Using GIS in Hotspots Analysis for Forest Fire Risk Zones Mapping in the Black Hills Region, South Dakota

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South Dakota, also known as prairie and forested ecosystem, has historically seen frequent occurrence of wildlife. The decade of the 1930s, 1939, and the year of 1974 hammered Black Hills with forest fires. The drought in 2012 invited more forest fires in Black Hills. The land cover, slope, elevation, aspects, and proximity from the settlement in the Black Hills make a perfect blend for the forest fires to occur. This study uses the historical fire data from FIRMS:

1) To identify forest fire risk zones from FIRMS fire hotspots reported between 2001 and 2015 in the Black Hills, South Dakota, and

2) To model fire hotspots through Gi(d) statistics to determine how and to what extent commonly known fire factors contribute to fire occurrences.

The study estimates that total 50 fires out of 245 fall under the very high-risk area whereas 140 fires fall under high risk area. 79.18% of the total fire risk area is high risk area. Similarly, 17.9% of the area falls under very high-risk area. Using historical fire data, a correlation between several variables and risk areas was determined. It was observed that 77.55% of historical fires occurred in very high and high-risk areas.

Introduction

As long as fuel, heat, and oxygen are supplied, there are other parameters such as weather (temperature, wind, relative humidity, precipitation), topography (elevation, altitude, slope, aspect), bio-physical features (flora and fauna, soil type and chemistry, proximity to water, population density), and socioeconomic variables (nearby population, roads, etc.) that determine the frequency, rate of spread and severity of wildland fires (Chuvieco and Salas, 1996; Chuvieco and Congalton, 1989; Sunar and Ozkan, 2001; Hernandez-Leal, Arbelo, and Gonzalez-Calvo, 2006).

South Dakota, also known as prairie and forested ecosystem, has historically seen frequent occurrence of wildlife. The decade of the 1930s saw periods of extended drought throughout the region and large fires burned in the central and northern Black Hills and across the state line in Wyoming during that time. In recent years, an increasing focus has been directed towards understanding the impact that human activities have had on the environment. Climate change is causing a fluctuation in frequencies and amount of precipitation, as a result the temperature is rising and so is the risk of forest fires (Cotter, 2009).

The Gi(d) used in this study measures concentration or the lack of weighted points within a radius of a specified distance d from an original weighted point according to Getis and Ord (1992).

The main objectives of this analysis were to:

1) identify forest fire risk zones from FIRMS fire hotspots reported between 2001 and 2015 in the Black Hills, South Dakota, and

2) model fire hotspots through Gi(d) statistics to determine how and to what extent commonly known fire factors contribute to fire occurrences.

Study Area

The Black Hills is an important ecoregion, mostly dominated by ponderosa pines. It covers an area of 210,000 hectares in South Dakota and Wyoming. The region is mostly at higher elevations (Orr, 1959). The climate is characterized as continental, having low precipitation, hot summers, and cold winters (Johnson, 1933). Mean annual temperature is 43.90 F and mean annual precipitation is 18.61 inches (Driscoll, Hamade, and Kenner, 2000). For my study, I selected the portion of Black Hills that lie in South Dakota only (Figure 1).

Data and Methodology

The data for fire is available online in Fire Information for Resource Management Systems (FIRMS) website (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms). FIRMS distributes Near Real-Time (NRT) active fire data within 3 hours of satellite overpass from both MODerate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS). I chose to use MODIS data because these data were available from 2001 to 2015. FIRMS also provides users with near real-time hotspots/fire information through their Web Fire Mapper, email and cell phone text messages. FIRMS provides information on active fires using the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board NASA's Aqua and Terra satellites (NASA/University of Maryland, 2002).

