Forest Fire Risk Mapping Using Multi-Criteria Decision Analysis (MCDA) and GIS in British Columbia, Canada

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Introduction

Wildfires can significantly impact the ecology, economy, environment, biodiversity, and climate change of an area. Wildfires have been happening in B.C. since the pre-1900s to date (B.C. Wildfire Service, 2021). In recent years, the frequency of wildfire events has increased, leading to severe environmental impacts in B.C., such as loss of biodiversity, bad air quality, loss of timber and recreational sites, and economy.

In recent years, GIS has become increasingly significant in firefighting operations. Responders may use sophisticated GIS-driven mapping to follow events and place resources, adding on meteorological and demographic data to give them a complete view of the situation on the ground. Another example could be before a fire, GIS may be used to assist towns to designate the exact positions of fire hydrants. Geospatial visualizations can aid rescuers in planning routes, tracking a fire's progress, and identifying communities at imminent risk during an emergency. This study aims to design a GIS aided decision support system to manage the annual wildfire occurrence from 2013 to 2021 in B.C. by incorporating many GIS layers and climatic datasets. The designed support system would help identify the high-risk zones for which recovery and mitigation plans could be prepared.

Wildfires result in the loss of environmental, cultural and ecosystems services such as conservation, timber, recreation, and water and air quality. The residents of British Columbia (B.C.) are threatened by their vulnerability to wildfires (Krishnaswamy et al., 2012).The 2003 fire season in B.C. was the worst season ever in the history of Canada. It resulted in the loss of 334 homes and businesses and displaced 45,000 people after a forced evacuation (Beck & Simpson, 2007). The 2017 wildfire in BC burned 1.2 million hectares of land. Wildfires can impact the environment severely. The areas burnt by the wildfires get turned the scorched soil layers into hydrophobic layers. The hydrophilic layers are susceptible to erosion which can lead to landslides, floods, and undrinkable water. Similarly, smoke produced because of wildfire can significantly decrease the air quality of the atmosphere for weeks. For example, the 2017 wildfire season the worst in provincial history made the B.C. hazy for (Schmunk, 2020). The bad air quality and haziness can lead to several health and economic issues. To address the environmental impacts in B.C., an efficient wildfire management system needs to be created. GIS is capable of capturing, storing, querying, analyzing and displaying the information (Bolstad, 2016). Considering such capabilities of GIS, this study would capture the historical wildfire occurrence data, digital elevation model, settlements and road network layers, land use and land cover, vegetation cover, climatic data layers (min-max temperature, precipitation) and air quality data layers.

Research Questions

• Which are the high-risk wildfire areas based on the local conditions (e.g., climate, land cover type, proximity to roads, etc.) and impacts of wildfires in British Columbia?

• How can we use GIS to aid disaster management officials and policy makers?

Literature Review

Researchers have developed diverse methods to assess different wildfire aspects linked to specific regions' environment and climatic conditions. For example, Adaktylou et al., (2020) utilized GIS modeling for predicting the high-risk areas in Greece. They incorporated the weighted linear multicriteria overlay method to generate the fire risk thematic maps. The multicriteria overlay method evolved during the 1970s (Carver, 1991) provides the capability to analyze the complex trade-offs between different variables (e.g., geographic layers). Through the multicriteria overlay method, a number of choices possibilities are considered and ranked as per their possibility to impact. Adaktylou et al., (2020) ranked 7 geographic layers (Land use land cover (LULC), Normalized Difference Infrared Index (NDII), solar Illumination, slope, road proximity, settlement proximity, and elevation) into five categorical values and modeled the fire risk map.

