, all database manipulation tools were placed under the heading "Managers Toolbox". When an authorized user is logged onto the system, the program will check the user's access rights and make available the appropriate toolbars. If a general user is logged onto the system the Manager's Toolbox is invisible and cannot be accessed by the user. A sample screen capture of the WMMS is shown in Figure 5.3. This screen capture depicts the setup for a user with managerial capabilities. This sample can be accessed from the Internet site,

- http://cfei.geomatics.ucalgary.ca/firepub_com/firepub.php.

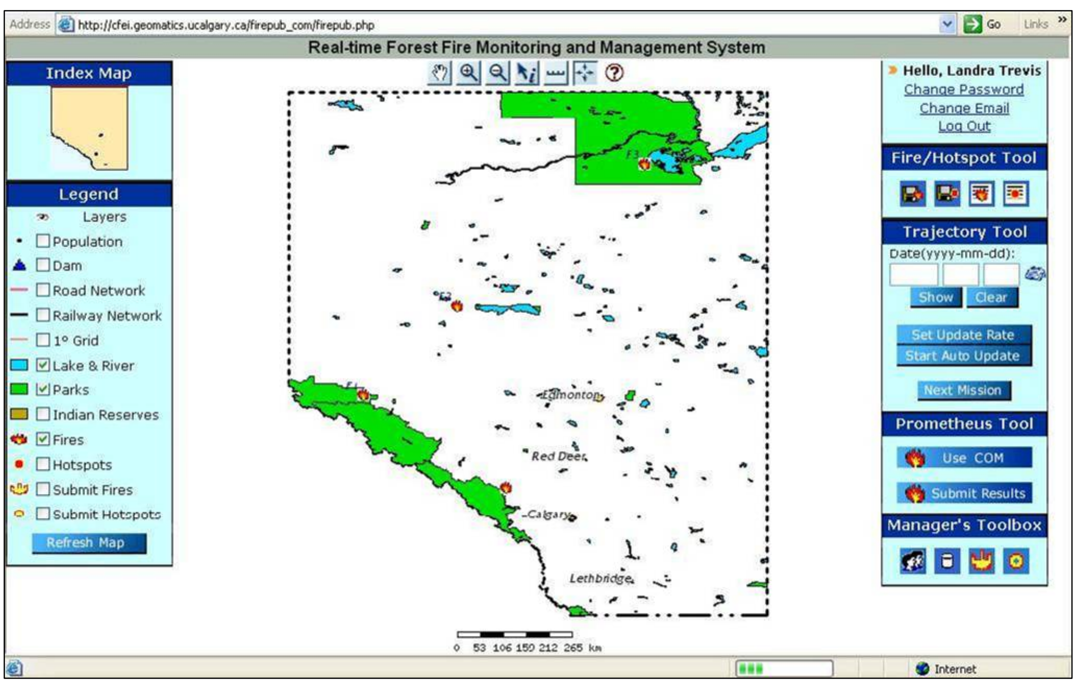

Figure 5.3: Screen Shot of Main Interface of the WMMS System

The left hand side of the screen shows the reference map and legend which contain the possible layers that can be added to the display. For Figure 5.3

the Lakes and Rivers, Parks and Fires layers are turned on. The center of the screen shows the province of Alberta which can be panned or zoomed-in to any area in order to show the user a more detailed map. Currently, the province of Alberta is shown to have four fires burning.

All fire information displayed on any map or depicted in tables and charts on this webpage is hypothetical data and does not represent fire situations that have happened in Alberta. This information has been temporarily entered into the databases to test the model and webpage implementation.

On the toolbar directly above the map, fifth button from the left is a tool that looks like a ruler. This tool is called the Nearest Distance to Lake Tool and is able to calculate the distance between any point on the map and the nearest major lake or river. To activate this tool one clicks on the Nearest Distance to Lake Tool button (fifth button from the left) and then makes a second click on any location within the main map of Alberta. This will indicate the position from where the user wants to allocate the nearest lake. A screen shot of this process is shown in Figure 5.4 below.

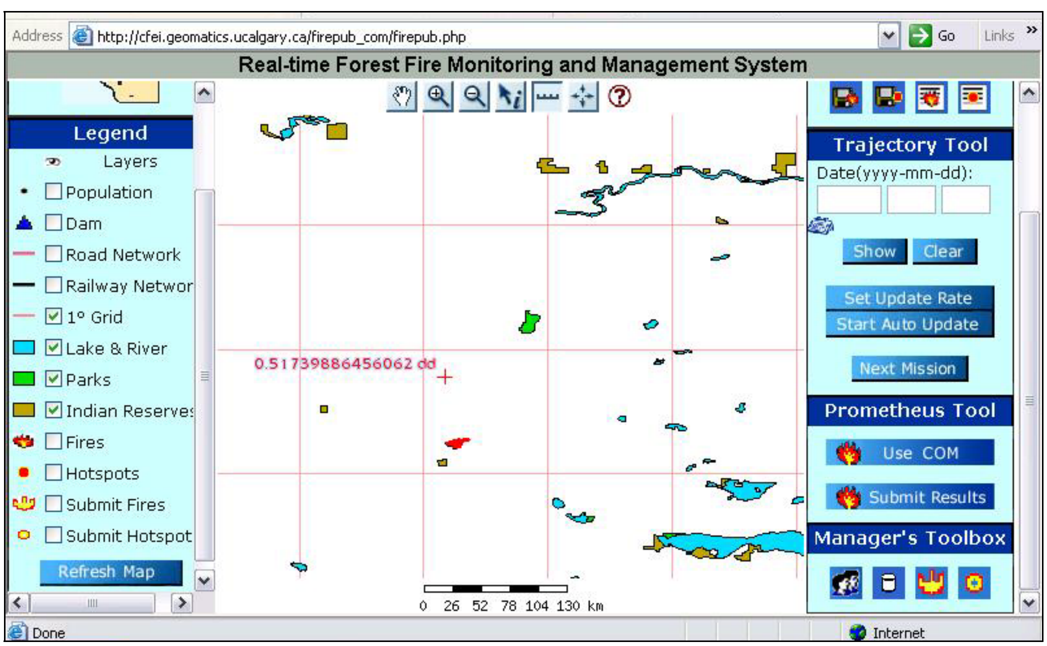

Figure 5.4: Screen Shot of Distance to Nearest Lake Tool

Once the user has clicked the location of interest, the nearest lake will be highlighted in red and the distance to the lake will be displayed in decimal degrees above the marked point. This tool could be very useful for fire managers who are planning their initial attack on a fire and want to determine the locations of any primary water resources.

The remaining items on the toolbar above the map of Alberta from left to right are pan, zoom-in, zoom-out, identify, and full extents. As one uses the zoom-in tool more detailed information regarding roads, rail and rivers appear on the map.

Another toolbar is located on the right hand side of the screen. Each of the tools found in this toolbar are explained individually in the next section. The names of the tools, listed from top to bottom on the toolbar are the Fire/Hotspot Report Tool, Trajectory Tool, Prometheus Tool and Manager's Toolbox.

5.4 Tools

5.4.1 Fire/Hotspot Reporting Tool

The purpose of the Fire/Hotspot Reporting Tool is to display information pertaining to the provincial fire situation. It enables the user to view Fire Summary Reports for the different fire districts in the province. These reports contain information such as the number of active fires, cause of fire and fire status. Using this tool, information can be browsed based on year or by management district. Any fire that is currently active can be selected from within the Fire Summary Reports and a Fire Status Page will be displayed containing the real-time information relevant for that fire.

One of the first pieces of information displayed on the Fire Status Page is the latitude and longitude of the center of the fire or hotspot. To help the user put the coordinates of the fire into perspective, the location of the fire is also displayed on a reference map of Alberta, shown on the same screen. Supplementary information such as fire status, fire management district and most up to date aerial photos are also shown on this screen. All current fire information has the potential to be uploaded to the system in real time using the Data Acquisition System described earlier.