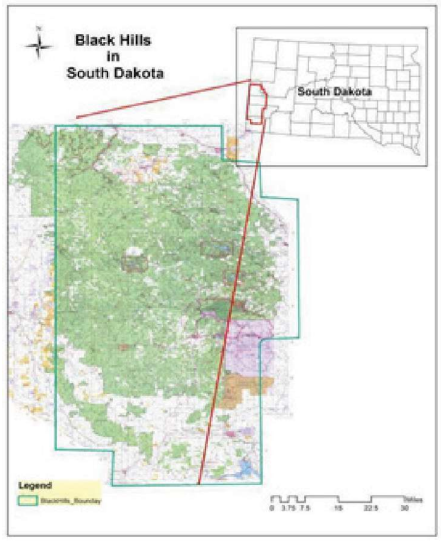


Figure 1: Study Area: Black Hills in South Dakota

The data was delivered through email and was in shapefile format. The file included the following fields: latitude and longitude (center of point location), brightness (brightness temperature measured in Kelvin), scan and track (spatial resolution of the scanned pixel), acqdate (Acquisition date), time (time of the overpass of the satellite), satellite (Terra or Aqua), and confidence (quality flag of the individual hotspot, this is an experimental field) (NASA/University of Maryland, 2002).

The data was then clipped with the South Dakota state boundary layer and Hot Spot analysis was done to see the fire concentration in South Dakota. Fire was mostly concentrated in the Black Hills region and North Central region of South Dakota (Figure 2). Using R interface, the data graphs of the fire occurrence by year for (a) South Dakota, and (b) Black Hills were produced (Figure 3).

Fire detection is based on the absolute recognition of its intensity. If a fire is weak, the detection is based on the emission of surrounding pixels (Justice, Giglio, Korontzi, Owens, Morisette, Roy, Descloitres, Alleaume, Petitcolin, and

Kaufman, 2002).
Forest Fires in the Black Hills Region The data from 2001 to 2015 shows that there were huge number of fires in 2012. The total number of fires were 245, which is 12.23% of total fire (2002) occurred in 15 years. The fires mostly occurred in the month of July. A total number of 151 fires occurred in July which is 61.63% of total fires that occurred in the year.

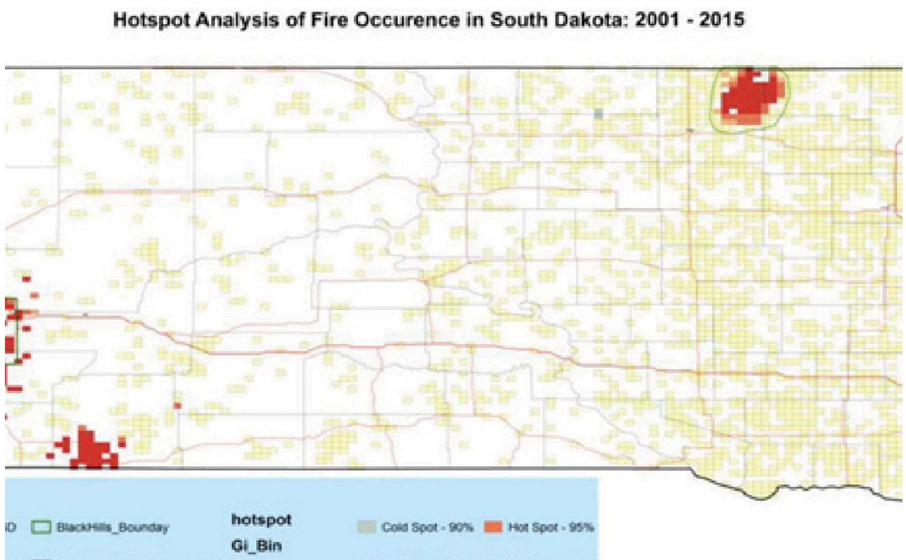


Figure 2: Hotspot Analysis of Fire Occurrence in South Dakota: 2001-2015. The fire data obtained from FIRMS were clipped with the South Dakota state boundary layer and Hot Spot analysis was done to see the fire concentration in South Dakota. Fire was mostly concentrated in the Black Hills region and North Central region of South Dakota. The Black Hills region is mostly dominated by forests while the north central region is dominated by agricultural and grass land.

