USING REMOTE SENSING TECHNIQUES TO SIMULATE WILD FIRE

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ENFO 410

ENFO 410 DISSERTATION REPORT

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Contents

Acknowledgements:

First, during this hard time of COVID-19, I would like to thank my parents and all my family members, appreciate them supporting my education in the University of Canterbury and I would like to take this opportunity to express how much I miss my family in China.

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Abstract:

Understanding the incidence and causes of wildfires in connection to fuels, weather, and geography enables fire management to effectively evaluate fire risk and focus mitigation actions to lower particular threats. This research sought to predict forest fire behaviour using an advanced fire behaviour model called FlamMap. The software was used to simulate fire behaviour geographically and temporally using the 2019 Pigeon Valley fire in New Zealand's Tasman area. It takes into consideration the fuel, geography, and prevailing weather. To evaluate the impact of employing spatially gridded wind data in fire modelling, a WindNinja model was used to create local winds affected by vegetation and terrain in the region. These winds were then employed in the FlamMap model.

Validation of the simulations was performed using a real-world mapping fire scar. Using spatially gridded wind data, the simulations determined the extent of the actual burnt area. Using spatially gridded wind data resulted in accurately estimating the actual burnt area. Due to the sheltering effect of the canopy layer, low density woods had high intensity fireline, while high density forests experienced low intensity fires.

This research showed the applicability of the FlamMap model in Nelson's hilly topography, confirming the concept's applicability in New Zealand. However, for accurate fire simulations it is necessary to map the fuels to create realistic fuel models that are condition-specific. The purpose of this project was to show the feasibility of calculating wildfire spread rate, flame length, and fireline intensity from forest fires utilising GIS and remote sensing methods in conjunction with commonly produced fire behaviour models.

1. Introduction

While it may be possible to destroy all sorts of forest species and ecosystems as a result of forest fire, and it also demands a large amount of resources to combat, and typically results in significant losses to people's lives and property. At the present, decision support for forest fire extinguishing is mostly based on remote sensing, observation decks, and other monitoring data, with assistance from two-dimensional geographic information systems for analysis and decision-making. This approach provides rather basic and restricted information. The spreading process of forest fires may be reproduced in a three-dimensional virtual forest setting using virtual reality and geographic information system technologies in conjunction with the more mature FlamMap forest fire spreading two-dimensional simulation system. Simultaneously, the intuitive, vivid, and dynamic representation of the spreading process of forest fires may significantly improve people's comprehension of the spreading process and forecast of forest fires, increase decision-making efficiency and accuracy, and decrease fire-related losses.

Because wildfires behaviour is generally affected by terrain, vegetation conditions, and weather, the intensity of the fire and carbon emissions will be estimated using forest fire simulations. Understanding the carbon cycle is critical for building an effective strategy for addressing the global warming challenge. (Sibanda, 2011)

Forest fire behaviour models will be used to mimic the particular fire occurrence that occurred in Pigeon Valley, Nelson, in 2019. FlamMap has not been widely utilised in New Zealand as a realistic simulator capable of simulating fire behaviour under a variety of topography, forest, and weather circumstances. Thus, this study will be the first to re-simulate a forest fire in Pigeon Valley forest using remote sensing data and compare it to real data, thus determining the viability of employing FlamMap in New Zealand.

This project included three main purposes:

- To model forest fire spread and assess the influence of employing both uniform and regionally variable wind data in explaining fire spread.
- To compare the simulated scorched regions in FlamMap to a real-world burn scar map.

- To assess the distribution of fireline intensity across various forest cover types in the study region under known meteorological conditions.

The FlamMap fire spread model was first developed to replicate controlled burns in the national parks and wilderness areas of the United States of America (Arca et al., 2007). Prescribed fires are intentionally caused wildfires that are used to manage surface fuels, reduce disease, and improve grazing pasture (Wade et al., 2000). Typically, the FlamMap concept has been extensively implemented and validated around the globe, including Europe and Australia (Arca et al., 2006). It has been examined the FlamMap model's ability to accurately duplicate fire distribution and behaviour using a historical fire event, detecting a high degree of agreement between simulated and real fire scars. Additionally, the simulations assessed the effect of geography, weather, and fuel models. When custom fuel models were utilised, more accurate estimations of fire spread were achieved than when standard fuel models were used. They discovered that proper fuel models and wind data are required for realistic fire modelling when using the FlamMap fire spread model. Historical fire simulation is crucial for comparing simulated and observed fire development and for adjusting/validating the model for a specific location.

Past fires study will indicate how to simulate previously known fire behaviour given the supplied data. The modelling of previous fires is the most critical basis for forecasting future fire events.

Study area

The Pidgeon Valley Fire started as a small wildfire in the Tasman District and quickly escalated to become New Zealand's biggest wildfire. On February 5th, 2019, the Pigeon Valley Fire began as a result of a spark created by agricultural equipment. It expanded swiftly and threatened to engulf the neighbouring town of Wakefield, causing a mass evacuation of its 3,000 people.

2. Literature Review

FlamMap is a piece of software designed to aid in the simulation and modelling of fire behaviour. This application has a function for creating spatial maps of fire behaviour, which is critical when using GIS to analyse fire behaviour and effects. Nowadays, FlamMap is widely used across the world, and the requirement and benefit of combining it with a vegetation data base in order to adequately predict fire behaviour in forests has been recognised. FlamMap's primary purpose as a simulation programme is to simulate:

- Past fires
- Active fires
- Potential fires

Based on these three primary applications, wildfire models have been typically constructed for a long-term meteorological scenario that will determine the growth trend of wildfire over an extended time. FlamMap analyses the possibility for fire development under various weather conditions and uses the simulation findings to make firefighting decisions. FlamMap is most often used to manage fire planning; possible fire behaviour may be simulated under a variety of weather, topography, and vegetation circumstances (Finney, M. A., & Andrews, P. L., 1999).

Wildfires are a huge tragedy in New Zealand and across the globe, claiming human lives and property. Each year, on average, approximately 3,000 wildfires flare throughout New Zealand, mostly in the southland. According to research (Figure 1), the trend of annual VH+E (Extremely High and Extreme) risks from 1997 to 2019 indicates that the following regions are very likely to see an increase in risk:

- Queenstown
- Gore
- Gisborne
- Masterton (Holdsworth)
- Lake Tekapo
- Napier

In New Zealand, wildfires occur annually as a result of climate change and human activity in the forest. Fire is one of the primary elements that disrupt the structure and dynamics of a forest; after a forest fire, a large volume of dead wood is created as a result of tree loss. Indeed, it will cost a large amount of money to avoid each year in nations, and each country's primary objective is to mitigate the consequences and manage the ecosystems (Bayne et al., 2019).

To manage effectively, it is critical to understand the fire behaviour components that might cause and affect fires in the environment. FlamMap is one of the most convenient and accurate models available for forest fire management. FlamMap has a consistent structure and is the most widely used programme for simulating fire propagation. FlamMap has always been regarded as the primary fire simulation system for the purpose of "describing fire release and behaviour."

Five ArcGIS layers are required for the FlamMap simulator: height, fuel type, direction, canopy, and slope. These geographic coordinates are used to characterise the area's landscape. Topographic data is used to represent terrain information such as elevation, slope, and inclination that may be taken from satellite images and translated to ASCII data format (Kanga & Singh, 2017).

Another key input data source in FlamMap is meteorological data, which includes temperature (hot), humidity, and wind speed. To handle climatic data, an observation of weather change in a certain time period within the research region would be made. The standard burning model's description would be chosen and utilised as the foundation for the fire extension model in the burning model. The chosen burning model was created by analysing the map of vegetation data, and the observations and field studies will be constructed using the model's similarity description. Meanwhile, create a suitable format in the FlamMap model to simulate the five levels and the classification of the fire zone according to its extent (Zigner et al., 2020).

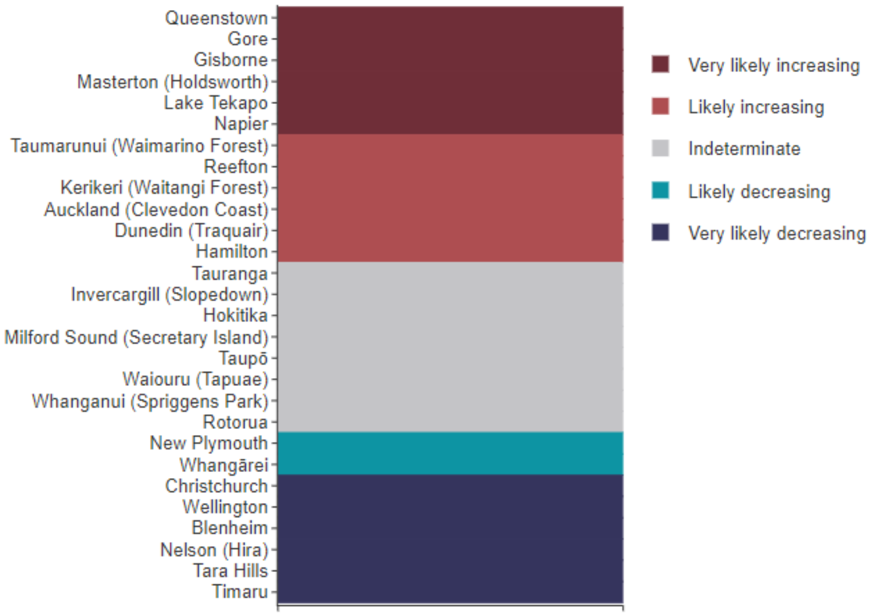

Figure 1. New Zealand trend in annual VH+E (Very High and Extreme) from 1997 to 2019.

Fuels, oxygen, and heat all contribute to the "wildfire behaviour triangle." In contrast, the "wildfire environment triangle" in the forest has a structure that includes fuels, terrain, and weather. The leading factor, such as meteorological conditions, is utilised to predict the spread and severity of wildfires. The strong wind event is the primary component that will contribute to the quick spread of wildfire.

