FIRE MODELLING TO ASSESS SPATIAL PATTERNS OF WILDFIRE EXPOSURE IN ARDABIL, NW IRAN

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ABSTRACT:

Fire exposure describes the spatial juxtaposition of values with fire behaviour in terms of likelihood and intensity. Wildfire exposure analysis is based on the estimation of the potential wildfire intensity and on the burn probability. Fire modelling can produce spatially explicit information on fire spread and behaviour, and offers a feasible method to simulate, map, and analyse fire exposure. FlamMap Minimum Travel Time (MTT) algorithm (Finney, 2006) was used to conduct wildfire simulations considering historical data of fuel moisture conditions and winds, as well as the most frequent wind directions and historical ignition locations (2005-2018). Analysis was conducted on spatial and quantitative variations in selected fire hazard and exposure factors, namely Burn Probability (BP), Conditional Flame Length (CFL) and Fire Size (F). We observed pronounced spatial variations among and between municipalities in the factors, especially for those in the northern and southern parts of Ardabil. The variations across the burnable area of the municipalities can be fundamentally related to a number of factors, including spatial variation in ignition locations, fuel moisture and load, weather conditions, and topography of the terrain. The findings can provide information and support in wildfire management planning and fire risk mitigation activities.

1. INTRODUCTION

Available methods to estimate the potential fire impacts can be divided into two categories: risk-based and hazard-based. Both types of methods estimate the potential consequences of possible events. Risk-based methods also analyse the likelihood of scenarios occurring, whereas hazard-based methods do not (Hurley and Bukowski, 2008). Wildfire risk is the likelihood of a fire occurring, the associated fire behaviour, and the impacts of the fire. Risk mitigation is achieved when any of the three parameters (likelihood, behaviour and/or impacts) are reduced (Calkin et al., 2011; Scott et al., 2013).

A spatial wildfire risk assessment can provide information to support decision-making, for example, to optimize the allocation of wildfire prevention and fire-fighting resources and to reduce fire effects or impacts on valued resources (Taber et al., 2013; Ahmed et al., 2018). Wildfire exposure analysis is one component in risk assessment, and describes the spatial juxtaposition of values with fire behaviour in terms of fire likelihood and intensity, but does not explicitly describe the impact of wildfire events (Ager et al., 2014; Barnett et al., 2016). Quantitative, spatial wildfire risk and exposure assessment methods are increasingly being applied, to improve fire management programs (Chuvieco et al., 2012; Salis et al., 2013, 2015; Alcasena et al., 2015, 2017; Palaiologou et al., 2018). This paper presents a fire exposure assessment at landscape scales in Ardabil, NW Iran that may serve as a proxy for wildfire risk. Fire simulation modelling using the minimum travel time (MTT) fire spread algorithm of Finney (2002) are implemented in FlamMap 5 (Finney, 2006) to explore spatial patterns of wildfire exposure factors considering historical conditions of winds, and ignition locations.

2. MATERIAL AND METHODS

2.1 General Description of the Study Area

We considered Ardabil as our study area (Figure 1), in the northwestern of Iran. The population of Ardabil is approximately 1,270,000. The climate of the area is considered severe during winters, and mild to warm and dry summers for only three months. The annual average precipitation of the area is 230 mm, and rainfall events are limited in the summer period (33 mm from June to September). The annual mean temperature is 7.5 °C, while from June to September is 18 °C (Figure 2). Monthly average value of maximum temperatures in January, and June and July during 2005–2018 were recorded -30°C and +35°C, respectively. The area is characterized by semi-steppe rangelands, pastures and dry-land agricultures and on the southwest it is also covered with forestland.

During the study period (2005–2018), from June to September, Ardabil experienced ~100 fires and 650 ha of burned area per year. Approximately 80% of fires burned less than 10 ha, accounting for only 17% of the overall burned area. Less than 1% of the total number of fires had the area burned more than 100 ha. The year with the largest burned areas (2010) was associated with dry weather condition, severe heat waves, strong winds and considerable accumulation of fine dead fuel. Almost all ignitions are related to anthropogenic factors, and were mostly concentrated from June to September.

2.2 Data Requirements

In order to conduct the fire simulations for the study area, data on historical wildfires, weather parameters and spatial data such as topography and fuels are needed. Historical fire occurrence database (ignition dates, municipality of ignition, coordinates, and final fire size) included observations from 2005 to 2018 (from the Ardabil Natural Resources Department and FRWO, Iran, 2018).

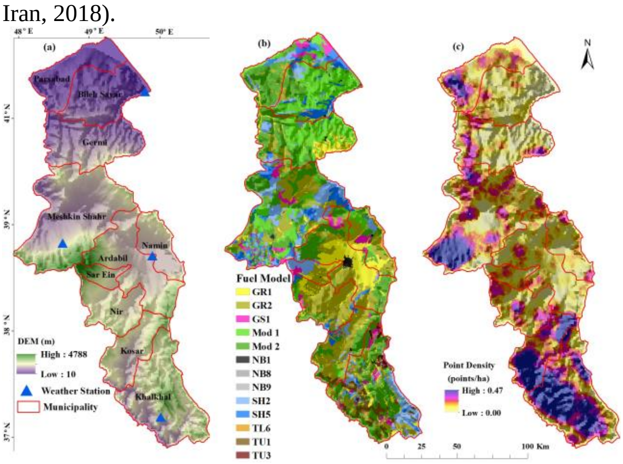

Figure 1. The spatial extent of the study area, showing the province boundaries, weather stations, and elevation (a), Fuel models (Anderson, 1982; Scott and Burgan, 2005) (b), and Ignition probability grid (IP), generated from the historical fires for the period 2005–2018.