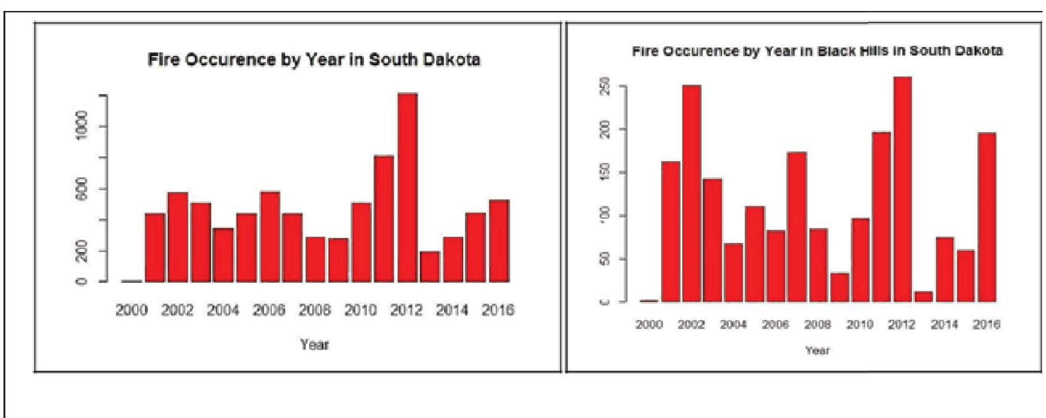


Figure 3: Fire occurrence by year (left) in South Dakota, and (right) in Black Hills region.

By the ArcGIS Kernel Density tool, a fire occurrence density map for the year 2012 in Black Hills (Figure 4) was created.

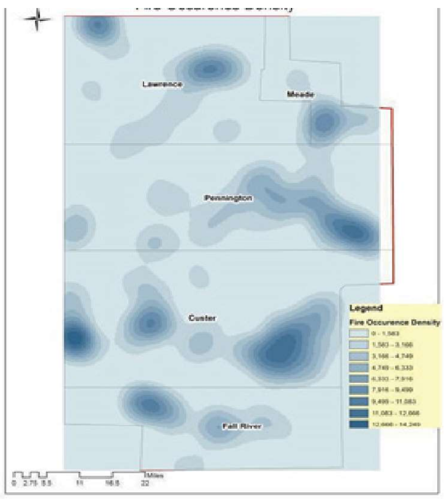


Figure 4: Fire Occurrence Density (fire/km2). The fires were mostly occurring in the Southeast and East central parts of Black Hills.

Human Factor

The two main sources of fire ignition in Black Hills are lightning and human activity (Myers, O'Brien, and Morrison, 2006). Even with lightning fires, which are highly under-reported in many areas, local authorities conclude majority of fire ignition is due to human activity. Human activity may be often difficult to understand due to the vague nature of how precisely fire ignition may begin. Lightning may Chuvieco and Congalton (1989) suggest the type and character of the vegetation is the main factor in determining the manner in which a forest fire might spread. They also suggest that the fuel available for fire is of primary importance (Chuvieco and Congalton 1989). For the purpose of land cover and vegetation, I used National Land Cover Database 2011 (NLCD 2011). The data is available online (https://www.mrlc.gov/nlcd2011.php). It is the most recent national land cover product created by the Multi-Resolution Land Characteristics (MRLC) Consortium. NLCD 2011 provides the capability to assess wall-to-wall, spatially explicit, national land cover changes and trends across the United States from 2001 to 2011. It has 16-class land cover classification scheme at a spatial resolution of 30 meters. NLCD 2011 is based primarily on a decision-tree classification of circa 2011 Landsat satellite data.