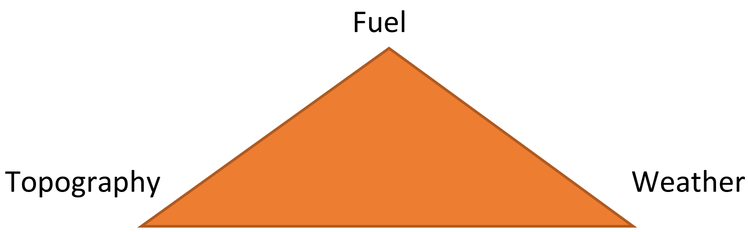

Figure 2: Wildfire environment triangle

In late January 2015, a wildfire spread over 330 hectares of the burnt region near Arthur's Pass. This incident was said to have expanded swiftly due to the dry weather and windy conditions, the dry grass and shrub served as fuel for the fire, and the fire travelled across the region covered in dry grass and shrub right into the wilding pine and beech forest. If dry grass and shrub fuels deteriorated into heavy fuels, a high-intensity crown fire would form and would be impossible to extinguish even with an optimum number of helicopters equipped with water bombers. While the fire was blazing, the embers spread and created a new burning zone with a circumference of 500 metres.

The Flock Hill fire event's fire behaviour has been restricted; this fire event was horrible due to its rapid spread and unrestrained intensity. Scion's Fire Research Group anticipated the causes after their work modelling fire behaviour and developing an effective strategy for fighting flames.

Almost all wildfires in New Zealand are caused by humans, either accidentally or deliberately. Approximately half of the causes of wildfires are unknown or various, however this percentage is decreasing as fire investigation improves. Taking into consideration the known causes of forest fires, about 40% of the overall affected area is due to the loss of control of neighbouring land clearance and burning, while 20% is due to fireworks or weapons, and 10% is due to chainsaws and vehicles. Lightning and other naturally occurring phenomena account for less than 1% (Harnett, 2015).

3. Methodology

3.1: Forest fire behaviour modelling

To start, the fire spread model in FlamMap must be developed. Before the model can be built, five spatial input raster layers must be analysed: slope, fuel, elevation, canopy cover map, and aspect. Non-spatial data are also necessary; these data include precipitation, humidity, temperature, wind direction and speed, and wind direction and speed at the time the fire incident occurred (Finney et al., 2011).

For the input data which need to be created as necessary input factors in the fire behaviour model, the main five of them are:

- Elevation, slope and aspect maps
- Canopy cover map
- Fuel map
- Gridded wind data
- Weather data in text format

3.2: Creating topographic maps (slope, elevation, and aspect)

As the initial step in creating a digital map, a Digital Height Model (DEM) of the study region must be constructed using ArcGIS software to determine its elevation, slope, and aspect. The rationale for developing the DEM model is because topographic characteristics have a strong impact on fire behaviour. For example, a fire may readily spread on a sloped surface because the ground surface produces a better contact than a level surface; hence, a slope favours heating up the fuel (Wechsler, 2007).

Due to New Zealand's southern hemisphere location, the slope to the north will get more sunshine than the hill to the south. As a result of New Zealand's geographic location, the north side will absorb more heat from the sun, directly causing the temperature to rise and the atmosphere to become drier. The ignitability of the fuel will be greater in the north than in the south.

Weather factors such as precipitation have a direct effect on the occurrence of fires; typically, the probability of precipitation is greater at high altitudes than at low altitudes; this is because the temperature at high altitudes is lower than at low altitudes; consequently, the probability of fire occurrence is lower at high altitudes due to the high moisture content of the fuel (Zhang, 2010). As previous mentioned, topographic map is an important input to analyse fire spread. In ArcGIS, a tool called spatial analyst to determine the slope, elevation, and aspect of the specific study area.

3.3: Creating a canopy cover map

Crown cover, often known as forest canopy cover, refers to the fraction of tree crowns that are covered vertically. Canopy cover (CC) denotes the total amount of tree canopy cover in a stand, as well as the percentage of coverage. CC shows the vertical projection of the tree canopy on a digital horizontal surface, which is an illusory data base (Jennings et al., 1999).

Prior to constructing a canopy map, the research forest area's cover types must be specified. The study forest area's fundamental cover types are classified as high-density forest, medium density forest, low density forest, and shrub. Canopy cover is a factor that may help lessen the wind impact of the flame and can help decide the fuel's moisture content. The thick and closed canopy state reduces the air's relative evaporation. Under a thick and closed canopy, the soil's humidity will remain constant. Meanwhile, the meteorological conditions under this canopy region might be calculated.

To create a canopy cover map of the study forest region, the spatial analyst (reclassify) tool is used to locate and select the canopy cover areas on the map, then identify these pictures as the input raster for forest density. Following the reclassification stage, the cover type class must be chosen (NWCG, 2019).

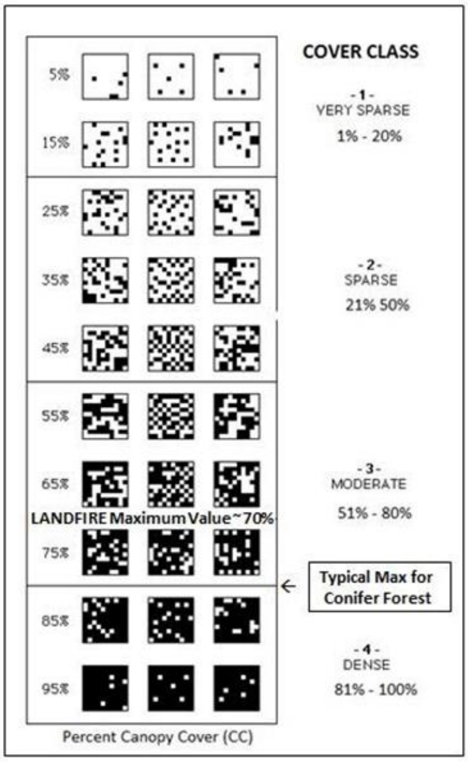

Figure 3: The scale illustrates representative CC percentages and ranges within each cover class (NWCG, 2019).

Table 1: Canopy cover percentage with wind sheltering (NWCG,2019).

Canopy Cover	Wind Sheltering
C ≤ 5%	Unsheltered
5% < C ≤ 10%	Partially Sheltered
10 % < C ≤ 15%	Partially Sheltered
15% < C ≤ 30%	Fully Sheltered, open
30% < C ≤ 50 %	Fully Sheltered, open
C > 50%	Fully Sheltered, closed

3.4: Creating a fuel map

A map of forest density was developed during the process of developing a canopy cover map. To construct a fuel map, the forest density map will be used. A similar strategy will be employed on this project, which will categorise and create a new raster of fuel maps. The data gathering phase of the research is the most difficult; it must be assumed wildly that every combustible in the study forest area may be classified as a sort of fuel (Andersen et al., 2005).

During this process, it is important to:

- Resample the raster data
- Convert the data to ASCII format

Because models of fire behaviour such as FlamMap are controlled by fuel inputs like as load, heat content, and moisture of extinction, representations of fuel attributes in the form of fuel models are required. Fuels relate to the physical properties of living and dead biomass that contribute to wildfires, such as loading, depth, height, and bulk density. These qualities all contribute to a fire's size, intensity, and longevity. A fuel model is a numerical representation of the physical properties that define each kind of fuel, including the fuel load, bulk density, particle size, heat content, and moisture of extinction (Arroyo et al., 2008). These types are classified according to the kind of fuel they transport, which may be grass, shrub, timber, or non-burnable (Scott and Burgan, 2005).

The quantity of fuel transported, the distribution of the load's size classes, and the architecture of the load, such as compactness or bulk density, all affect the ignition that results in a sustaining fire. Horizontal continuity has an effect on whether or not a fire spreads and at what rate, while loading and vertical organisation have an effect on the size of the flame. The combination of low fuel moisture content and strong winds has a substantial effect on fire behaviour, since an extreme fire behaviour may occur. Certain chemical constituents of fuel, such as explosive oils, contribute to the spread of fire (Anderson, 1982). Fuels, climate, season, and local weather all interact to affect the amount of live and dead fuel, hence affecting the pace of fire spread.

Surface fuels may be input using either standard or custom-built fuel models (Finney, 1994). It has been developed the first 13 fuel models for calculating the spread rate and intensity of active flames during the peak of the fire season, in part owing to the dry circumstances associated with the season. 40 additional models has been developed to increase the number of fuel models suitable for high-humidity environments. These more modern fuel models are more often employed in fire modelling than the previous 13 models, owing to their ability to be applied to a broader range of plant species. This is because the models characterise fuels based on their physical characteristics, as opposed to previous models, which classified fuels based on their vegetation or species types (Anderson, 1982).

3.5: Collecting weather data

The behaviour of fire is influenced by a variety of meteorological variables, including precipitation, temperature, wind speed and direction. While precipitation is related to the moisture content or state of the fuel, temperature is a characteristic that may help assess the fuel's dry condition. Wind is a direct element in the propagation of fire and the drying out of fuels; hence, wind increases the risk of burning. The three components that contribute to fire are heat, fuel, and oxygen; this is sometimes referred to as the fire triangle. The reason why wind favours burning is because as it blows, it provides oxygen and pre-heats the fuel at the same time (Marsden-Smedley & Catchpole, 1995).

The research demonstrates that the wind has an effect on the intensity, direction, and form of fire, such as the shape and intensity of fire are impacted by the direction of the wind, and the strength of the wind has an effect on fire spread behaviour and intensity.

During the weather data collecting process, the local weather station of the study area should be located and record the weather information includes:

- Minimum temperature
- Maximum temperature
- Relative humidity

These data are going to be used as the input to build the climate model of the study area and insert into the FlamMap model after it was converted to text format.