Researchers such as Jung et al., (2013) and Nuthammachot & Stratoulias, (2021) also used the multicriteria analysis technique in the GIS environment to model the fire risk zones. Jung et al., (2013) considered five geographical datasets, classified, weighed, and ranked them into five classes and generated the fire risk zones in Kolli Hills, India. In contrast, Nuthammachot & Stratoulias, (2021) applied Analytic Hierarchical Process (AHP) to rank 6 geographic factors to generate a fire risk map in Hua Sai district, Thailand. Their fire risk map exhibited a high correlation with the past fire events. Jung et al., (2013) took more high-resolution datasets (e.g., 15m Digital Elevation Model), while Nuthammachot & Stratoulias, (2021) used comparatively low resolution (30 m DEM) in their studies. Moreover, Jung et al., (2013) did not consider the climatic factors in their risk mapping.

No doubt, fire risk mapping can help mitigate the possible fire events in an area. The planning to provide the rescue to the fire is also important when forest fire happens. The GIS- based service area analyses have served as a critical tool for planning rescue operations and vehicle movement. Akay et al., (2012) built a GIS-based Decision Support System (DSS) to assist the fire manager in reaching fire areas through the safest and fastest route in the Kahramanmaras Forestry Regional Directorate in the Mediterranean region of Turkey. In that DSS, they utilized the road network, location of fire brigade offices, and fire locations. They also built a simulation method for providing an alternative route if a fire happens in an area and roads become inaccessible. Urquhart, (2018) applied geospatial hydrological modeling on a post-wildfire event area in Central British Columbia to predict the slope stability changes due to wildfire. Their principal findings were the impact of wildfires on landslide susceptibility.

Emergency Management British Columbia, (2018) published a comprehensive report which summarized the governmental response to wildfires and floods in B.C. This comprehensive report discusses the occurrence of 108 wildfire incidents, their current status, actions taken to date, next steps, and recommendations. Castrillón et al., (2011) built a GIS-based three-dimension (3D) model to simulate and predict the wildfires by taking the meteorological data as input. Novkovic et al., (2021) 's study employed the index-based fuzzy AHP method along with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method for wildfire susceptibility zonation. Ohlson et al., (2003) 's Wildfire Threat Rating System (WTRS) provides a platform for fire management in Greater Vancouver Watersheds. Although such studies discuss some objectives of the present study, such as GIS analysis and data layers, yet they consider a different geographic location and span. Novkovic et al., (2021) 's study employed almost the same technologies for high-risk areas mapping, but it lacks the involvement of climatic parameters. The design and analysis (climatic correlations, proximity analysis, risk analysis) would be helpful by adding to the present research. Unlike Castrillón et al., (2011), the purpose of the present study is to accurately map the high-risk wildfire areas in B.C through incorporating the local climatic, land cover, geographic conditions, historical fire events, local road network, slope, and aspect.

Study Area

Forest fires in BC are a natural occurrence and they can also become uncontrollable and lead to catastrophic events. The location map of BC is shown in figure 1.

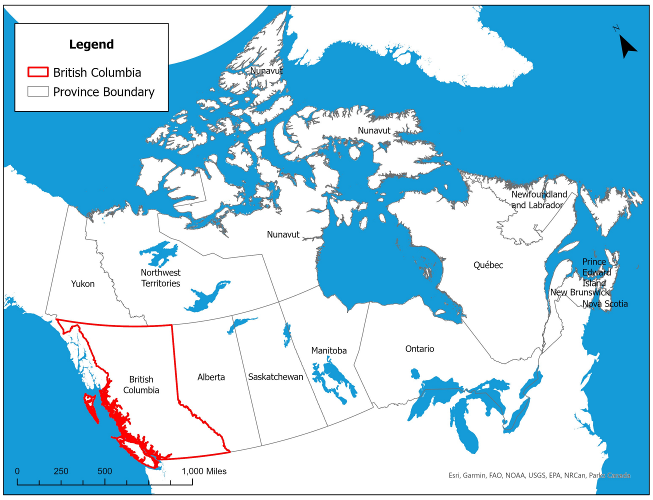

Figure 1 Study Area Location

This study performed a multicriteria weighted overlay analysis. i.e. Multicriteria Decision Analysis (MCDA) to identify the highly impacted areas resulting from wildfires in British Columbia.