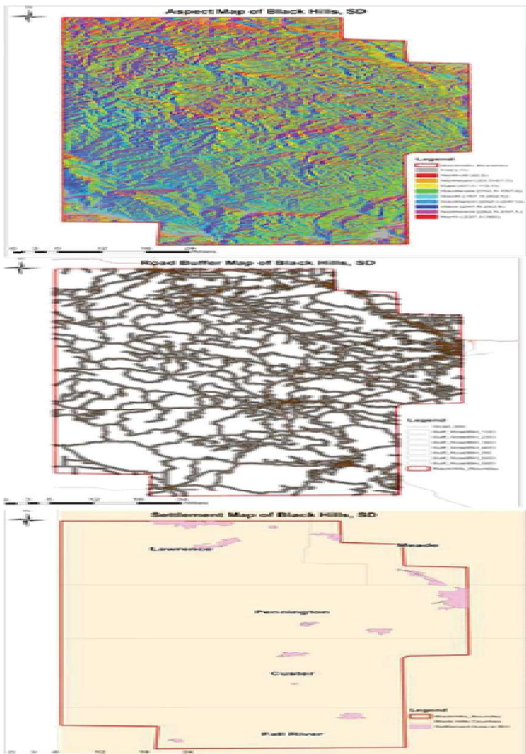
NLCD data layer has 95 different classes.

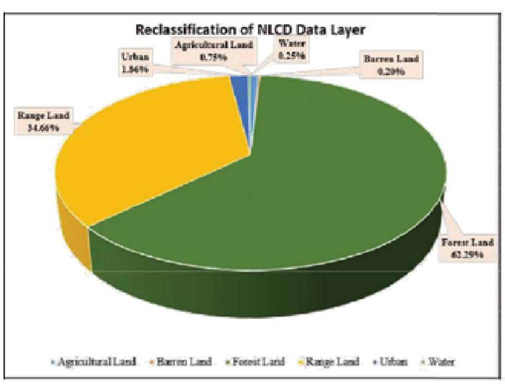
These classes were reclassified into 6 major groups:

(1) Agriculture Land, (2) Barren Land, (3) Forest Land, (4) Range Land, (5) Urban or Built-up Land, and (6) Water. The reclassification of NLCD layers was done using modeling procedure in ArcGIS. A glimpse of reclassification is given in table 1.
From the resulting analysis, 62.29% of the study area was forest land, 34.66% rangeland, 0.75% agricultural land, 0.20% barren land, 1.86% urban or built up land and 0.25% water (Figure 5a). Land cover is summarized in pie chart 1.

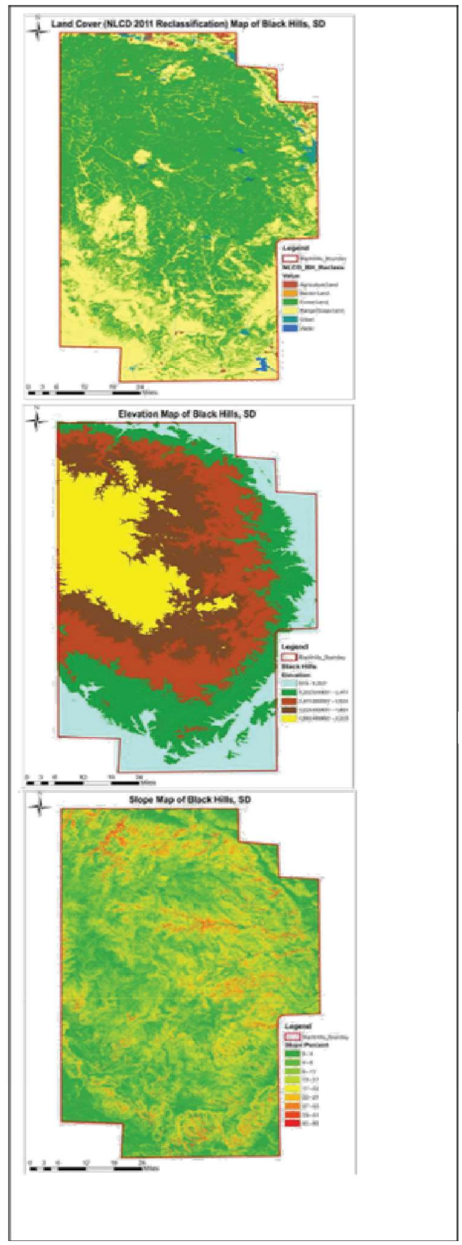
Topographic Data
A main factor in any risk analysis is the topography with slope being a critical factor. Fire travels up slope faster than down (Chuvieco and Congalton, 1989; Jaiswal et al., 2002).