Temperature, precipitation, relative humidity, wind speed, and wind direction all have an effect on fire behaviour. Extreme weather events have the ability to modify the moisture content of fuels, hence influencing their combustibility. Wind quickly dries out fuels, increases the preheating of the fuel before to ignition, and provides oxygen. The direction of the prevailing wind has an influence on the shape and intensity of the fire, whilst the strength of the wind has an effect on the speed with which the fire spreads and its intensity (Finney, 1999). The research region's climate was created using daily minimum and maximum temperatures, as well as relative humidity, as observed at a weather station located inside the study area. It was converted to a text format before to being integrated into the FlamMap model. Due to the difficulties in acquiring wind data for the study region, daily wind speeds for February were collected from a meteorological station located outside the study area.

3.6: Using FLAMMAP model simulate fire spread

The landscape file will be constructed in the FlamMap model using the five maps provided in ArcGIS (fuel, canopy cover, aspect, slope, and elevation). At the same time, the wind file will be built and combined with the weather file for the precise day when the fire occurred. The table below summarises the weather data that would be entered to FlamMap (Weinstein et al., 1995).

The next step is to define the time period; for example, during the fire spread simulation, the time interval for the fire event would be set to 30 minutes using spatial data. The time interval specifies how much time it would take to maintain consistent environmental conditions. The resolutions are perimeter and distance; both are set to 30 metres because the perimeter will control the front of the fire and the distance resolution will regulate the anticipated fire spread distance.

Prior to running a simulation, the ignition location to be specified, and in FlamMap, the ignition point may be any value. It is capable of controlling several types of fire behaviour, which may be selected, for example, whether the surface fire will be simulated and the crown fire model will be closed.

As noted before, weather data collection is critical. Wind simulation is the most challenging stage in this procedure, since it is tough to mimic due to its diverse intensity and direction. On the basis of this challenge, a software named WindNinja is built to calculate changing wind speeds caused by inadequate descriptions. This software would be employed in a variety of situations depending on the height, topography, and vegetation cover. After simulating wind data, the gridded wind data files will be entered to the FlamMap model (Sanjuan et al., 2020).

In FlamMap, the time and time error tolerances must be configured, as well as the limitations for fire behaviour space computations. These two processes of parameterization enable the calculation of frequency in time and distance in space.

The word "fire behaviour" refers to the manner in which a fuel burns, flames expand, and heat and fire spread. This behaviour is determined by the kind of fuel used, the topography of the region, and the local weather circumstances. Fire models have been developed to anticipate fire behaviour and measure the rate of fire spread. Fire models have been developed as mathematical linkages that depict the features of a future fire.

The bulk of fire models are based on Rothermel's (1972) model of fire propagation, which mimics the spread of fire. These models anticipate fire behaviour by including data on fuel loads, terrain, and climatic conditions. They generate numerical values for fire parameters such as the fireline's intensity, the rate of spread, the hazard of ignition, and the flame height. Modeling is the prefered tool for studying forest fire dynamics over wide geographical and temporal dimensions due to its cost efficiency and non-destructive nature.

3.7: Wind behaviour modelling

Wind is an important environmental factor that contributes to the spread and intensity of forest fires. The velocity and direction of wind are significantly influenced by topographic features such as mountainsides, valleys, and ridges. However, the lack of approaches for assessing the effect of local topography on wind is a key source of uncertainty for predicting fire behaviour (Butler et al., 2005). Wind data is utilised to model fire behaviour because meteorological observations reliably capture broad, large-scale trends but do not provide information on local, terrain-influenced winds. This complicates fire behaviour forecasting. The difficulty is compounded further by the fact that wind often oscillates on very small temporal and geographical scales. Rothermel (1972) asserts that the relationship between wind speed and spread rate is nonlinear, implying that a change in wind speed may result in a larger change in spread rate.

Forest fires on steep terrain are highly influenced by sophisticated, spatially varied wind patterns, where topographically caused changes in wind direction and speed result in unexpected, erratic fire behaviour. Accurate modelling of the behaviour of local winds has been shown to improve fire behaviour prediction. Replicating wind behaviour requires simulating "the influence of terrain on wind flows" (Butler et al., 2006). The simulation considers the influence of elevation, geography, and vegetation on the total wind flow. Numerous models have been developed to forecast the wind's behaviour. They are classified as either prognostic or diagnostic models. Prognostic models forecast the future using an initial wind field, while diagnostic models re-create a single moment in time (steady-state models).

For this research, the WindNinja model was employed since it is open-source and capable of accurately simulating local wind dynamics. WindNinja is a diagnostic model that forecasts fire behaviour by estimating regionally varying wind fields (Forthofer et al., 2007). As input data, elevation, mean wind speed and direction, and a description of the dominant vegetation in the study area are required. It has a resolution of around 100 metres and is capable of functioning on domains up to 50 kilometres by 50 kilometres. This model creates raster grids representing wind speed and direction for use with spatial fire behaviour models such as FlamMap, shapefiles for showing wind vectors in GIS applications, and kmz files for viewing in Google Earth.

Wind is taken into account when predicting fire behaviour using the FlamMap fire spread model. However, it makes the assumption that wind fluctuates in time but not in space. This description of the wind field is imprecise, resulting in ambiguity when forecasting fire behaviour. As a result, the use of high-resolution winds improves the accuracy of projections of fire development (Butler et al., 2005). FlamMap supports gridded wind fields. A comparison of simulations of fire development using the FlamMap fire growth simulator with and without high resolution wind data demonstrates that utilising this wind data considerably improves the accuracy of fire growth forecasts (Forthofer et al., 2007). Thus, in this project, the WindNinja model will be utilised to create gridded wind data, which will then be integrated into FlamMap to simulate fire behaviour.

4. Results

4.1 Pigeon Valley fire event background

The February 2019 Pigeon Valley wildfire, which was the most expensive in New Zealand's history of vegetation fires, has also been named the most catastrophic plantation fire in 60 years by others. On 5 February 2019, the Pigeon Valley fire damaged over 2,300 hectares of woodland areas located 30 kilometres south-west of Nelson. This fire demanded the mobilisation of resources from around the country. On the basis of expected and actual weather conditions during the first week of this wildfire, this raises questions about whether appropriate consideration was given to meteorological data when resource deployments were planned. Additionally, it was assessed if the fire weather indices during the first several days of the fire supported the decision to build firebreaks outside the plantation and to evacuate inhabitants from villages to the wildfire's south-east. Additionally, the likelihood of this wildfire spreading to open regions next to the plantation grounds on the south-eastern side is evaluated in the days after the fire's first 18-hour period.

4.2 Data resource

A New Zealand DEM model with an 8-metre resolution taken in 2012 and upgraded in 18th Aug 2016 was used for this study. The reason of choosing this model was based on the suitability for this research which has a higher resolution comparing to the other model resources from Land Information New Zealand – LINZ DATA SERVICE.

The vegetation classification will be closely relating to the analysis of canopy cover percentage and creating the local fuel map. Thus, The Land Cover Database of New Zealand LCDB is a system for classifying land cover and land use. It is an important and authoritative source of national land cover data and is differentiated by the fact that it offers data at typically 5-year intervals, detailing changes in land cover. The Land Cover Database of New Zealand (LCDB) is a multi-temporal, thematic categorisation of the land cover of New Zealand. At each nominal time step, land cover features are represented by a polygon boundary, a land cover code, and a land cover name. LCDB is well suited for environmental monitoring on a national and regional scale, forest and shrubland inventories, biodiversity evaluation, trend analysis, and infrastructure planning. The table below lists the data used for this specific case study.

Table 2: FlamMap inut data resources.

Data	Source
Topography data (DEM, slope, aspect)	NZ 8m digital elevation model provided by LINZ
Climate data (temperature, rainfall, relative humidity, wind information)	History weather report provided weather underground Nelson
Canopy cover / Forest cover	Land Cover Database New Zealand
Fuel models	Standard fuel models