Data sources

The present study used the Environmental Systems Research Institute's ArcGIS Pro software for processing, modeling, and mapping. ArcGIS Pro was used: to generate the proximity layers, reclassify them, score, and rank them, and overlay them to produce a fire risk map. In this study, there are total 8 geographical datasets have been utilized and their source of downloading is mentioned below:

1. Past Fire Occurrence:

- Source: Government of British Columbia
- Source Link: **BC Wildfire Service - Data Catalog** (https://catalogue.data.gov.bc.ca/organization/bc-wildfire-service)

2. Landuse Landcover (Global Landcover Data - Landsat 30-m):

- Source: Global Landcover Data
- Source Link: **ESRI Global Landcover Data - Landsat 30-m** (https://livingatlas.arcgis.com/landcoverexplorer/)

3. Climate Data:

- Source: The NCEP Climate Forecast System Reanalysis (Saha et al., 2006)
- Source Link: **NCEP Climate Forecast System** (https://developers.google.com/earth-engine/datasets/catalog/NOAA_CFSV2_FOR6H)

4. Digital Elevation Model (DEM - SRTM):

- Source: Shuttle Radar Topography Mission (SRTM) Digital Elevation Model
- Source Link: **USGS Earth Explorer** (http://earthexplorer.usgs.gov/)

5. Road Network:

- Source: OpenStreetMap
- Source Link: **OpenStreetMap - Data Export** (https://www.openstreetmap.org/export)

These datasets were crucial for conducting a comprehensive analysis of wildfire risk in British Columbia. The past fire occurrence data from the BC Wildfire Service provided insights into historical fire events, aiding in understanding fire patterns. The Global Landcover Data offered valuable information about land cover types, which played a significant role in assessing fire vulnerability. Climate data from The NCEP Climate Forecast System Reanalysis contributed to evaluating temperature and precipitation patterns influencing fire behavior.

Additionally, the Digital Elevation Model (SRTM) helped assess terrain characteristics, such as slope and elevation, which influenced the spread and behavior of wildfires. The road network data from OpenStreetMap was essential for analyzing access and connectivity for firefighting efforts and resource allocation.

The combination of these diverse datasets allowed for a holistic understanding of the factors influencing fire risk and facilitated the development of an effective multi-criteria decision analysis (MCDA) model for mapping and identifying high-risk wildfire areas in British Columbia.

Methodology

To determine the vulnerability of the forest to the fire, a GIS-based risk assessment model was used. This risk assessment model (as shown in Equation 1) assessed the relative importance of 8 geographic layers (layers shown in Figure 1 and ranks shown in Table 1).