For this study, the Digital Elevation Model (DEM) data (Quad 1:24,000, topographic map sheet from USGS (30m x 30m cell size; heights in meters) was used to determine slope and aspects of the study area (Figures 5b, 5c, and 5d). Distance to Roads and Settlements Identifying distance to roads in the area can be useful in locating possible paths used for fire suppression as well as identifying risk areas where a high level of human activity might occur (Chuvieco and Congalton, 1989). For this study, multiple buffers with 7m intervals were created starting with a 50 m interval and then 100 m intervals thereafter (Figures 5e and 5f).





Pie-Chart 1: Summary of the land cover in Black Hills, SD. 62.29% of the study area was forest land, 34.66% rangeland, 0.75% agricultural land, 0.20% barren land, 1.86% urban or built up land and 0.25% water.



Fire Risk Model

Several studies have proposed the integration of variables into a single fire model (Chuvieco and Congalton, 1989; Hernandez et al., 2006; Carrão et al., 2003; and Jaiswal et al., 2002). This study integrates six layers of information: slope, vegetation, aspect, distance from roads, distance to settlements, and elevation.

Chuvieco and Congalton (1989) suggest a hierarchical scheme of fire rating (Table 2) which was followed in this study. Layers of importance from highest to lowest were as follows: land cover, vegetation, slope, aspect, proximity to roads, proximity to settlements and elevation (Chuvieco and Congalton,1989).

The fire risk model can be summarized in the following equation:

$$FH = 1 + 48LC + 30S + 10A + 5R + 5Sm + 2E$$

Where LC, S, A, R, Sm, and E are land cover, slope, aspect, roads, settlements and elevation respectively.

Fire risk modeling involved several steps. First layers were weighted depending on the risk they represented. Land cover was weighted the highest, followed by slope, aspect, distance to roads, settlements, and elevation. Every layer was assigned a coefficient starting with 0, 1, 2, etc. with 0 being the highest hazard.

Land cover was evaluated first as an estimate of fuel available for a fire. Weighting of the classes in the land cover layer were determined by the moisture; the dryer the vegetation, the higher the risk of flammability (Figure 6a).

Aspect was the second factor to be evaluated. It was divided into seven categories. South and southwest aspects were given the highest weight due to a higher insolation. Southeast and the east were weighted as medium risk, while north, northeast, and northwest were weighted as low risk (Figure 6c).

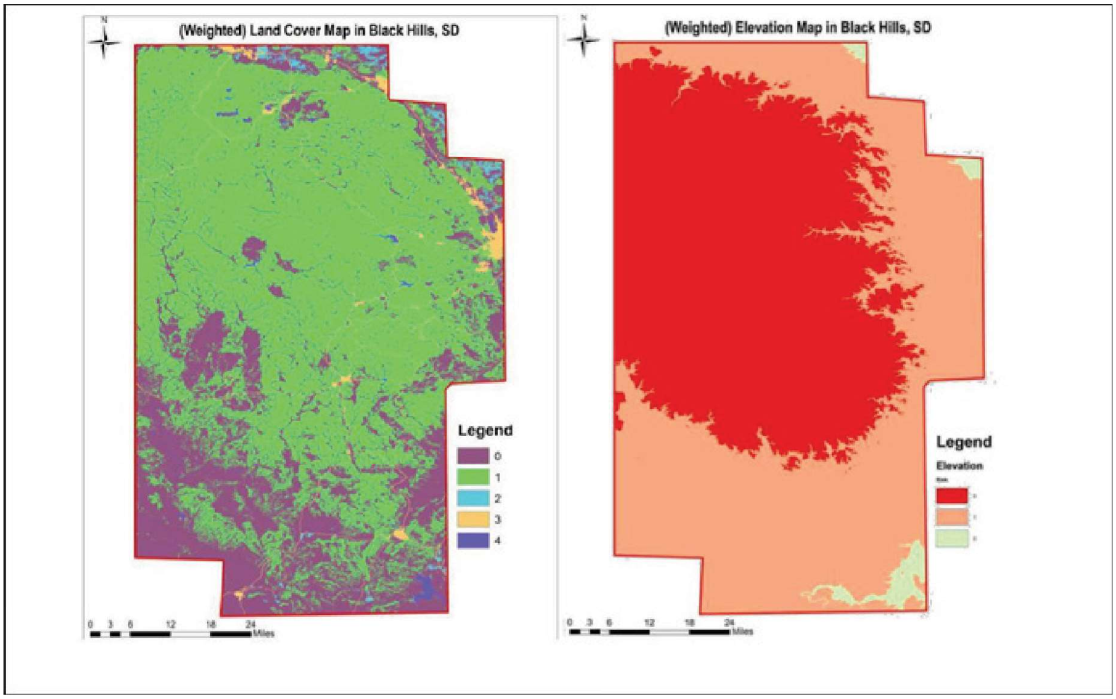
Slope was the third factor to be evaluated. Weighting was determined by the fact fire travels more rapidly in up slope. Slope layer was divided into five groups: greater than 35% (very high hazard), between 35% and 25% (high), between 25% and 10% (medium), between 10% and 5% (low), under 5% (very low) (Figure 6c).