4.3 Flowchart of the process

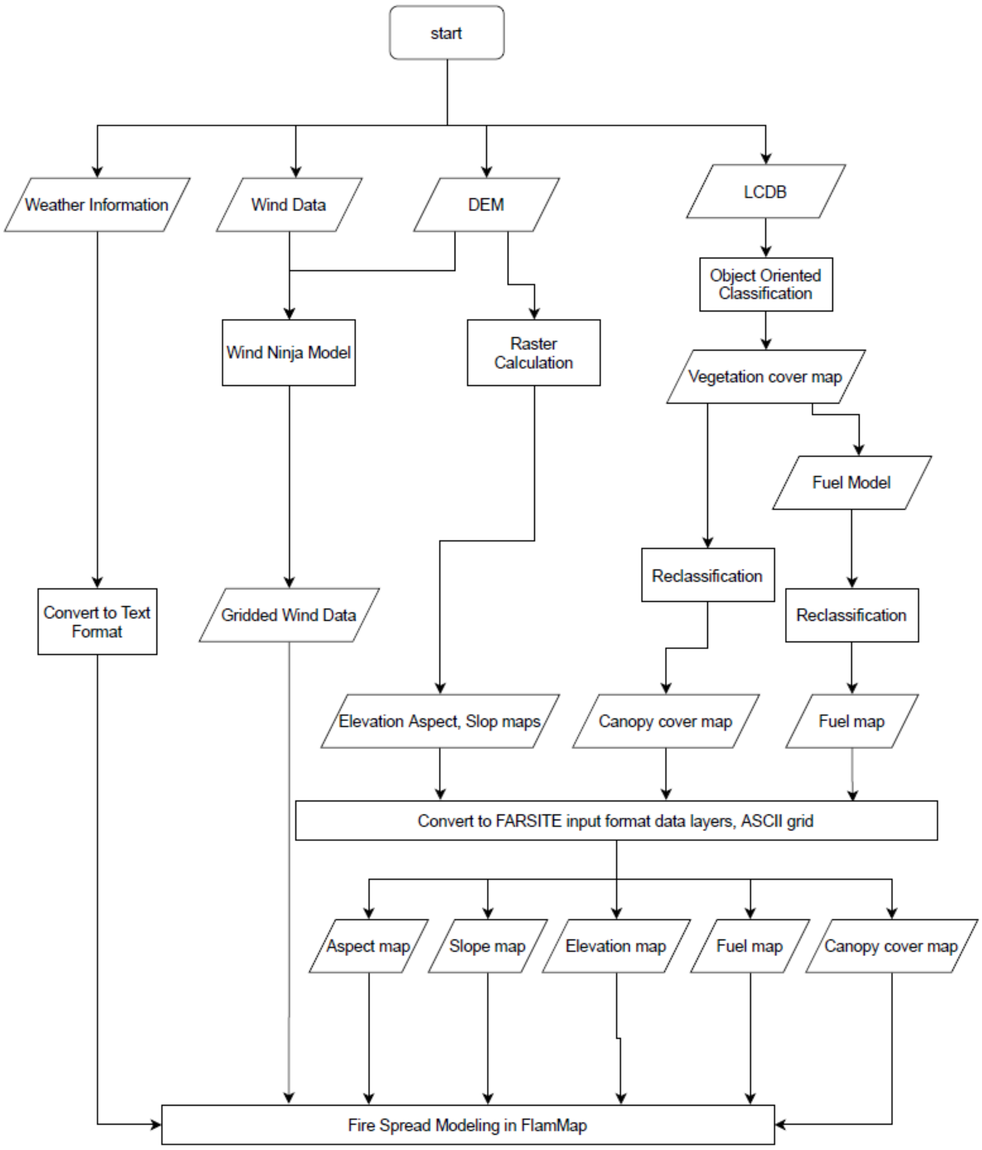

Figure 4. Flow chart of the simulation process.

4.4 Fire behaviour modelling using FlamMap

4.4.1 Input function

Five spatial input raster layers are required for the FlamMap fire spread model, including elevation, slope, aspect, fuel model, and canopy cover percentage. Additionally, the model needs non-spatial variables, such as temperature, relative humidity, precipitation, wind speed, and direction during a fire outbreak. Table below shows all input spatial and non-spatial data corresponding with their functions which has been used in this research.

Table 3: FlamMap input with the function description.

Input class	Inupt	Function
Landscape	Elevation	Temperature and humidity regulation through adiabatic means
	Slope	For the purpose of calculating the immediate impacts of fire spread
	Aspect	Determines the angle of incident solar radiation in conjunction with slope and latitude.
	Canpoy cover	Determines the average shadowing of the surface fuels, which has an on the computation of the fuel moisture content and the wind reduction factor.
	Fuel model	Provides a detailed explanation of the surface fuel complex's physical properties.
Weather	Temperature	Fuel moisture content has an effect
	Relative humidity	Affects the amount of moisture in the air and the pace at which it s
	Wind direction and speed	Influences fire spread
	Precipitation	Affects the amount of moisture in the air and the pace at which it s

4.4.2 Terrain modelling (Topography)

Aspect, slope, and elevation are all crucial factors in determining how a fire behaves. A fire that starts on a slope is more likely to spread, since the flames make direct contact with the ground, heating the fuel (Finney, 1999). As a result, when a fire originates on a mountain, it spreads more slowly than when it begins in a canyon. Aspect is defined as the direction in which a slope face which means the orientation of the topographical relief. It also plays a significant role in fire behaviour, affecting the quantity of radiation that reaches a particular feature.

In reality, Northern hemisphere slopes get more sunshine than southern hemisphere slopes, making them hotter and drier. As a result, fuels positioned on the north and western horizons are more flammable. Elevation does not cause flames to occur more often; nevertheless, it alters the climate, which is directly tied to the incidence of fires. At higher altitudes, the temperature is lower than at lower elevations. Additionally, precipitation is often greater at higher elevations than it is at lower elevations, lessening the likelihood of fires caused by moisture in the fuel.

The area's elevation, slope, and aspect maps were derived using the Spatial Analyst tool in ArcGIS software using a digital elevation model (DEM) of Pigeon Valley in Nelson. There was no need for resampling since the produced maps had an 8m resolution. Following that, these layers were translated to ASCII format and imported into the FlamMap model. The flowing figures shows the elevation, slope, and aspect model created for the case study area.

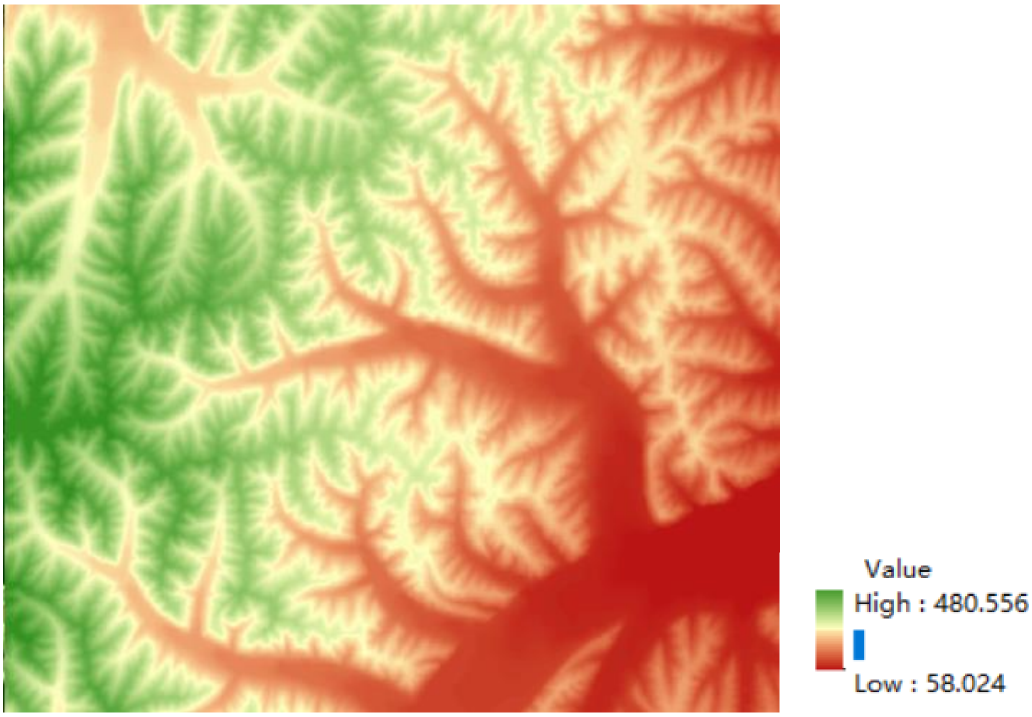

Figure 5. Elevation model created by ArcGIS.

From the elevation model, the range of the elevation is from 58.024m to 480.556m which shows in the green colour in the lower area and red colour in the higher zone.

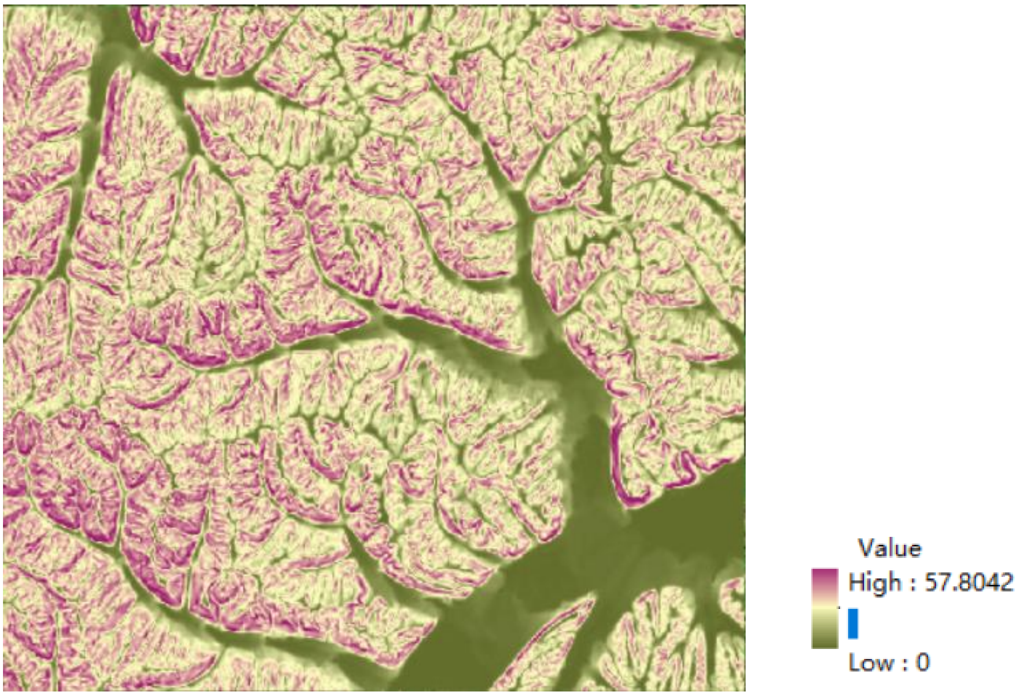

Figure 6. Slope model created by ArcGIS.

As the model shows, the flat area is appearing in green colour which is 0 degree in slope, and high slope area which can be reach to 57.8042 degree.