5.4.2 Trajectory Tool

The second tool that is currently available on the WMMS is the Trajectory Tool. This tool is capable of reporting the real-time trajectories of a spotter aircraft's flight path and displaying on the webpage the locations of any spotted fires or hotspots along that flight path. Points along the plane's trajectory are collected using the WADGPS receiver that is mounted on the spotter aircraft and transferred to the system in the same manner used by the Fire/Hotspot Reporting Tool. The trajectories are then displayed on the base map. Fires and hotspots are also recorded during this process and any incoming fire coordinates are uploaded to the website and marked on the base map with a fire icon. If the fire has been extinguished but is still smoldering, the locations of hotspots within the smoldering area will also be automatically uploaded to the web site as the spotter aircraft passes over.

5.4.3 Prometheus Tool

The third tool that is available on the WMMS is the Prometheus Tool. This tool allows fire managers to determine how a current or hypothetical fire will propagate across the terrain. Alberta Sustainable Resource Development has permitted the Geomatics department of the University of Calgary to use Prometheus as a tool in its WMMS system. Prometheus is currently able to model wildfire behavior based on topography, the Canadian standard fuel types and the Canadian standard weather index system from the Canadian Forest Fire Danger Rating System (CFFDRS) (Prometheus, 2004).

Prometheus was the most recently developed fire propagation model in Canada as of its introduction in 2003. The development of this model was endorsed and administered by the Canadian Interagency Forest Fire Center (CIFFC) where Alberta Sustainable Resource Development acted as the lead agency for the project (Prometheus, 2004). Although this model has just recently been developed, Prometheus will become the new model used by Canadian forest fire managers. It is possible to obtain this model from the Internet site www.firegrowthmodel.com.

Prometheus is a spatial model that uses the fire spread equations inspired by Byram's Fire Intensity Equation and the Wave Propagation Technique to simulate the growth of a fire front. It is currently able to model wildfire behavior based on topography, the algorithms of the CFFDRS discussed in Chapter 3.

To use Prometheus the six input parameters for the FBP and FWI system must be entered. These six parameters are:

1. Fuel type
    - Determined using a list of sixteen general fuel types that are some of the major fuel types in Canada
2. Weather
    - Encapsulated using hourly data on wind speed and direction and the output from the Fire Weather Index (FWI) System
3. Topography
    - Defined by percent slope and aspect
4. Foliar moisture content
    - Determined using elevation, latitude, longitude and date
5. Type and duration of prediction
    - Determined using the elapsed time since the fire began and whether it began by a point or line ignition
6. Fire line and fuel break data

Once these parameters are entered, the system will produce the primary outputs of rate of fire spread, fuel consumption, head fire intensity and fire type. From these parameters two-dimensional views can be produced to illustrate fire spread as a function of time.

Prometheus was chosen for this system since it possesses three key advantages that are not available together in any other model. The first advantage is that Prometheus provides an intuitive pictorial view of the spread of fire through the landscape. This enables users to quickly view how the fire is spreading instead of having to interpret textual values of rate of spread and fire intensity. The second advantage is that Prometheus uses the Fire Behavior Prediction (FBP) and Fire Weather Index (FWI) systems of the CFFDRS. Using the standard CFFDRS helps make Prometheus a desirable application to use in any province or territory in Canada. Finally, Prometheus can be integrated into the WMMS using its Microsoft COM (Component Object Model) interface. The COM interface allows easier integration of Prometheus with other Microsoft applications, permits additions to be made to the model and allows the model to work seamlessly through a web browser. The CFFDRS and Prometheus COM will be discussed in more detail in the following sections.

5.4.3.1 Prometheus' Component Object Model

The Prometheus COM is one feature that makes Prometheus an attractive option for researchers. Essentially, the Prometheus COM can be described as the Prometheus application programmed into a number of individual components where each component makes up a piece of the original Prometheus model. If all of the components are used together the user has nearly all of the functionality of the original Prometheus model. The beauty of the COM is that additions can be made to the individual components resulting in the ability to alter the original Prometheus model so that it meets the requirements of the researcher (Prometheus, 2003).

Some of the advantages of Prometheus have already been implied in the above paragraphs however, for the sake of completeness, a list of Prometheus' major features is shown below (Prometheus, 2004):

- Allows users to modify fuel and weather data
- Output is compatible with Arc software
- Computes spatially explicit fire growth for single ignitions
- Uses point, line or polygon ignitions
- Uses daily or hourly weather information
- Allows user to evaluate different scenarios
- Permits the model to be altered and/or integrated with other Microsoft applications
- Is the model that Canada will be using in the upcoming months

Despite these features Prometheus does have some limitations, such as (a) it is incapable of using satellite images as base maps (b) it is unable to compute fire behavior prediction perimeters for more that one ignition point at a time, (c) it is limited to computing only eight timed perimeters for a single fire scenario. To create larger fire perimeter predictions a larger time lapse must be entered in between fire perimeter predictions and this can greatly affect the performance of the model.

To use the Prometheus COM, the user must first check the structure of the input data so that it matches the way that the COM reads input files. If the data is not consistent a conversion must be completed so that no errors will occur when reading the files. This conversion would be performed in the user's application. The converted data can then be used as input into the Prometheus COM. The Prometheus COM Model is built using five separate low-level COMs. Since low-level COMs are very difficult to use directly, a higher level Prometheus COM has been built by the Alberta Sustainable Resource Development Department to access the five separate low level COMs (Prometheus User manual, 2004). The Prometheus COM architecture is shown in Figure 5.5.

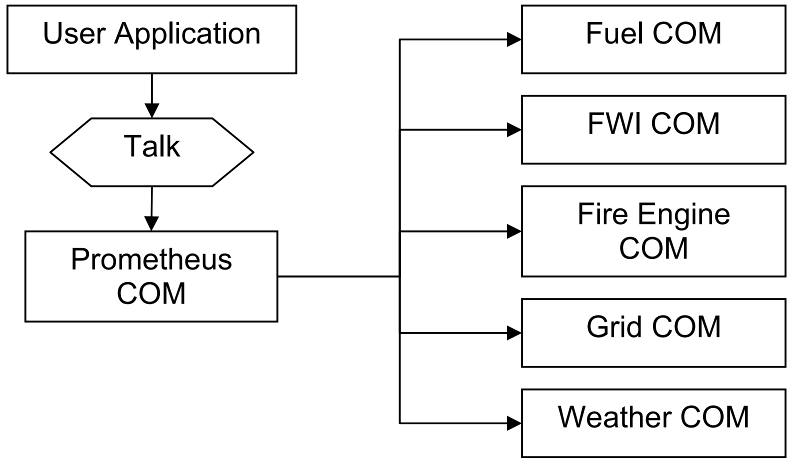

Figure 5.5: Prometheus COM Architecture

With this structure, all the functions available in the low level COMs can be called individually and used by this system. To activate the COM on the WMMS Webpage the user would click the "Use COM" button seen in Figure 5.4. Next, the user must go through a sequence of five screens to enter the necessary parameters for all of the low level COMs. On the web page these screens are designed to look like a file folder with five separate tabs. The defining name of each screen is written on the tab of the file folder. This was done so that the user can quickly flip back and forth between screens to enter in all the necessary information. The first of the five screens is shown in Figure 5.6.