$$FRZV = \sum_{i=1}^{n=5} WiSi$$

Where FRZV is the fire risk zone value, Wi is the weight of the ith layer and Si is the risk score for the category in the ith layer. The five FRZV (i.e., 1,2,3,4,5) from figure-2 represents the risk areas as very low, low, medium, high, and very high respectively. The selection of risk scoring, and weighting process was a critical part of this study. The 8 geographic layers were weighted and scored chronically as per their vulnerability to fire (Table 1). In this method, the variables were classified in a pairwise comparison scale, defining a linear hierarchy of importance among them. For example, the evidence of previous fire locations is the most important and weight was 0.22 and the forest class from landuse raster has given the second highest weight of 0.19, whereas the traffic passing by forests through roads are set on the lowest weight. These layers were ranked as per their potential to possible forest fire and proximity, mostly adopted from Jung et al., (2013) and Nuthammachot & Stratoulias, (2021).

```
##
## | Main criteria        |Rank| Weight          | Sub-criteria           | Score        |
## |----------------------|----|:---------------:|:----------------------:|:------------:|
## | Fire Locations       | 8  | 0.22            | 0 - 5,000              | 5            |
## |                      |    |                 | 5,000 - 15,000         | 4            |
## |                      |    |                 | 15,000 - 30,000        | 3            |
## |                      |    |                 | 30,000 - 70,000        | 2            |
## |                      |    |                 |  >70,000               | 1            |
## |                                                                                      |
## | Landuse Landcover    | 7  | 0.19            | Forest                 | 5            |
## |                      |    |                 | Grassland / Shrubland  | 4            |
## |                      |    |                 | Cultivation Land       | 3            |
## |                      |    |                 | Others                 | 1            |
## |                                                                                      |
## | Temperature          | 6  | 0.17            | -5.3 - -1.5            | 1            |
## |                      |    |                 | -1.5 - 0.54            | 2            |
## |                      |    |                 | 0.54 - 2.5             | 3            |
## |                      |    |                 | 2.5 - 5                | 4            |
## |                      |    |                 | 5 - 10.75              | 5            |
## |                                                                                      |
## | Precipitation        | 5  | 0.14            | 231 - 780              | 5            |
## |                      |    |                 | 780 - 1273             | 4            |
## |                      |    |                 | 1273 - 1818            | 3            |
## |                      |    |                 | 1818 - 2727            | 2            |
## |                      |    |                 | 2727 - 3857            | 1            |
## |                                                                                      |
## | Aspect               | 4  | 0.11            | Southwest              | 5            |
## |                      |    |                 | South                  | 4            |
## |                      |    |                 | West                   | 3            |
## |                      |    |                 | Other                  | 1            |
## |                                                                                      |
## | Slope                | 3  | 0.08            | 0 - 3                  | 1            |
## |                      |    |                 | 3 - 5                  | 2            |
## |                      |    |                 | 5 - 10                 | 3            |
## |                      |    |                 | 10 - 50                | 4            |
## |                      |    |                 | 50 - 90                | 5            |
## |                                                                                      |
## | Elevation            | 2  | 0.06            | -246 - 500             | 1            |
## |                      |    |                 | 500 - 1000             | 2            |
## |                      |    |                 | 1000 - 1500            | 3            |
## |                      |    |                 | 1500 - 2000            | 4            |
## |                      |    |                 | 2000 - 4652            | 5            |
## |                                                                                      |
## | Distance from road   | 1  | 0.03            | 0 - 500                | 5            |
## |                      |    |                 | 500 - 2500             | 2            |
## |                      |    |                 | 2500 - 5000            | 1            |
## |                      |    |                 | > 5000                 | 1            |
```

The forest fire risk map was generated by taking forest fire past events, landuse landcover, temperature, precipitation, slope, aspect, elevation and road network shown from Figure 2 - 5