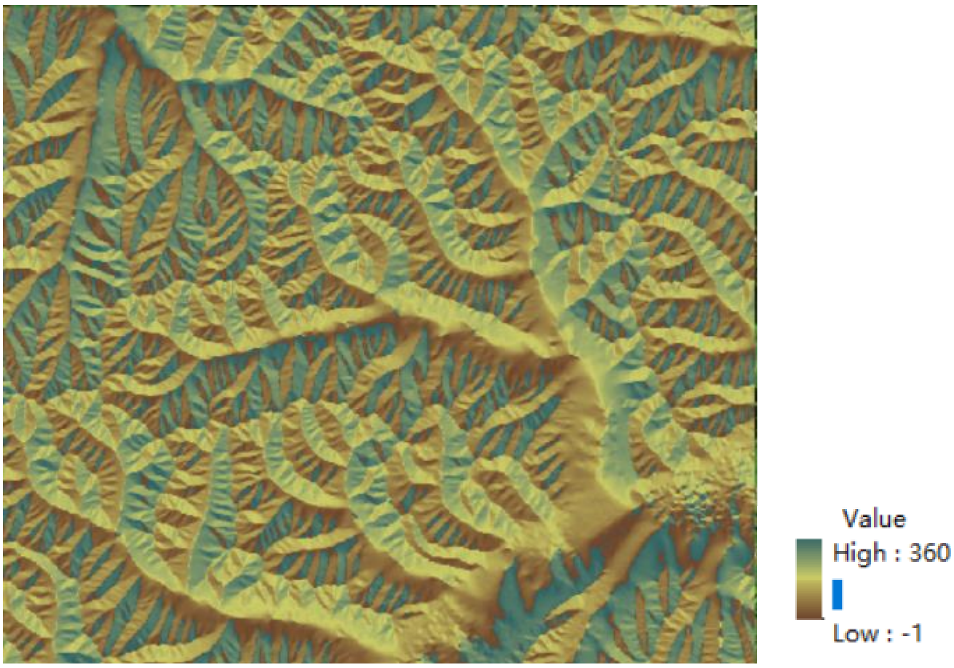

Figure 7. Aspect model created by ArcGIS.

From the legend, it can be told that the aspect of the case study area's range is from -1 to 360.

4.4.3 Canopy cover map & Fuel map

Keane et al. (2000) defined canopy cover (percentage) as the average vertically projected tree crown cover in the stand. It is a factor in determining the quantity of moisture in the fuel and also has an effect on the wind reduction factor under a forest canopy. A tightly packed closed canopy minimises relative evaporation and retains soil moisture, hence affecting the climate and weather patterns of the surrounding region. The canopy cover map shows in figure below which includes different types of canopy cover and the types are introduced in the flowing attribute table.

Figure 8. Canopy cover map data classification from LCDB created in ArcGIS.

Table 4. Classification of canopy cover in case study area.

1	Indigenous Forest
2	Forest - Harvested
3	High Producing Exotic Grassland
4	Exotic Forest

The cover type and canopy cover class of the case study region – Pigeon Valley Forest – are shown in Table 3. The canopy cover class ranges from class 1 to class 4 based on the size of the whole forest.

- Indigenous Forest concerned as medium density forest which has average canopy cover percentage as 50%.
- Forest – Harvested has the average canopy cover as low-density forest concerned as low density forest, canopy cover percentage as 30%
- High Producing Exotic Grassland was estimated as shrub land which has average canopy cover percentage as 5%.
- Exotic Forest has the largest area of case study area which concerned as high density forest, it has the average canopy cover percentage as 80%.

Each location utilises a unique fuel model. The most appropriate fuel models are determined by comparing real vegetation features to standard fuel model specifications. To select a fuel model, one must first determine the stratum of surface fuels most likely to maintain the fire, considering the fuel's overall depth, density, and size, and also the relative abundance of active plants. The new fuel models include the following parameters:

- the load by class and component.
- the surface area to volume ratio by class and component.
- the fuel model type.
- the depth of the fuel bed, the extinction moisture content.
- the heat content of the fuel particle.

In this research, standard fuel models were used since they are appropriate in places with high humidity. When a conventional fuel model is unable to adequately capture the vegetation features of a given location, new fuel models must be constructed. (Scott and Burgan, 2005).

4.4.4 Weather simulation using WindNinja

Temperature, precipitation, relative humidity, wind speed, and wind direction are all examples of meteorological variables that affect fire behaviour. Extreme weather conditions may have an effect on the moisture content of fuels, consequently affecting the likelihood of combustion. Wind rapidly dries out fuels, enhances preheating of the fuel for ignite, and supplies oxygen. The fire's shape and intensity are influenced by the prevailing wind's direction, while the strength of the wind speeds up the spread and increases the severity (Arca et al., 2006).

In this study, the only weather station which located close to the study area is Nelson Airport, although the other weather stations were not able to provide the history weather data when the fire happened. Therefore, the weather simulation results are only reliable on daily minimum and maximum temperature, relative humidity, and precipitation.

Before being imported into the FlamMap model, it was transformed to a text format. Accessing wind data for the research region proved problematic; daily wind speed data for February were obtained from a meteorological station situated outside the study area; however, wind direction data were not accessible. Thus, wind direction was determined in this research using data from a weather station situated at Nelson Airport, 25.8 kilometres from the Pigeon Valley woodland, on the premise that wind direction remained constant across such great distances. Additionally, since the locations have similar climatic characteristics, data from this station were utilised.

The FlamMap model is based on the assumption that wind fluctuates temporally but not geographically throughout the modelling domain (Rothermel, 1972), which results in an inaccurate depiction of the wind field, particularly in a mountainous terrain. As a result, a WindNinja model was used to generate spatially variable wind fields, gridded wind data that take into consideration the impact of height, topography, and vegetation on the overall wind flow. This was accomplished by combining the DEM with the area's forest cover map. The WindNinja model's gridded wind data files (wind speed, wind direction, and cloud cover) were then merged to generate an atmosphere file, which serves as an input format for the FlamMap model.

The table below recorded the weather information since the data of the fire start at 5th of February 2019.

Table 5. Wind information of case study area.

Date:	Time:	Direction (12AM):	Direction (6AM):	Direction (12PM):	Direction (6PM)	WindSpeed (12AM)	WindSpeed (6AM)	WindSpeed (12PM)	WindSpeed (6PM)
2019/2/5	12AM - 6PM	SW 225	SW 225	SW 225	SW 225	14 mph	10 mph	18 mph	21 mph
2019/2/6	12AM - 6PM	SW 225	NNE 22.5	NNW 337.5	ESE 112.5	10 mph	14 mph	6 mph	14 mph
2019/2/7	12AM - 6PM	NNE 22.5	ESE 112.5	NNW 337.5	NNW 337.5	3 mph	8 mph	14 mph	20 mph
2019/2/8	12AM - 6PM	SW 225	SW 225	N 0	NE 45	6 mph	3 mph	12 mph	15 mph
2019/2/9	12AM - 6PM	S 180	SW 225	NNE 24.5	NE 45	1 mph	2 mph	20 mph	18 mph
2019/2/10	12AM - 6PM	S 180	WSW 247.5	NNE 24.5	NE 45	3 mph	3 mph	14 mph	18 mph
2019/2/11	12AM - 6PM	S 180	SW 225	N 0	NNE 24.5	3 mph	3 mph	16 mph	17 mph
2019/2/12	12AM - 6PM	ESE 112.5	SSW 202.5	NNE 24.5	NNE 24.5	5 mph	5 mph	16 mph	13 mph
2019/2/13	12AM - 6PM	ESE 112.5	SSE 157.5	NNE 24.5	N 0	3 mph	6 mph	14 mph	9 mph
2019/2/14	12AM - 6PM	S 180	S 180	N 0	NE 45	5 mph	6 mph	12 mph	10 mph
2019/2/15	12AM - 6PM	E 90	SSE 157.5	NNE 24.5	N 0	3 mph	2 mph	22 mph	8 mph

Table 6. Weather information of case study area.

Date:	Time:	Temperature (12A	Temperature (6A	Temperature (12P	Temperature (6	Cloud cover (%):	Humidity (12AM)	Humidity (6AM)	Humidity (12PM)	Humidity (6PM)
2019/2/5	12AM - 6PM	71 °F	66 °F	80 °F	76 °F	35%	59 %	57 %	34 %	47 %
2019/2/6	12AM - 6PM	71 °F	66 °F	69 °F	63 °F	35%	60%	78%	57%	49%
2019/2/7	12AM - 6PM	59 °F	55 °F	65 °F	66 °F	35%	52%	50%	50%	56%
2019/2/8	12AM - 6PM	59 °F	52 °F	67 °F	67 °F	35%	61 %	82 %	61 %	75 %
2019/2/9	12AM - 6PM	56 °F	59 °F	63 °F	60 °F	35%	79%	89 %	78%	71%
2019/2/10	12AM - 6PM	67 °F	61 °F	71 °F	72 °F	35%	78 %	89%	66%	67%
2019/2/11	12AM - 6PM	64 °F	58 °F	72 °F	72 °F	35%	78 %	93 %	74%	63%
2019/2/12	12AM - 6PM	66 °F	65 °F	74 °F	74 °F	35%	73 %	79%	78 %	73%
2019/2/13	12AM - 6PM	66 °F	61 °F	74 °F	73 °F	35%	69 %	81 %	66 %	70 %
2019/2/14	12AM - 6PM	63 °F	64 °F	73 °F	74 °F	35%	87 %	84 %	74 %	68 %
2019/2/15	12AM - 6PM	68 °F	64 °F	74 °F	69 °F	35%	81 %	86 %	72 %	78 %

4.5 The simulation of fire spreading by using the FlamMap model

4.5.1 6th February 2019 Pigeon Valley fire spread simulation

This section focuses largely on the fire spreading indicators, such as the rate of spread and the duration of the fire, that correspond to the derived gridded wind data on the case study area's unique data. The image depicts the size of simulated fire perimeters created using wind data that is both regionally homogenous and spatially varied in distribution (gridded). Because to the use of gridded wind data, the intensity of the fireline ranged between 1,731 and 3,461 kW.m-1 throughout the fire. The results are comparable with the reported rate of fire spread in this simulation, which is expected given the fact that greater intensity flames spread more quickly in general. The spread rate is measured in metres per minute (m/min) and is defined as the pace at which the fire spreads away from its origin. The wind, moisture, and slope all contribute to the fire's ignition. The blazing zone, or fire head, accelerates away from the source at a high rate of speed. The distance measured between the average flame tip and the centre of the blazing zone at the base of the fire is known as the "flame length." When the flames are skewed as a result of the impacts of wind and slope, it is measured on a slant. The length of the flame is a good estimate of the intensity of the fireline.