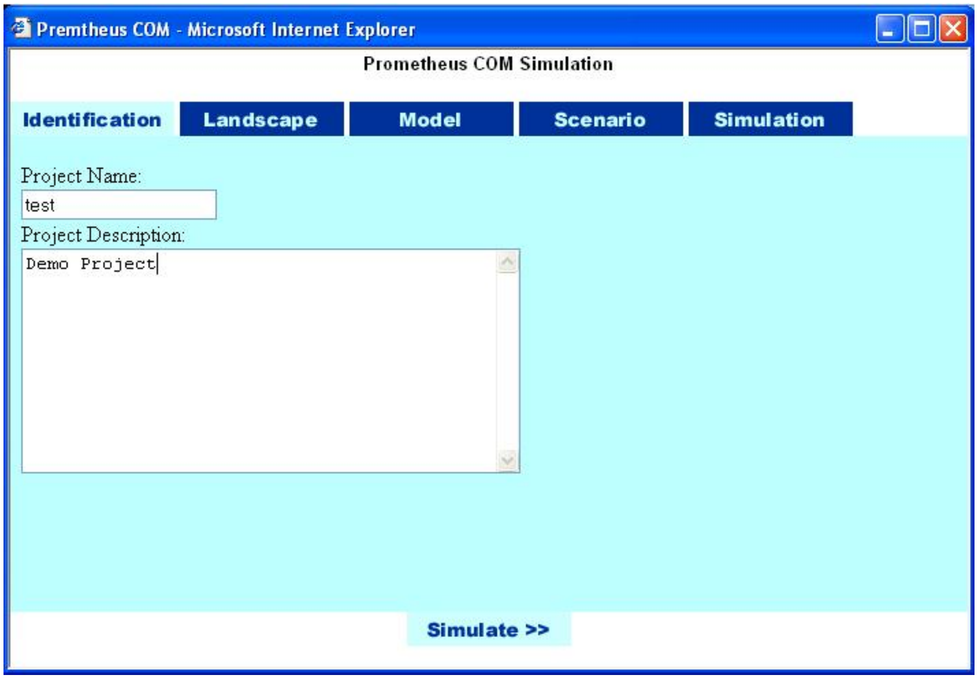

Figure 5.6: Screen Shot of First Screen used to Implement COM

The information requested for each screen of the COM interface is shown in Figure 5.7.

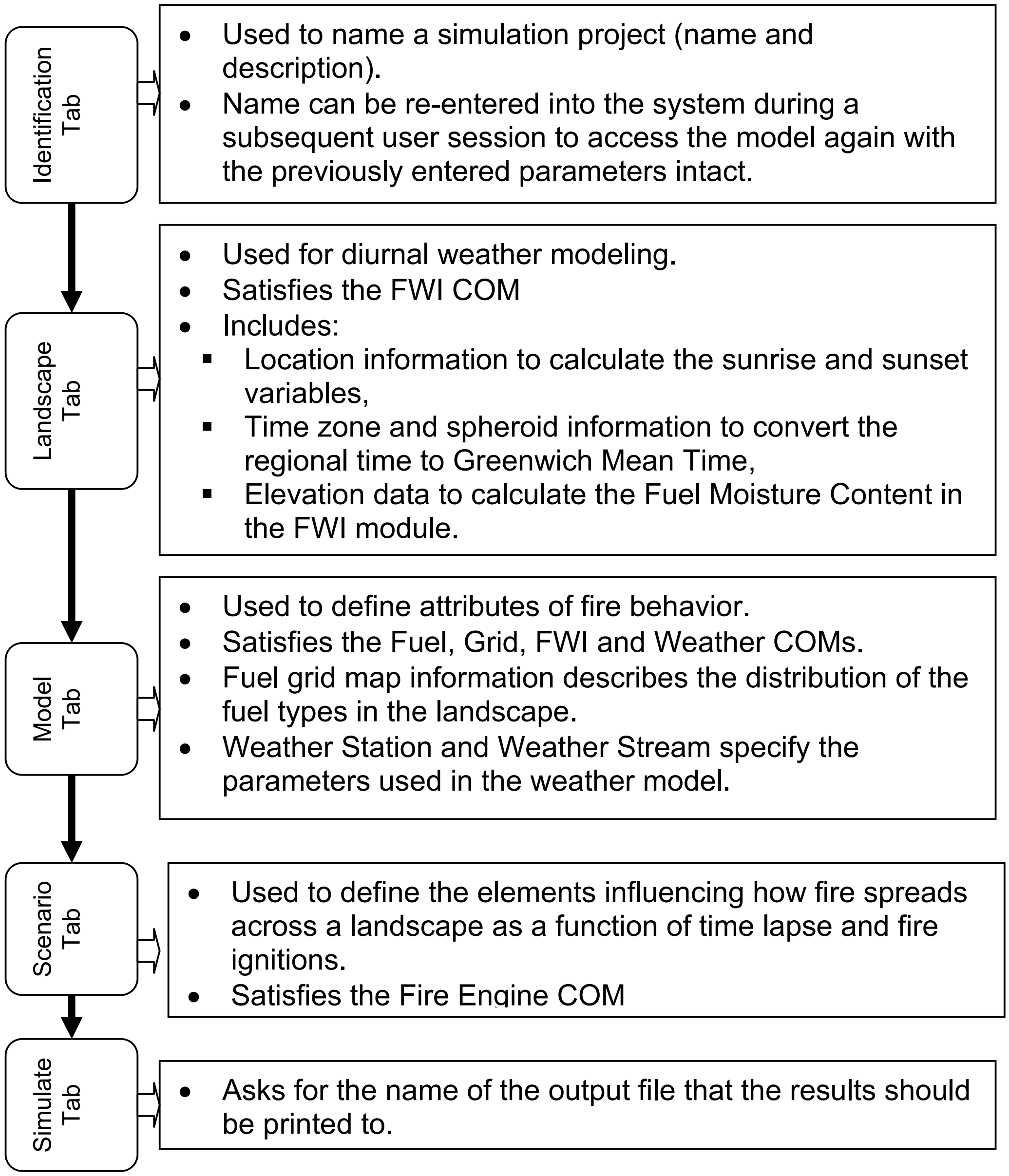

Figure 5.7: Flow Chart Describing the Necessary Parameters for the COM

Pressing the “Simulate” button on the Simulate page allows the COM to compute a fire perimeter on the map of Alberta that is displayed on the main page of the website. All of the variables used by the Prometheus model can be entered in real-time to the system. This allows users to simulate fire propagation scenarios at any time and location. After all the necessary information is entered (projection, fuel grid, weather condition, etc.), the website will link to the necessary components of the Prometheus COM via the

PHP Server and MapServer to display an image, on the main map, of the predicted growth perimeter for the fire.

Two example screen shots have been taken to illustrate the performance of the Prometheus COM. These examples are of the same test site as Ignition Point 1 that was used in the model comparison in Chapter 5. The difference between the two images is that Figure 5.8 shows the results of the COM for the wind speed of forty-three kilometers per hour. Figure 5.9 shows the results for the same fire with the same parameters except the wind speed has been changed from forty-three kilometers per hour to five kilometers per hour. It is important to note that all topographic, fuel, elapsed burning time, and location data is consistent between the two fires. All DEM, and fuel type maps are identical to the parameters input into the CWSPM. To see the parameters that were entered into the COM to obtain both image results refer to Table 5.1. Both fires were set to burn for an eleven hour period.

Table 5.1: Parameter Entries for the Fire Perimeters of Figure 5.8 and 5.9

	Wind direction	**Precipitation**	**Max Wind Speed**	**Max Temp**
Figure 5.8	45 °	0mm	43 km/h	15.8 ° C
Figure 5.9	45 °	0mm	5 km/h	15.8 ° C

The values entered in the table were found in the help files of the Prometheus desktop application. The results of the COM are shown below.