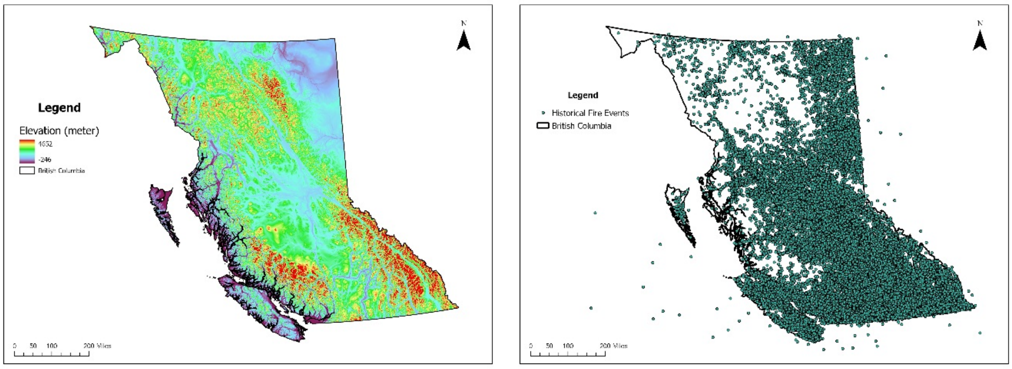

Figure 2: Elevation (meter) Map & Historical Forest Fire Events in BC

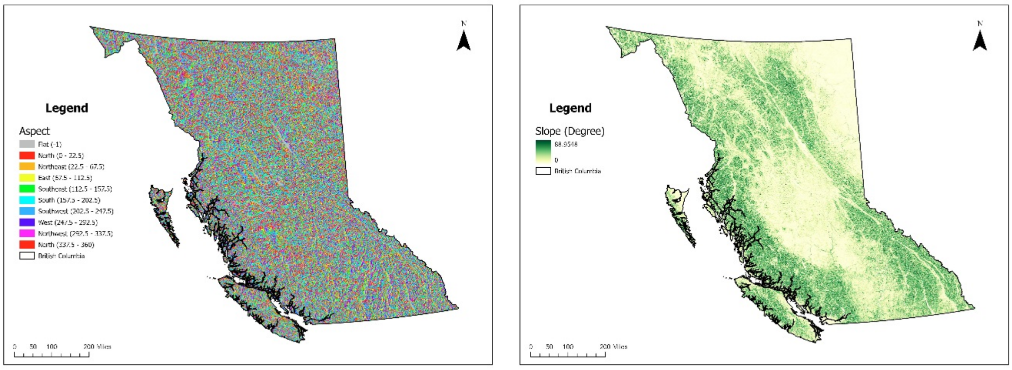

Figure 3: Aspect & Slope Map in BC

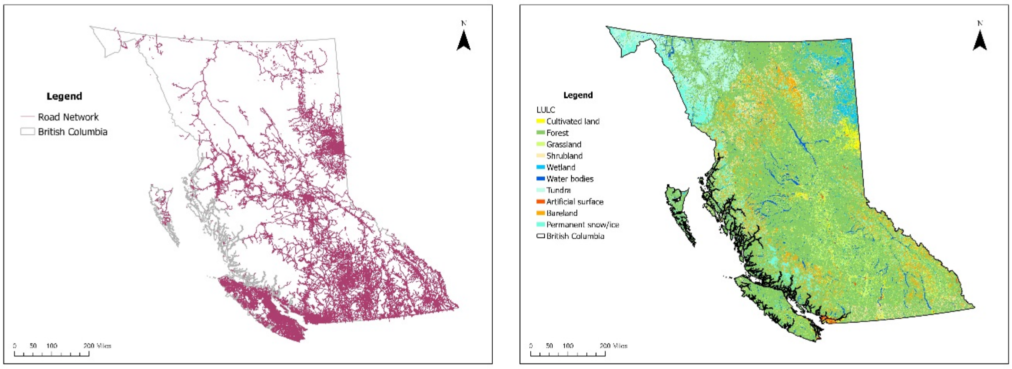

Figure 4: Distribution of Road & Land Coverage in BC

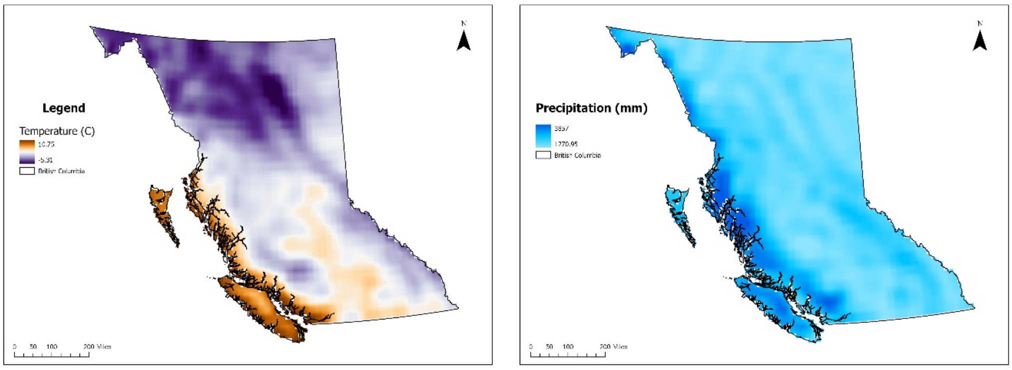

Figure 5:Mean Annual Temperature & Mean Annual Precipitation (mm) from 1990 – 2020