When spatially varied wind data were employed, the fire spread at a pace ranging from 1.68 to 6.71 m/min, and the flame length in the main burning zone reached 3.35 metres when it reached the high-density exotic forest area.

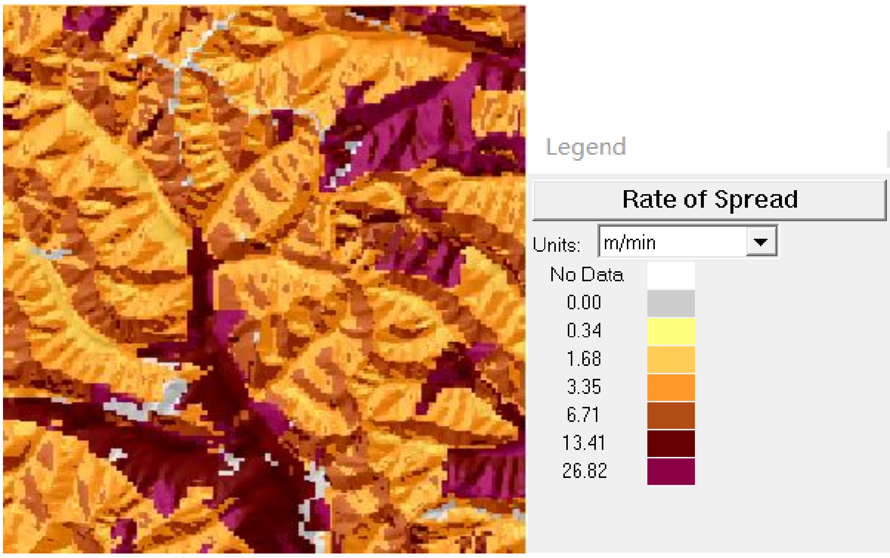

Figure 9. 6th February 2019 fire spread rate.

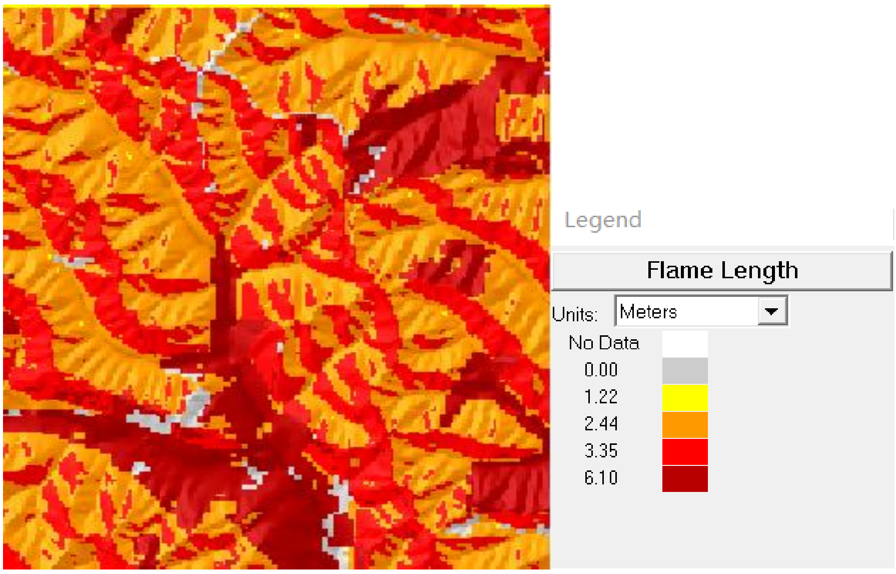

Figure 10. 6th February 2019 flame length

Thus, the incorporation of spatially variable wind data increased the velocity of fire spread, the severity of the fire, and the degree of concordance between simulated and observed burn scars. The model worked well in this circumstance when simulated using gridded wind data. The findings for this fire incident are very consistent, with large positive differences in fire spread, fire intensity, and, subsequently, in the shape of the observed burn scar estimated using gridded wind data. However, when spatially changing wind data were used, the spread pattern and form of the simulated fire scar approximated those of the real fire scar, demonstrating the model's applicability in the research region. The figure below illustrates the fire progression of the Pigeon Valley fire from 5th to 6th from Fire and Emergency New Zealand – (Tasman Fires Operational Review and Plan, 2019).

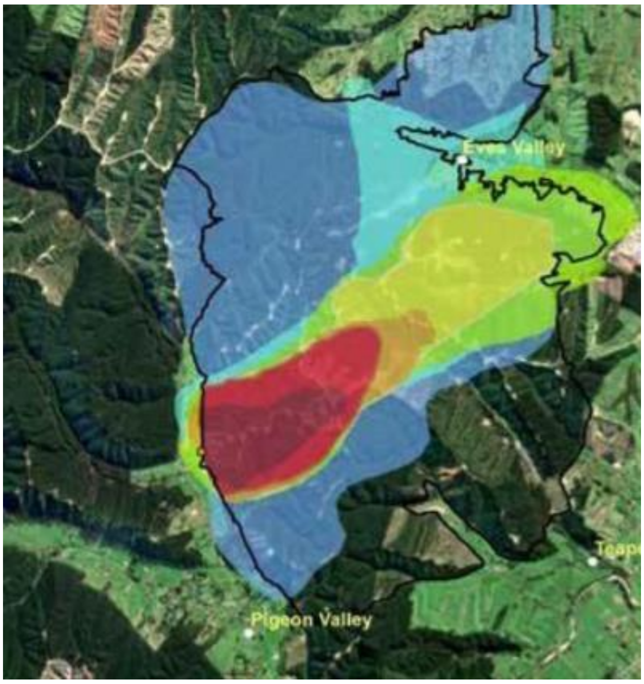

Figure 11. Estimated progression of the Pigeon Valley fire on 5th and 6th February 2019 (AFAC, 2019)

The region shown in red, orange, yellow, and green on the picture corresponds to the fire expanding area on February 5th, 2019, as the straight trend of north-eastern direction reaches the Evea Valley. The blue colour depicts the area that was impacted by the fire on February 6th, 2019, which began in the centre and spread to both the upper and lower sides. On the specified day, the fire made contact with Redwood Valley.

According to the comparison of the observed and simulated burning scar regions, the main direction of the fire spread and the area boundary are more similar. According to the simulation results, the fire occurred in the north-western and south-western areas of the Pigeon Valley forest, which were not affected by the fire in reality. This is because the study area's boundary was defined as a larger area during the simulation process. As a result, the simulation's underlying premise encompasses all conceivable effects on the forest ecosystem.

4.5.2 12th February 2019 Pigeon Valley fire spread simulation

The fire consumed a variety of plantation forest fuel complexes throughout the first three days of fire activity (from recently harvested, to newly established, immature pine and mature pine forests). On Sunday 10 February (day 5), a short but effective controlled burn (2.5 km x 50 m) was undertaken to clear unburned trash and light vegetation underneath mature woods where flareups had occurred the previous two days. This was done to avoid further spot fires igniting and endangering other forests and Sunrise Valley inhabitants. On 12 February, the state of local emergency was re-evaluated and prolonged for seven days beyond its expiration date, until 20th February (and then 27th February), owing to the prognosis for extra severe weather in the coming days.

The fire's mop-up and control took an extended period of time. The region had gone 22 days without rain, and the dry circumstances before and during the fire, along with second and third cycle forest fuels, resulted in significant fuel loadings and a highly flammable fuel load, resulting in deep-seated burning inside the fire area. Within the fire region, patches of unburned or fire-cured vegetation constituted a danger of re-ignition. The rate of spread is a quantitative measure of the rate at which a fire perimeter advances and may be defined as the forwards, backwards, or flanking speed relative to the direction of the prevailing wind causing fire spread. Additional metrics, such as the rate of expansion or growth of the fire area or perimeter, may be used to assess the pace of advancement of a wildland fire.

As the image shows below, the fire spread rate of almost all the exotic forest area reaches to 13.41 m/min and for the area of high producing exotic grassland, the fire spread rate reached to the maximum 26.82 m/min, this indicates that the fire is extremely severe and uncontrollable at this time and that the study area is at highest risk.

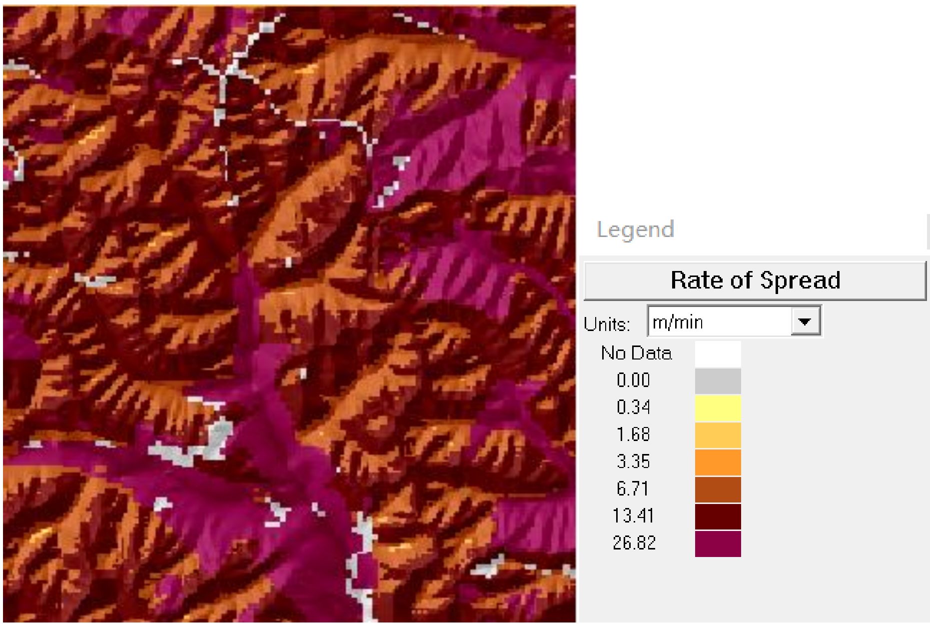

Figure 12. 12th February 2019 fire spread rate

The image of the flame length is able to serve as a reference and gives a side view of the intensity of the fire, the form and distribution of the simulated fire scar created using spatially gridded wind data is very similar to that of the observed fire scar. The flame length increases at a rate of between 3.35 and 6.1m.