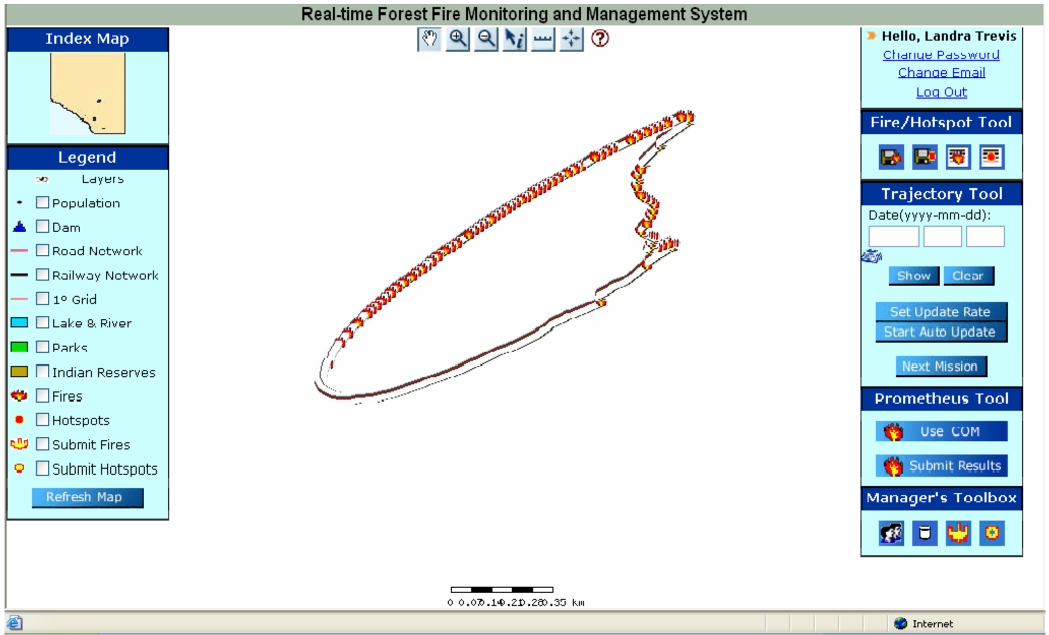

Figure 5.8: Example 1Perimeter for Fire Spread Using Prometheus COM

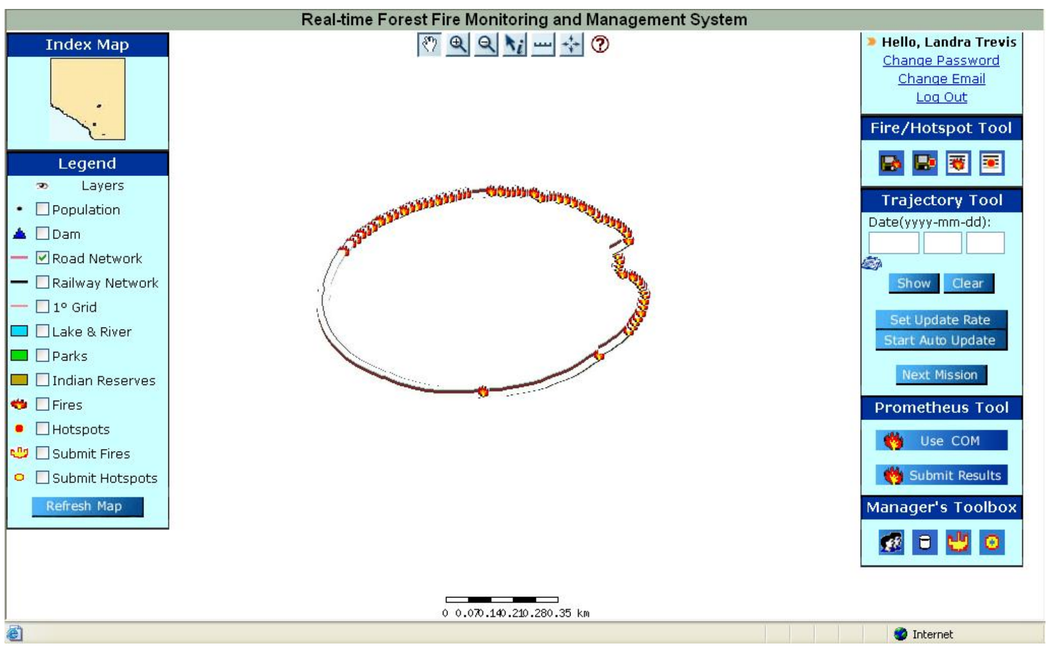

Figure 5.9: Example 2 of Predicted Perimeter for Fire Spread Using Prometheus COM

From Figures 5.8 and 5.9, it is evident how wind influences the predicted spread of the fire. The decreased wind speed for Figure 5.9 has influenced the predicted fire perimeter to take a rounder and smaller shape. In the case of the true wind speed (Figure 5.8), the fire spreads in a direction consistent with the direction of the wind and is stopped at the river bank in the same manner as was predicted in Chapter 5.

As a further comparison Figure 5.8 can be compared to a burn perimeter prediction calculated by the Prometheus desktop application. The perimeter is shown in Figure 5.10 below.

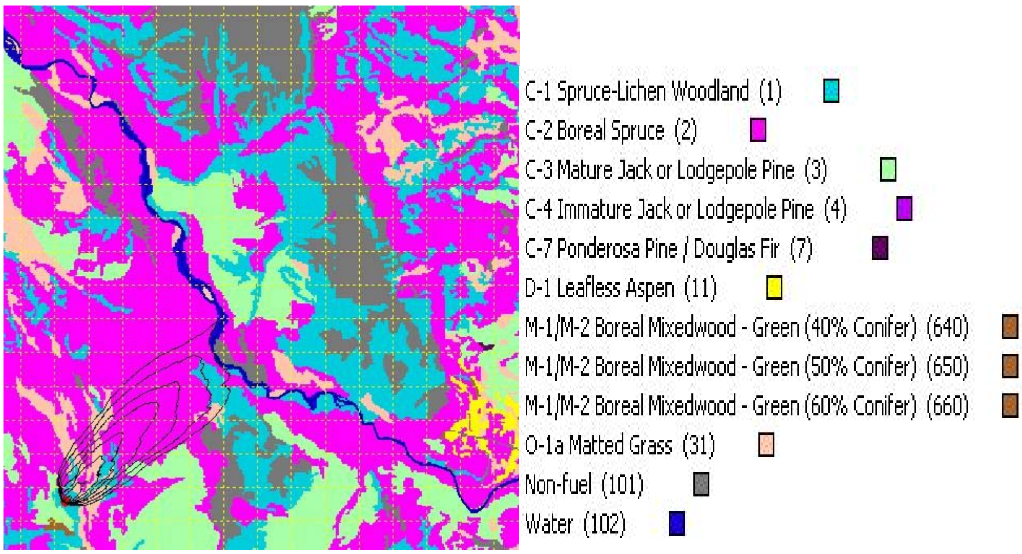

Figure 5.10: Prometheus Model (Ignition 1)

Comparing the two images is apparent that there are differences between the desktop application and the COM. The desktop application is capable of computing multiple (up to a maximum of eight) time lapsed fire perimeters for a single ignition. In Figure 5.10 above each perimeter is calculated at twenty minute intervals. The consistency between the general shape of the largest perimeter calculated by the Prometheus desktop application and the perimeter calculated by the Prometheus COM ensures that the Prometheus COM is operating correctly.

It must be noted that Prometheus's COM is still under development. Version 2.0.1 is currently being used in this application. Some functions and capabilities are currently unavailable in the COM. One such function is that the creation of fire lines is not available. Ideally, ignitions should be specified as points, lines or polygons; however the current version of the COM limits fire ignition specifications to points only.

5.4.4 Manager's Toolbox

Using the tools in the Manager's Toolbox, the user can update user accounts, update database data and update user submitted fires and hotspots.

Update User Accounts

This tool allows a manager to see information about the users who have accessed the site. Information about the users includes:

- their user status,
- name and
- Email.

Only an existing manager can upgrade a general user to manager status. Similarly, only a managerial user can demote a user to general status or delete a user from the system.

Database Management Tool

This tool is still under development. Once completed, this tool will allow users, with managerial status, to access or update the fire information database. Data in the fire information database will include fire weather information, provincial fuel type information and fire location information.

User Submit Fires and Hotspots Tool

This application provides tools for managing and monitoring fire and hotspot situations. Using these tools, managers can view new fire information as it is submitted by other fire managers. Managerial users can also edit or update information about fires as it becomes available.

Wildfires and hotspots require fast response times. This system provides the manager with the ability to work on any computer at any time, and from any location. To ensure quick fire response times, the system will send an email to the fire managers the instant a user submits new fire or hotspot information to the system. In addition, having the detection software, reporting functions, fire simulation model and decision-making support tools available on the same website provides a seamless fire report and management tool that will help mitigate wildfire disasters.