Each layer was reclassified into five classes and ranked 1 to 5, from very low to very high. Through this reclassification process, each criterion's influence on fire risk was translated into quantifiable values as shown in the table above. These values were then integrated into the MCDA framework by applying the assigned weights. The weighted and reclassified criteria were combined using GIS spatial analysis techniques to produce a comprehensive risk assessment map. This map offered insights into wildfire vulnerability across British Columbia, enabling informed decision-making for effective fire prevention, resource allocation, and management strategies.

Results and Discussion

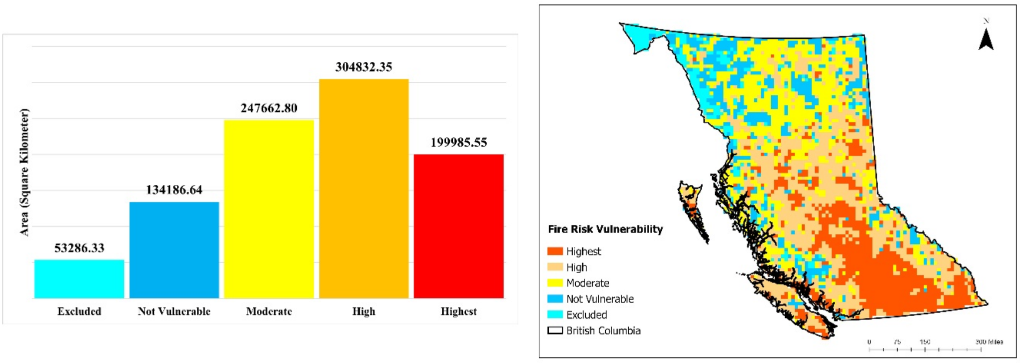

Figure 7: Fire Risk Vulnerability Map & Aerial Coverage of all Fire Risk Vulnerability Zones

The study area covers a total area of 939953.68 km2, the highly vulnerable area for forest fire is covering the 199985.55 square kilometer which is 21.28% of the whole study area. Similarly, one of the forest fire vulnerability zone is “Excluded” due to glacier and snow cover where forest is very minimal which is covering the 53286.33 km2 and making 5.67% of whole study area. Whereas “Not Vulnerable” zone is covering 134186.64 km2 and making 14.28% of whole study.

It is clear that the low-risk zones are mostly in the north, while very high- risk zones are situated in the south of B.C. The low latitude areas are more vulnerable to fire risk. For which forest cover, temperature, precipitation, and anthropogenic could be responsible. A further investigation of forest cover types can reveal their role with wildfire. For example, the deciduous forest with dry and thick vegetation can catch fire more quickly than the pine forest. Since the South part of B.C. has more human settlements, intentional and unintentional human activities such as fire ignition and crop residue burning can trigger forest fires. These events can be minimized by implementing strict regulations during the dry days of the season. Mostly the remote areas are less vulnerable to wildfires. The high risk and very high risk collectively contribute to 53% of the total area of B.C. It is an alarming situation as it requires a lot of resources to fight wildfire.

The use of MCDA GIS has proved to be a valuable tool in identifying and mapping vulnerable areas, which can help in mitigating the impact of forest fires on the environment, economy, and society. Therefore, the results of this forest fire risk mapping study using MCDA and GIS provide important information for policymakers and forest management agencies to develop strategies and action plans to prevent and control forest fires in BC.

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