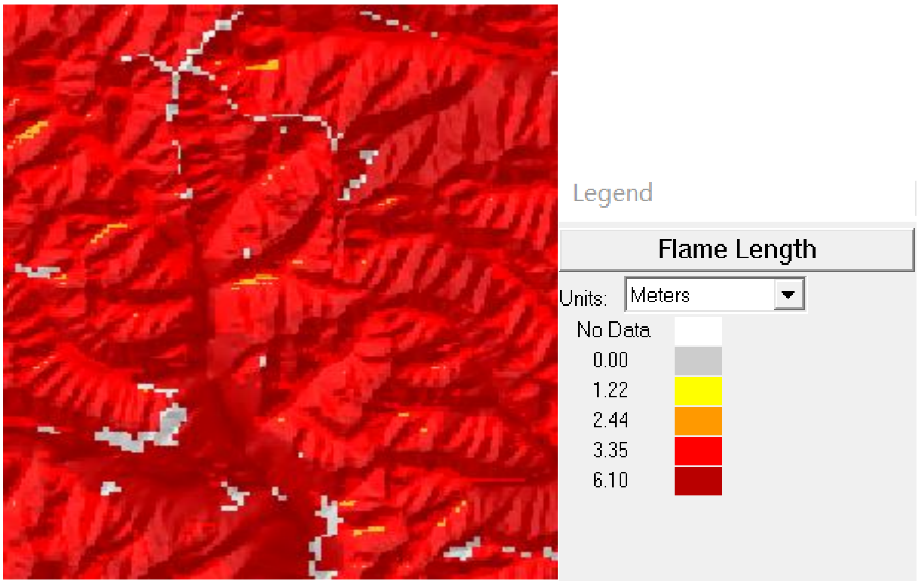

Figure 13. 12th February 2019 flame length

The observation area impacted by the fire is shown in the map below; it is the estimated region on the date of 12th February 2019. In comparison to the map generated six days earlier on the 6th of February, the area has clearly grown due to the fire's rapid progress and harsh weather conditions in reality.

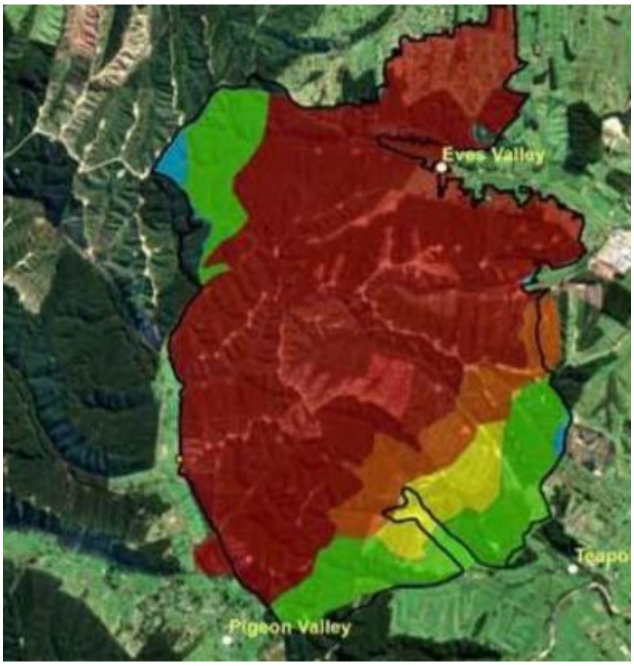

Figure 14. Estimated progression of the Pigeon Valley Fire perimeter on 7-12 February 2019 (AFAC, 2019).

4.6 Analysis of the fireline intensity in the simulation

The rate of energy or heat release per unit time per unit length of fire front (kW/m) is called the fireline intensity. It is equal to the product of the low heat of combustion of the fuel, the amount of fuel burned in the flaming front, and the linear rate of fire spread. Because fireline intensity is a good indicator of how likely a fire is to spread and how difficult it will be to extinguish, it is an important component of the fire behaviour models used to advise fire-suppression actions. Rarely is fireline intensity assessed directly; instead, it is inferred from flame length, which has been shown to correspond with fireline intensity.

As Alexander (2019) concluded, the table below illustrates the range in fireline intensities and average flame heights in Australia's open eucalypt forests by multiple categories, which is ideal for explaining the study of fireline intensity in the Pigeon Valley wildfire incident in Nelson.

Table 7. Fireline intensity which the corresponding description (Alexander, 2019).

Fireline intensity rating	Fireline intensity (kW/m)	Maximum flame height (m)	Remarks
Low	<500	1.5	Upper limit recommended for fuel-reduction burning
Moderate	500–3000	6	Scorch of complete crown in most forests
High	3000–7000	15	Crown fires in low forest types – Spotting > 2 km
Very high	7000–70,000	>15	Crown fire in most forest types – Fire storm condition at upper intensities

As shown in the table above, a low rate of fireline intensity indicates a value less than 500 KW/m and a maximum flame height of 1.5 metre in this situation. Maximum recommended for fuel-efficient combustion. For the moderate rating, the fireline intensity is between 500 and 3000 KW/m, resulting in a flame height of up to 6 metres. In the majority of forests, the whole crown is burned by fire. When the fireline intensity reaches between 3000 and 7000 KW/m, it is considered to be the maximum rate, and the maximum flame height is 15 metres, which implies that crown fires will arise in low forest types and will spread further than 2 kilometres. Between 7000 and 70000 KW/m, the fireline intensity is defined as the rate at which the maximum flame height exceeds 15 metres; under these conditions, crown fires occur in the majority of forest types – High-intensity fire storms.

4.6.1 Fireline intensity analysis for the 6th February 2019

The quantity of energy released by a fireline during the duration of a fire is described as the intensity of the fireline. Throughout a simulated fire scar, the geographical distribution of fireline intensity is shown in Figure 15. Fires were set in three different types of forest cover, which were classified as low-density forest, medium-density forest, and high-density forest. There was a wide range of intensity throughout the fireline, ranging from 0 to 13,845 KW/m, with an average of 1,731 KW/m. During the study period, moderate fireline intensity values were mostly found in high-density forest regions, but high-intensity fireline intensity values were found in both medium- and low-density forest areas. According to a cross-analysis of the fire intensity and forest cover map, the low-density forest had moderate to severe fire, but the high-density and medium-density forests both experienced 100 percent low-intensity fire, respectively.

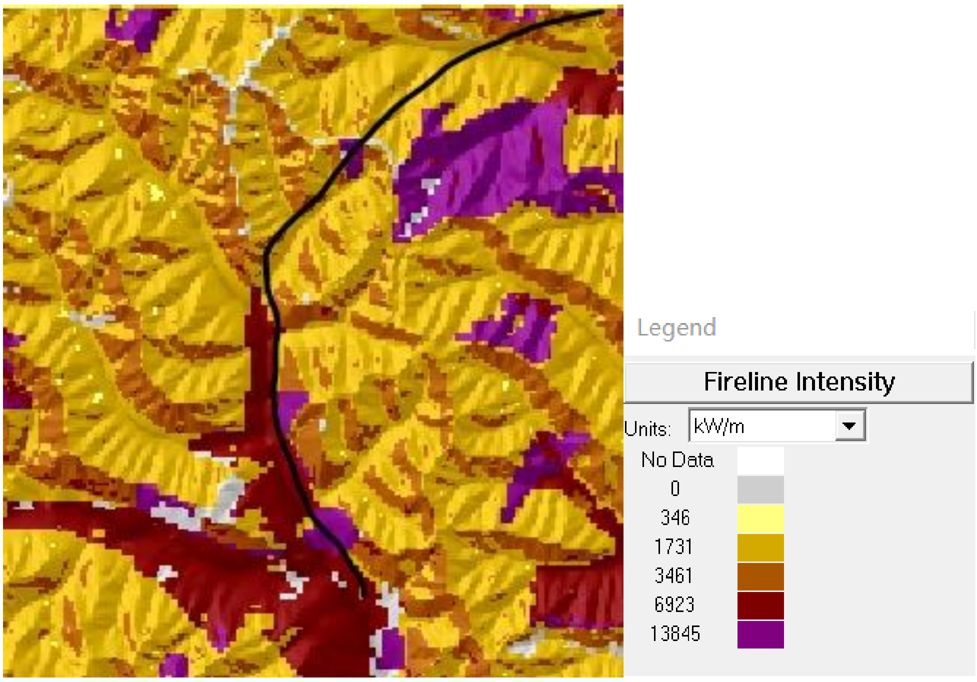

Figure 15. Fireline intensity with the estimated reality boundary

These results are consistent with the discoveries made in the image taken after the wildfire disaster, to a certain extent. In the low-density forest, there was evidence of burned lower regions of tree trunks, which might suggest a high fire intensity, while there was no evidence of tree charring in the high-density forest, which could indicate a low fire intensity. According to Keeley (2008), the intensity of a fire is positively related to the severity of the fire. Damage and mortality of plants are significantly reduced as a result of this factor. As a consequence, it is believed that the level of plant damage seen in the field corresponds to the intensity of the fireline.

4.6.2 Fireline intensity analysis for the 12th February 2019

The relationship between fireline intensity and flame length is the intensity of the fireline grows considerably as the flame length and spread rate increase. Anything that changes about a fire, such as the fuel type as it spreads, the direction or strength of the wind, etc., may result in drastic variations in fire behaviour.