5.5 Summary

This research has the potential to greatly benefit fire managers in predicting and managing forest fires. This presented a solution to the third problem existing in wildfire management. Communications between fire management districts can be improved with the introduction of this Internet based wildfire management and modeling system. The WMMS could help minimize suppression efforts by directing the supplies to the areas of active heat emissions via real-time thermal images and modeling techniques. As a result, this system could not only save time and money but also improve the safety of the ground based fire-fighters. This system will also be updated and improved as future versions of the Prometheus COM are released. Additional functions could also be created to supplement the Prometheus COM. Proposed functions for future research are to incorporate additional variables that affect fire behavior. Two additions could be researched. One addition would involve the incorporation of a resource location/allocation function. The second addition would be to include a danger vs. economic loss rating variable into the Prometheus model.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

The success of this work can be gauged by the ability to supply solutions to the three current problems existing in wildfire management. Solutions to these problems will greatly improve communications in the wildfire industry and make wildfire management more efficient. The three problems are:

1. Wildfire policy does not adequately outline guidelines that should be followed when conducting prescribed burns
2. Canadian fire modeling programs are sub optimal and should be improved
3. Communications between fire management districts are sub optimal and should be improved with the introduction of an Internet based wildfire management and modeling system

Through the completion of the thesis objectives outlined in Chapter 1 solutions to the three problems have been created. The first completed objective was to investigate the parameters that influence fire behavior and to learn how wildfires react to various parameters in the environment. It is now known that fires are very dependant on fuel, topography and weather. Weather is the most influential factor in fire behavior and wind is the most influential factor of the weather. Other parameters such as the Fine Fuel Moisture Code and Buildup Index are also important parameters but these parameters are used to fine tune a forest fire model and improve its precision in wildfire modeling. Atmospheric conditions can also influence fire behavior but these conditions are very difficult to incorporate into a model and are often omitted. Much research is currently being conducted in this area to see how atmospheric models can be merged into fire models efficiently (Clark, 1996; Jenkins, 2002).

The second objective of this thesis was to investigate existing wildfire management policy and to make recommendations for a prescribed fire policy for Alberta. Since no Canadian prescribed fire policy exists, this objective was achieved by investigating the existing American prescribed fire policies and identifying their merits and shortcomings. Reasons for policy failure were also investigated and recommendations were made to the future Albertan policy. With the advent of this new policy it is hoped that runaway prescribed burns will be reduced.

The third objective of this thesis was to investigate existing fire models and determine their benefits and short comings to help aid the development of a new Canadian fire model. This objective was achieved by looking at six of the most well known fire models used in North America. Behave Plus, FireLib, EMBYR, Farsite, FIRE! and NFDRS were analyzed. Some features from these models that would be useful in the devlopment of a new Canadian model are listed below:

- Spatial modeling capabilities
- Huygen's principle of Wave Propagation for simulating the growth of a fire front
- A methodology based on the algorithms of the CFFDRS.
- User-friendly
- Applicable for a wide range of areas
- Having the flexibility to change the resolution of the model depending on the input data that is available

Some other features that would be useful in the development of a new Canadian model that were not available in the researched models are listed below:

- High-resolution images could be added to the background of spatial models
- Model could be implemented on the Web so that data regarding people and resources could be included and updated from multiple fire stations.
- A distance to nearest water sources tool could be included in the model
- If one zooms into the fire on the computer screen each zoom-in results in a more detailed image on the screen

Using this information the CWSPM was developed to provide a superior wildfire modeling tool. The results of the CWSPM are compared to an actual burn perimeter and show good correlation with the true data. The newly developed CWSPM is able to follow the general direction of an actual burn perimeter. The model is able to compute fire perimeters quickly and is also able to compute multiple fire perimeter predictions simultaneously. Such features could be very useful to fire managers who are tying to control multiple fires in the same area. The CWSPM is user friendly; applicable to a wide range of areas, uses a methodology based on the CFFDRS, is flexible enough to use a wide range of images as background maps and is capable of being implemented on the Internet. This model was to be implemented as the wildfire modeling system in the WMMS internet application. However, with the development of Prometheus at the final stages of the CWSPM's development, it was decided not to include the CWSPM into the web application and instead to use the Prometheus model. This was done to help the WMMS system gain national acceptance since it uses a model that is to become the Canadian standard modeling system.

The fourth objective of this research was to find a way to improve communications between fire management districts with the development of an Internet based wildfire management and modeling system. The WMMS system is the first of its kind to combine a fire modeling system, data acquisition system and database management system into a single program capable of real time data updates. This system is also advantageous to the general public who could use the system to view fire situations in their area or educate themselves on fire behavior by having the freedom to grow fire predictions on their personal computers. It is anticipated that this research will spur fire managers to re-think the way that wildfires are managed and promote the development of a more robust, complete fire management and modeling system.

6.2 Recommendations

The WMMS system designed in this research is only a prototype. It will require a number of updates to be able to function as a commercially viable product. Tables and charts displaying historical fire data should be made to have factual instead of hypothetical information. The graphics displaying the fire perimeters when using the Prometheus COM could be improved. Satellite data showing highly detailed images of highly zoomed in sites could be used to help the user orient themselves when looking at small areas within the Alberta map. The entire system should be tested in real-time on an actual fire site.

It is hoped that this research will spark the imagination of some fire managers and influence them to integrate some of the elements of the WMMS into their own fire modeling systems (Trevis and El-Sheimy, 2004). With further research and the continued research in fire management, hopefully wildfires will be one natural disaster that mankind will be able to gain control of.

Glossary of Terms

Duff: Partially decomposed or fully decomposed layers of the forest floor. This includes partially decomposed leaves and twigs as well as the well-decomposed matter that rests below (Johnson, 2001).

Chutes: Steep valleys that cut into the slopes of the side of a mountain. Chutes run parallel to the slope of a mountain and greatly influence fire behavior by creating three up-slopes which accelerate fire spread. Chutes also influence fire behavior by funneling the smoke column up the chute which can increase spotting further up the mountain slope.

Crown fire: A fire involving the tree canopies or tree crowns (upper branches) of coniferous trees.

Fine Fuels: Includes grasses, leaves, needles, and ground litter. The moisture content of these fuels can fluctuate greatly depending on amount of precipitation they receive (Johnson, 2001).

Fire brands: Burning embers

Fire Intensity: Based on both rate of fire spread and fuel consumption. A fast moving fire that does not consume a lot of fuel may have the same intensity as a slow moving fire that consumes the tree crowns and duff layers.

Fire Spread: The rate that a fire will consume unburned vegetation and expand its parameters.

Fuel: The vegetative substances available for burning.

Inversion: Occurs when the air temperature increases as height above the ground increases. This is the opposite of what occurs normally.

Line Fire: Describes a fire that has reached a steady rate of acceleration.

Litter: The uppermost layer of ground cover on the forest floor. It is comprised of un-decomposed leaves, twigs and branches that have fallen from the trees and shrubs to rest on the ground (Johnson, 2001).

Point Source Fire: Describes a fire in the early stages, just after ignition. The rate of spread of the fire is still accelerating and gaining momentum.

Saddle Slope: Describes a depression or pass in a ridge line.

Spotting: Occurs when fire brands are lifted into the air by the updrafts resulting from the convection currents created by a fire. These fire brands are carried by the convection currents ahead of the current position of the fire front. Fire brands can ignite the vegetation surrounding the area where the firebrand was deposited and begin new fires (Johnson, 2001).

Stable Atmosphere: Stable atmosphere is the term used to describe the phenomenon when air temperature increases with increasing height above the ground. Stable air restricts convection column development and encourages more uniform and predictable burning conditions. This condition is also known as an atmospheric inversion.

Surface Fire: A fire not involving the tree canopies or upper branches of coniferous trees

Unstable Atmosphere: Unstable atmosphere is the term used to describe the phenomenon when air temperature decreases with increasing height above the ground. Unstable air allows a warm parcel of air created by the heat of the fire to rise to great heights and establish towering convection columns. The stronger the convective activity created by the fire, the stronger the in-drafts. This increases fire intensity and can create the conditions needed for long range spotting.

Vortex: A whirling mass of air like a dust devil or small tornado. Vortexes have a low pressure center which pulls in fire and objects. They can travel in upright, vertical positions or horizontal, rolling positions (Johnson, 2001). They are also called fire whirls.