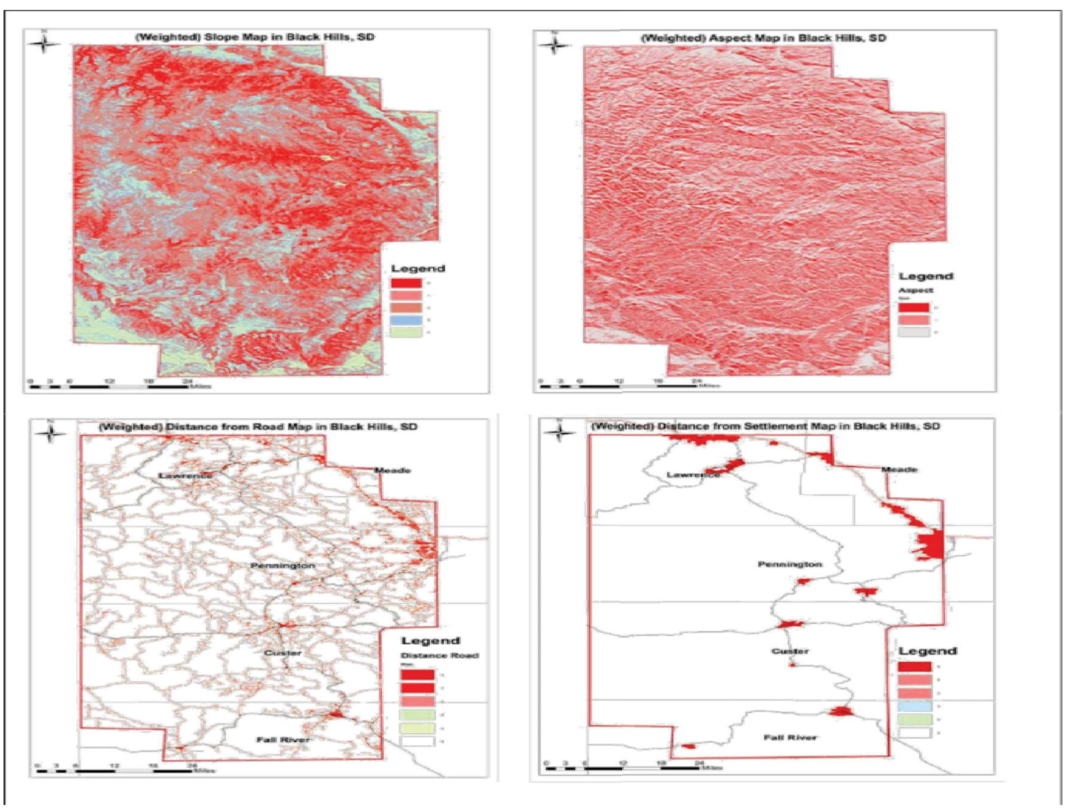
Proximity to settlements had a similar weighting as the distance from roads. Proximity was divided into five groups. Areas less 1000 meters at very high risk, 1000 and 2000 at high, 2000 and 3000 at medium, and areas at a distance greater than 3000 meters at low risk (Figure 6f).