The map in Figure 16 below illustrates the regional distribution of fire intensity during the February 12th incident. The intensity of the fire varied from 6,923 to 13,845 kW/m, with an average of 10,384kW/m. The region covered by this fire scar mostly comprised of two forest cover classes: high yielding exotic grassland and exotic forest, which are representative shrub land and dense forest, respectively. The shrub area was subjected to flames of extreme intensity, whilst the dense forest was subjected to fires of extreme intensity. Cross-analysis of the fire intensity and forest cover maps revealed that the majority of shrub land saw flames of moderate to extreme intensity, while 100% of the dense forest experienced fires of moderate to extreme intensity. It is well understood that open woods, especially shrub land, burn rapidly and with high fire intensity.

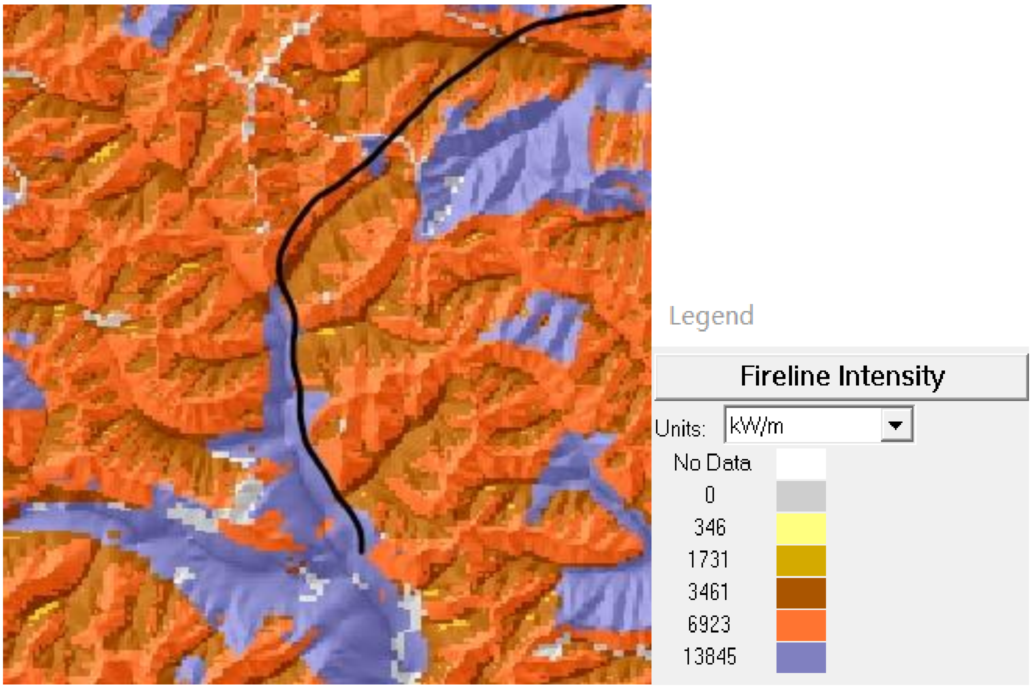

Figure 16. Fireline intensity with the estimated boundary in reality.

5. Discussion

Although categorisation of the forest cover on the LCDB satellite map was not one of the study goals, it was a critical step in modelling forest fire propagation since it supplied the foundation for constructing a fuel map. Falkowski et al., established the significance of the vegetation categorisation procedure, according to this, the majority of research that use remote sensing to assess surface fuels must first categorise an image into vegetation classes and then attribute fuel types or fuel models to each category.

Accurate fire development forecasts are highly dependent on the quality of the input data layers used to run spatially explicit fire growth models (Keane et al., 2000). However, because of their complexity and variety, fuels are difficult to characterise and map. "The advancement of modern improved sensors, such as LIDAR and hyperspectral, as well as approaches capable of integrating varied data sources and contextual information, has the potential to greatly improve fuel mapping tasks." (Arroyo et al., 2008).

The simulation of the observed fire scar utilising generated gridded wind data produced an abnormally small approximation of the observed fire scar. This is not typical of the FlamMap model, which normally works well even under situations of uniform wind. This implies that the fire was mostly driven by wind, and that the lack of locally variable wind contributed to the fire spreading slowly. The fire was contained inside a short area, as shown by the model's minor fire scar. The observed fire scar may be underestimated owing to terrain heterogeneity, this may be the reason of preventing the fire spread rate reach to the maximum. (Ryu et al., 2007). Additional explanations for the observed fire scar's underestimate include connecting with inaccuracies in the portrayal of local winds and pace of fire spread. (Finney, 1998 and Forthofer and Butler, 2007).

5.1 6th to 12th February 2019 Pigeon Valley fire spread simulation

The average rate of spread and fireline intensity increase from 1.68 to 6.71m/min and 1,731 to 3,461kW/m on 6th February. As for 12th February, 14.31 to 26.82 m/min have been estimated for the spread rate and 10,384 kW/m averagely on fireline intensity, respectively, when spatially gridded wind data were used. Thus, the propagation and form of the simulated fire scar resemble those of an observed fire scar. It is well established that spatially variable wind data properly represents local wind flows driven by elevation, topography, and vegetation, which explicates the pattern and form of the simulated fire scar being similar to the actual fire scar. In actuality, winds are quite variable, and fuel homogeneity was supposed to be at a resolution of 8m, implying that the raster landscape data include no variance in the fuel data finer than 8m. However, most fuels are more diverse in nature, with sections within each 8m cell including a mix of faster, slower, and mixed fuel types. Additionally, overestimation might be a result of a lack of knowledge on suppression efforts conducted during the fire outbreak. Increased overestimation is possible as a result of the FlamMap model's shortcoming in terms of the poor spatial and temporal resolutions employed in the simulation. In certain circumstances, overestimation is caused by inaccurate data about the moisture content of the fuel, the fuel's description, or the weather (Finney, 2004).

FlamMap models of fire development are substantially more accurate when gridded wind data is included. While incorporating gridded wind data improves accuracy in terms of understanding fire spread, overestimation happens during simulations.

The fire simulated in this study was extinguished mostly owing to the time span specified, although in actuality, fires are extinguished due to changes in geography, fuel, weather, and other obstacles such as roads and rivers. Because the FlamMap model implies that fire propagation is reliant on the fuel type and load, it lacks an automated extinguishing feature, the model believes that the fire is expanding as long as the fuel is available (Ryu et al., 2007). The fire mostly destroyed low-density forest, rather than medium- or high-density forest, which might have been attributed to the canopy's openness, which offers minimal cover from the wind, increasing the likelihood of fire spread. Additionally, an open canopy enables sunshine to enter and dry off surface fuels, lowering the moisture content of the fuel and making it more flammable.

5.2 Fireline intensity analysis

The majority of high intensity fires occurred in low density forest, which may be a result of fuel being exposed to sunlight and wind without the protection of a canopy, in contrast to high density forest with a closed canopy. Because the fuels exposed to sunlight have a low moisture content, they burn swiftly and with a high rate of spread and intensity. Additionally, the widths of woody branches are likely to be smaller in low density forests than in high density forests, enabling the fire to spread more quickly. The thick forest was protected from the wind by a closed canopy, and the high moisture content of the fuels kept fires at a manageable intensity.

In the majority of instances, the thick forest displayed a high or very high intensity fire, which is uncommon but not conceivable given the deep canopy that allows for the retention of high fuel moisture levels. High intensity fires may occur as a result of excessive horizontal continuous forest litter affecting the propagation of forest fires and thereby increasing fire intensity. Another idea is that trees and shrubs contain volatile compounds that aid in the ignition and maintenance of fires despite their high moisture content.

5.3 limitations

This case study is based on a simulation of surface fire rather than crown fire, due to the inability of three alternative inputs, canopy bulk density, canopy height, and canopy base height, to be determined. Crown bulk density is crucial for assessing the propagation of crown fires. By checking this option, the simulation is forced to alter the crown bulk density values for each cell based on the crown cover properties.

The elevation model was generated using the New Zealand 8m Digital Elevation Model, which is not as precise as the 1m LiDAR data; this option was chosen since the case study region was not completely covered by LiDAR data.

Wind speed statistics were acquired for this study using daily meteorological data gathered at a weather station. However, there was no information on the direction of the wind. As a result, data from a weather station at Nelson Airport, 25.8 kilometres from the research region, were utilised, with the premise that there is no substantial change or fluctuation in prevailing wind direction over such a short distance, given that the locations share the same climatic conditions. While this kind of wind data has the potential to introduce mistakes into the model, the excellent agreement between the predicted and real fire scars indicates the wind data's dependability. The WindNinja model's gridded wind data was not verified in this study since the method needed ground-measured data, which were not available for the study region.

6. Conclusion

Modeling forest fire behaviour with the FlamMap fire spread model works effectively in the tropical woods of Nelson's Pigeon Valley area. The similarity between the distribution pattern and form of the simulated fire scars and those seen in the research region indicates that the model is applicable in that location. The use of spatially gridded wind data produces very accurate approximations of observed fire scars, and the findings are statistically substantially more accurate.

The models of fire events corroborated the actual fireline intensity in the studied region. Generally, moderate-intensity fires occurred in high-density forests, but in this research, an extraordinarily high intensity of fireline occurred in a high-density forest owing to the unique circumstances, while high-intensity fires occurred in low-density forests.

With the advancement of technology, unmanned aerial vehicle(UAV) data may be utilised to improve the DEM model, which is capable of providing more accurate topographical data, even though satellite image categorisation is more accurate at the same time. The simulation's accuracy is also dependent on the acquisition of field data; hence, collecting more field data for either modifying field models or weather models might increase prospects for development. Further research might include examining several fuel factors that are capable of closely matching the canopy categorisation.

The FlamMap model was fitted with traditional fuel models in this investigation. When customised fuel models are employed, however, more realistic results are produced. As a consequence, further study is required to develop the unique fuel model, including real measurements of fuel parameters such as surface area to volume ratio (SAV), heat per unit area, fuel load, and fuel moisture. Furthermore, these researches may focus on calibrating the fuel model created from real-world fires.

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