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Appendices

Appendix A: Surface Fuel Consumption Curves

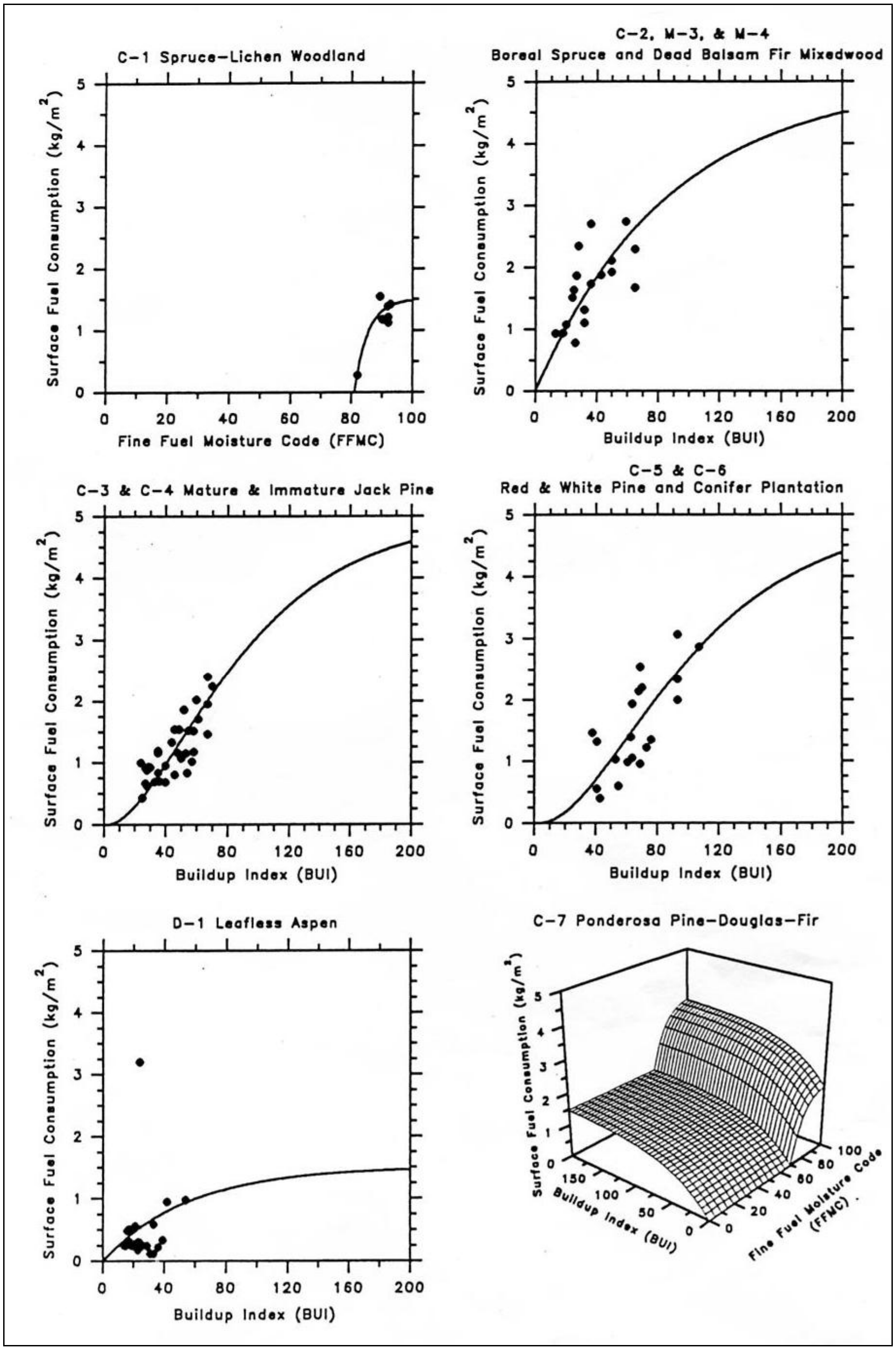

Figure A1: Surface Fuel Consumption Curves for Fuel Types C1-C7, M3, M4 and D1 (Van Wagner, 1987)

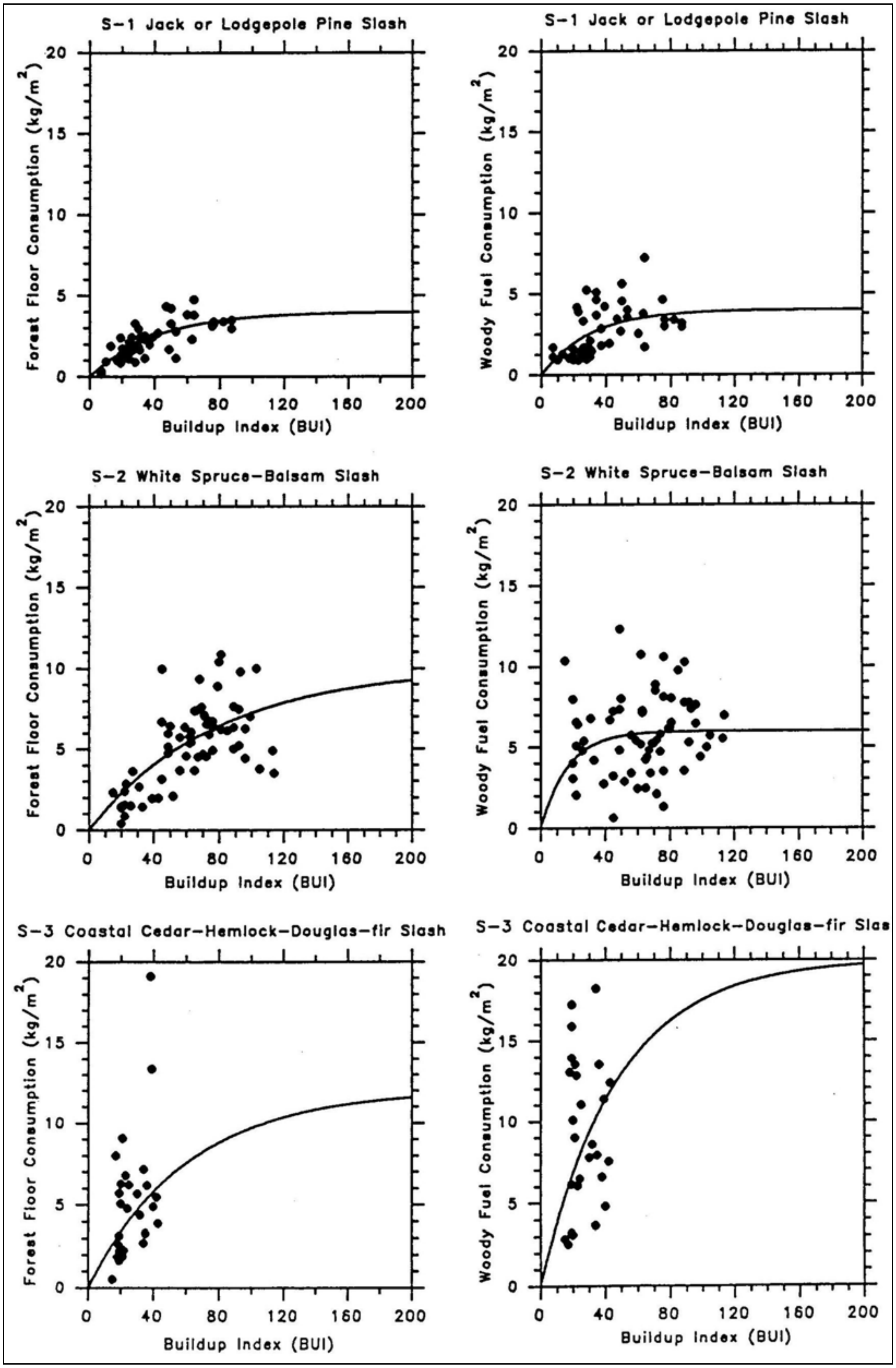

Figure A2: FFC and WFC Curves for S Fuel Types (Van Wagner, 1987)