The distance from roads was evaluated since nearby areas have a higher risk of a fire. The buffer layer was divided into six groups. The areas within a distance of less than 100 meters were noted at very high risk, between 100 and 200 meters was assigned high risk, between 200 and 300 meters was noted medium risk, between 300 and 400 was assigned low risk and areas with a distance greater than 400 meters were identified at very low risk (Figure 6e)

The last layer evaluated was elevation.

This layer was divided into four categories. Areas with an elevation greater than 1,500 meters were considered at very high-risk and areas less than 500 meters were considered having low risk (Figure 6b).





Classes	Coeff	Fire Rating
Land cover (weight 100)		
Rangeland (Scrub/ Shrubs)	0	Very high
Forest Land	1	High
Agricultural Land	2	Medium
Urban or Built-up Land	3	Low
Barren Land and Water	4	Very Low

Slope (weight 30)		
> 35 %	0	Very high
35 – 25 %	1	High
25 – 10 %	2	Medium
10 – 5 %	3	Low
< 5 %	4	Very Low

Elevation (weight 2)		
> 1501	0	Very high
1001 - 1500	1	High
501 - 1000	2	Medium
< 500	3	Low

Aspect (weight 10)		
South	0	High
Southwest	0	High
Southeast	1	Medium
East	1	Medium
North	2	Low
Northeast	2	Low
Northwest	2	Low

Classes	Coeff	Fire Rating
Distance from roads (weight 5)		
<50	0	Very high
50 - 100 m	1	Very High
100 – 200 m	2	High
200 – 300 m	3	Medium
300 – 400 m	4	Low

Distance to settlements (weight 5)		
<500 m	0	Very high
500 - 1000m	1	High
1000 – 2000 m	2	High
2000 – 3000 m	3	Medium
> 3000 m	4	Low

Hotspot Analysis

Another objective of this project was to determine how and to what extent commonly known fire factors contribute to fire occurrences. This was examined using the Spatial Statistics Hot Spot analysis tool from ArcGIS which uses the Getis-Ord Gi* algorithm (Figure 7).

The Getis-Ord local statistic is given as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\left[n\sum \quad -\left(\sum \quad\right)^2\right]}} \quad (1)$$

Figure 7: Getis-Ord Gi* (ESRI, 2009)

According to Getis and Ord, the Gi * statistic is used to measure the degree of association from a concentration of weighted points (Getis, and Ord, 1992). Greater Gi* values indicate significant spatial clustering with values >2 (Potter, 2009). A total weighted field calculated from the six layers used in the fire risk model was added to the total fire risk data. This new field was used as the input for the hotspot analysis.

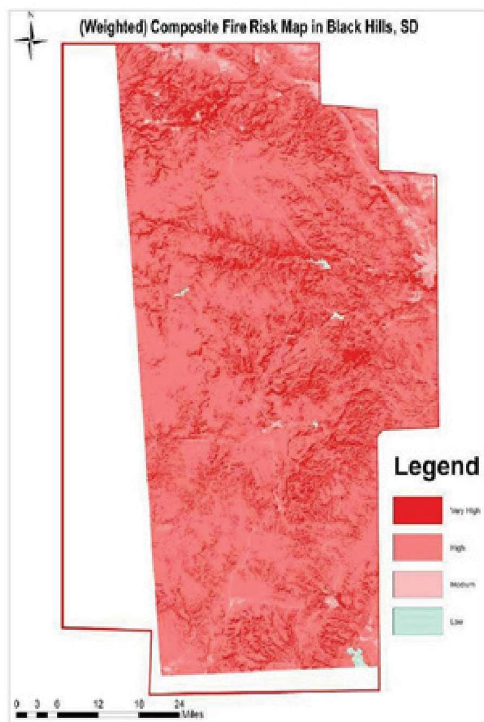
Results

Figure 8 estimates the High-risk area in Blacks Hill, SD. Total 50 fires out of 245 fall under the very high-risk area whereas 140 fires fall under high-risk area. 79.18% of the total fire risk area is high-risk area. Similarly, 17.9% of the area falls under very high-risk area (Figure 9). But, the medium and low risk area were nominal. The area included in the fire risk analysis included range land, forest land and agricultural la nd. The area that fall under very high and high-risk were mostly forest area.