Appendix B: Rate of Spread Curves

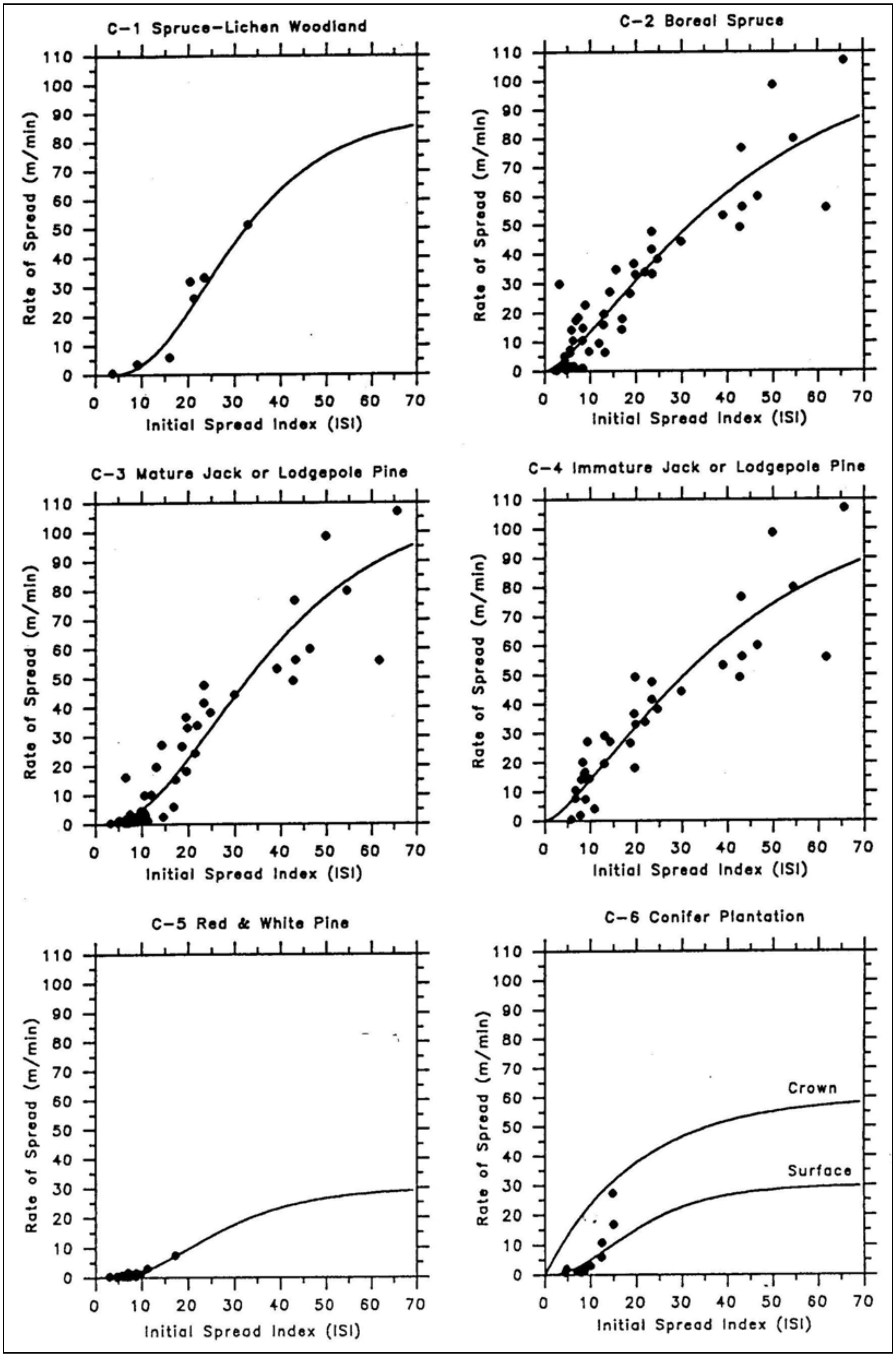

Figure B2: ROS Curves for C1 - C6 Fuel Types (Van Wagner, 1987)

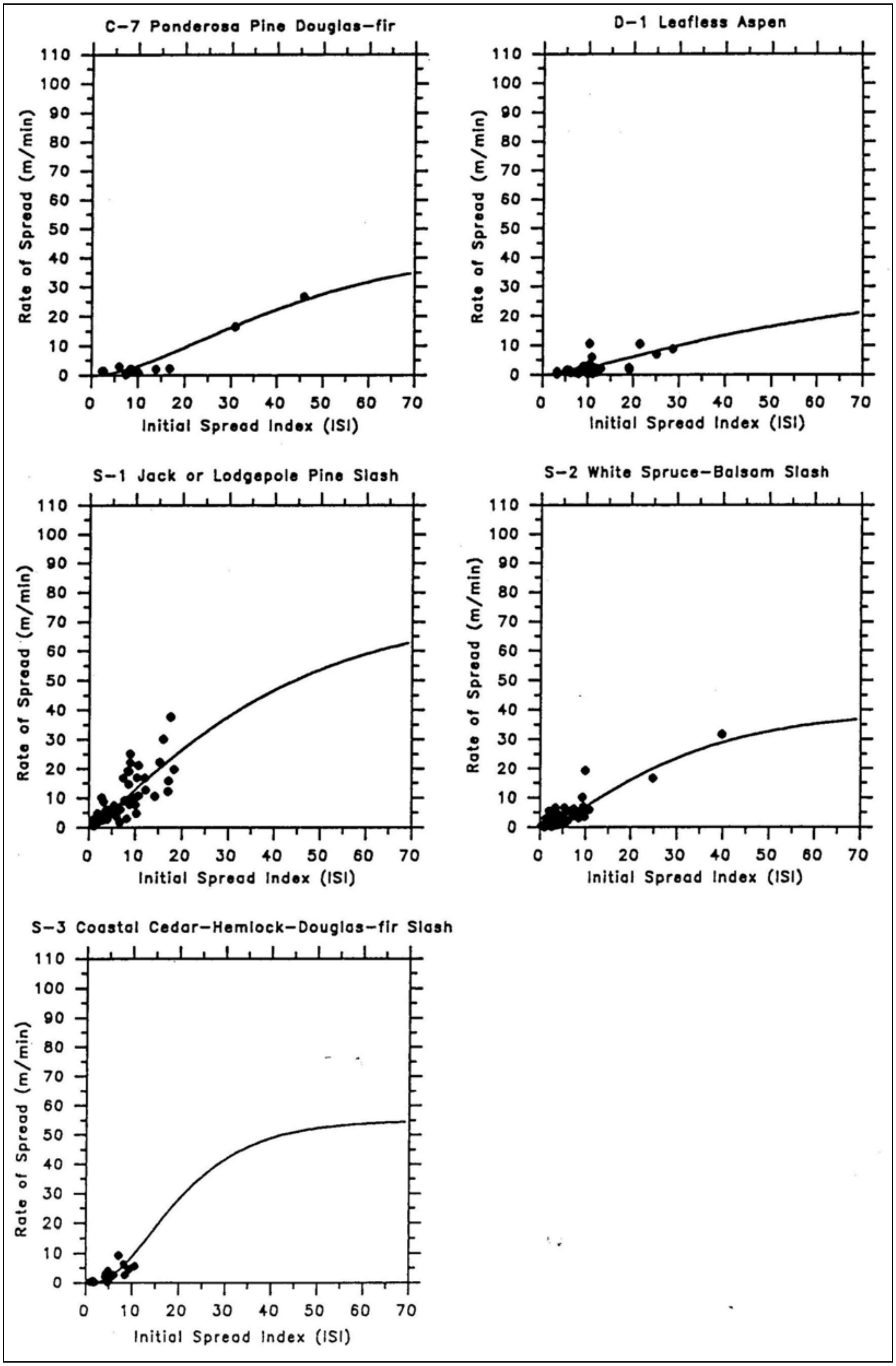

Figure B3: ROS Curves for C7, D1, and S Fuel Types (Van Wagner, 1987)

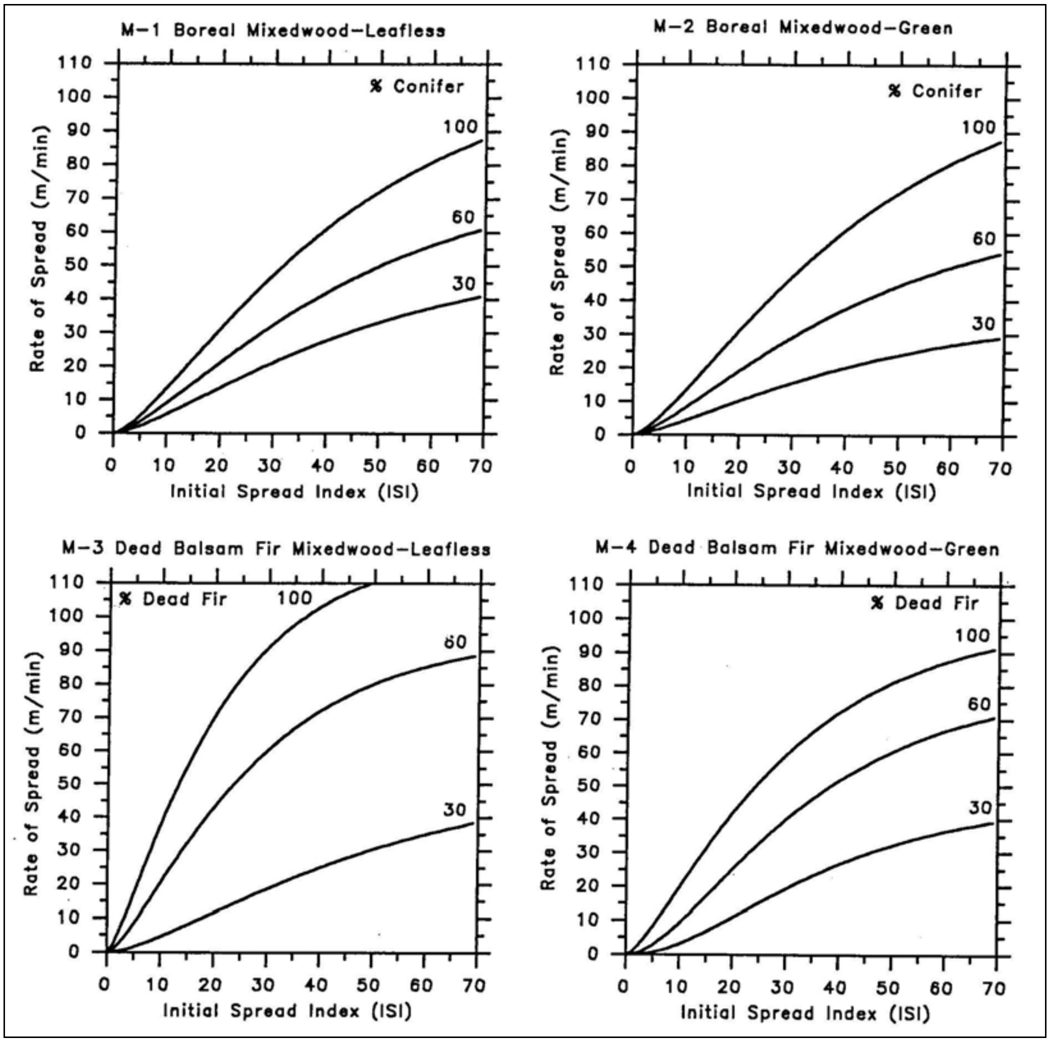

Figure B4: ROS Curves for M Class Fuel Types (Van Wagner, 1987)

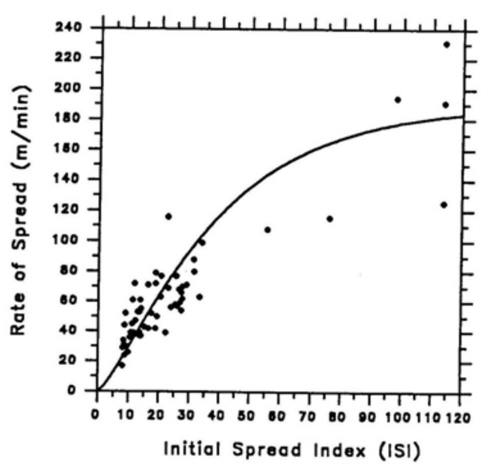

Figure B5: ROS Plot for Matted Grass (Van Wagner, 1987)

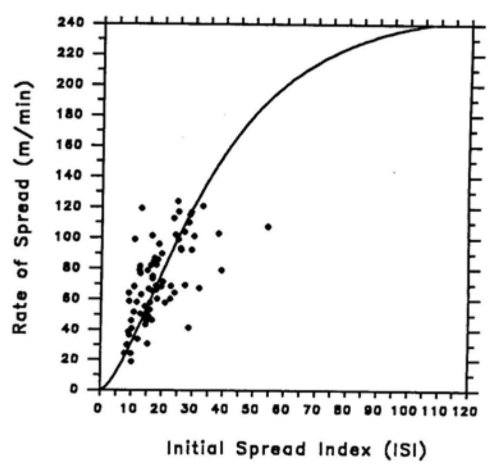

Figure B6: ROS Plot for Standing Grass (Van Wagner, 1987)

Appendix C: Methodology for CWSPM Fuel Type Weights

Table C1: Parameters Entered into Eleven ROS Scenarios

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 8	Run 9	Run 10	Run 11
Month	6	6	6	6	6	6	6	6	6	6
Day	1	1	1	1	1	1	1	1	1	1
BUI	40	70	70	70	40	40	50	100	90	50
FFMC	90	90	99	85	99	85	85	95	95	70
Latitude	55	55	55	55	55	55	55	55	55	55
Longitude	110	110	110	110	110	110	110	110	110	110
Elevation	0	0	0	0	0	0	0	0	0	0
Ignition	Point	Point	Point	Point	Point	Point	Point	Point	Point	Point
Wind speed	0	0	0	0	0	0	0	0	0	0
% Slope	0	0	0	0	0	0	0	0	0	0
Elapsed Time	30	30	30	30	30	30	30	30	30	30

Table C 2: ROS for all Fuel Types for the Eleven Scenarios

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11
C1	0.1	0.2	10.2	0	9.6	0	0	2.1	2	0	0
C2	3.6	4.3	22.4	1.6	18.5	1.3	1.4	12.3	12	0.2	0.6
C3	0.5	0.6	12.6	0.1	10.8	0.1	0.1	3.9	3.8	0	0
C4	4	4.5	23.1	1.6	20.5	1.4	1.5	12.4	12.2	0.3	0.7
C5	0.1	0.1	5.3	0	4.7	0	0	1.4	1.4	0	0
C6	0.7	0.7	29.2	0.1	9.1	0.1	0.1	7.4	5.3	0	0
C7	0.6	0.6	5.7	0.2	5.2	0.2	0.2	2.4	2.4	0	0.1
M1-25	1.5	1.7	9.1	0.6	8.1	0.5	0.6	4.7	4.7	0.1	0.2
M1-75	3.2	3.6	18.6	1.3	16.5	1.1	1.2	9.8	9.7	0.2	0.5
M2-25	1.1	1.2	6.5	0.4	5.8	0.4	0.4	3.4	3.4	0.1	0.2
M2-75	3	3.4	17.7	1.2	15.7	1.1	1.2	9.4	9.3	0.2	0.5
M3-25	0.7	0.7	4.7	0.2	4.2	0.2	0.2	2.3	2.2	0	0.1
M3-75	9.1	10.3	44.4	3.9	39.4	3.5	3.7	26	25.7	0.7	1.6
M4-25	0.3	0.3	5.2	0.1	4.6	0.1	0.1	1.9	1.9	0	0
M4-75	3.3	3.7	23.2	1.1	20.6	1	1.1	11.6	11.4	0.1	0.4
D1	0.7	0.8	4.5	0.3	4.3	0.2	0.2	2.2	2.2	0	0.1
S1	4.8	5.6	23.2	2.3	19.9	2	2.1	13.8	13.6	0.5	1.1
S2	1.7	2	11.6	0.7	9.9	0.6	0.6	6.1	6	0.1	0.2
S3	1.3	1.5	23.4	0.2	20.1	0.2	0.2	8.9	8.8	0	0
O1a	6.2	6.2	28.1	2.4	28.1	2.4	2.4	15	15	0.5	1
O1b	5.3	5.3	32.1	1.7	32.1	1.7	1.7	15.3	15.3	0.2	0.6