Conclusion

In this study GIS was used to integrate varying layers of data for use in forest fire risk modeling. Additionally, NLCD and other remotely sensed imageries (data) were used to analyze the Forest Fire Risk Zone in Black Hills region.

Using historical fire data, a correlation between several variables and risk areas was determined. It was observed that 77.55% of historical fires occurred in very high and high-risk areas.



OBJECTID *	Value	Count	RiskArea
1	1	116732	259605.8
2	2	514919	1145152
3	3	169005	37585.78
4	4	17389	3867.218

Recommendation

It will be interesting to look at the Fore Fire Risk Zone at the North Central South Dakota where 107 fires occurred in the 2012 which is 9% of total fires that occurred in entire South Dakota. The area is agriculture and grassland dominated, therefore it could have a different result than the Black Hills region because Black Hills is forest dominated area. Using the weather parameters such as temperature, precipitation, and relative humidity could give a different result in the same study area in the same study period. Additionally, it could be interesting to look at the total area burnt versus land cover versus topography. The data used for the study is only the number of fire occurrences in the study area in 2012.

Selected References

Bonazountas, M., Kallidromitou, D., Kassomenos, P., and Passas, N. 2005. Forest Fire Risk Analysis. Human and Ecological Risk Assessment, 11: 617-626.

Carrão, H., Freire, S., and Caetano, M. 2003. Fire Risk Mapping Using Satellite Imagery and Ancillary Data:

Towards Operationality. Remote Sensing for Agriculture, Ecosystems, and Hydrology Vol. 4879.

Chuvieco, E. and Congalton, R. 1989. Application of Remote Sensing and Geographic Information Systems to Forest Fire Hazard Mapping. Remote Sensing and Environment, 29:147-159.

Chuvieco, E., and Salas, J. 1996. Mapping the spatial distribution of forest fire danger using GIS. International Journal Geographical Information Systems, Vol. 10, No.3, 333-345.

Cliff, A.D., and Ord, J.K. 1981. Spatial Processes: Models and Applications. Pion, London, p. 266.

Cotter, J. 2009. Forest Fires: influences of climate change and human activity. Greenpeace Research Laboratories Technical Note 05/2009.

Getis, A., and Ord, K. 1992. The Analysis of Spatial Association by Use of Distance Statistics. Geographical Analysis 24:189-206.

Hernandez-Leal, P., Arbelo, M., and Gonzalez-Calvo, A. 2006. Fire risk assessment using satellite data. Advances in Space Research 37: 741-746.

Jaiswal, R., Mukherjee, S., Raju, K., and Saxena, R. 2002. Forest fire risk zone mapping from satellite imagery and GIS. International Journal of Applied Earth Observation and Geoinformation 4: 1-10.

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F., and Kaufman, Y. 2002. The MODIS fire products. Remote Sensing of the Environment 83, 244-262.

Myers, R., O'Brien, J., and Morrison, S. 2006. Fire Management Overview of the Caribbean Pine (Pinus

caribaea) Savannas of the Mosquitia, Honduras. GFI technical report 2006-1b. The Nature Conservancy, Arlington, VA.

NASA/University of Maryland, 2002. MODIS Hotspot / Active Fire Detections. Data set. MODIS Rapid Response Project, NASA/GSFIC [producer], University of Maryland, Fire Information for Resource Management System [distributors].

Potter, K. 2009. Detecting Large-Scale Spatial Hot Spots of Forest Fire Occurrence Using MODIS Satellite Data. Rawat, G. 2003. Fire risk assessment for fire control management in Chilla Forest Range of Rajaji National Park

Uttaranchal (India).

Sunar, F. and Ozkan, C. 2001. Forest fire analysis with remote sensing data. International Journal of Remote Sensing, Vol. 22, No. 12, 2265-2277.