An ignition probability grid (IP) was built from historical ignition locations using inverse distance weighting (ArcMap Spatial Analyst) with a search distance of 5000 m, considering all fire ignition coordinates for the study period (Fig. 1c).

Weather data for the fire modelling were derived from Bile Savar and Khalkhal weather stations located respectively in the north, and south of Ardabil (Figure 1a).

Topography data grids (elevation, slope, and aspect) were obtained from the 30-m resolution digital terrain model (Figure 1a). Surface fuels (Anderson 1982; Scott and Burgan, 2005) (Figure 1b) and the canopy cover characteristics (canopy height, canopy cover, canopy base height, and canopy bulk density) were assigned based on the 1:25000-scale land use land cover map of 2016. For the fuel model assignment to the different land cover, we considered the vegetation characteristics such as species composition, cover, thickness, and shrubs and herbaceous fuels heights. Topography, surface fuel, and canopy metric raster grids were processed with ArcFuels 10 (Ager et al., 2011) as required by FlamMap (Finney, 2006), in a 100-m resolution landscape file (LCP).

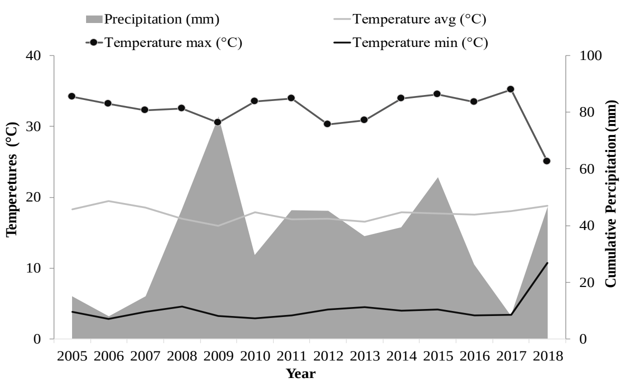

Figure 2. Average temperature (maximum, mean and minimum) and cumulative precipitation from June to September in Ardabil for the period 2005 to 2018.

2.3 Fuel Area by Municipality

Variation existed in the burnable area with different fuel models (Anderson, 1982; Scott and Burgan, 2005) among the municipalities due to different proportions of burnable fuels (Table 1). Non-burnable fuels resulted in burn probabilities of zero in the simulations. In particular, large areas of the Khalkhal, Kowsar, Meshgin Shahr, Nir and Ardabil with grasslands are considered burnable in a wildfire context.

Table 1. Area in burnable and non-burnable fuel models by municipality.

Municipality	Fuel Model (ha)											Total
	Burnable Fuel										Non Burnable Fuel (NB)	
	GR1	GR2	GS1	Mod1	Mod2	SH2	SH5	TL6	TU1	TU3		
Sareyn	102.9	126.9	19.3	-	2.3	137.9	7.3	-	-	-	3.5	400.4
Bileh Savar	16.2	63.5	-	945.8	357.6	120.3	275.8	-	-	-	16.2	1795.6
Germi	288.0	151.1	-	828.8	610.1	102.2	24.7	5.04	-	0.5	5.5	2016.1
Khalkhal	158.9	312.2	131.1	52.0	1073.1	475.2	66.9	0	388.0	127.4	9.1	2794.4
Kowsar	91.1	596.4	11.2	37.7	367.0	76.3	40.7	0	49.1	7.0	3.1	1279.7
Meshgin Shahr	207.9	762.0	223.3	384.5	898.1	736.5	505.2	18.5	-	2.2	25.9	3764.2
Namin	346.1	264.0	41.3	93.1	106.4	48.6	4.7	37.4	-	-	4.8	946.7
Nir	184.9	765.8	31.5	36.0	115.8	10.8	75.2	-	-	-	4.1	1224.6
Parsabad	27.43	60.3	128.2	169.4	701.0	125.3	185.1	-	-	-	16.32	1413.1
Ardabil	628.0	620.4	84.9	0	616.7	86.1	75.0	-	-	-	53.68	2164.9
Total	**2051.7**	**3722.9**	**670.9**	**2547.4**	**4848.4**	**1919.4**	**1260.9**	**60.9**	**438.1**	**137.2**	**142.74**	**17800**

2.4. Wildfire Simulation

According to fire modelling approach, multiple datasets and geospatial inputs are gathered, then separated simulations for the most frequent weather conditions of the wildfire season were conducted, to obtain different sets of outputs at modelling resolution in the study area. FlamMap fire model uses the minimum travel time fire spread algorithm (Finney, 2002), which is optimized for processing large numbers of fires. In this study, 10,000 wildfire events were simulated to replicate recent fire events in the area and generate detailed maps of burn probability (BP), conditional flame length (CFL), and fire size (FS). The BP for a given pixel is an estimate of the likelihood that a pixel will burn given a random ignition within the study area and burn conditions similar to the historical fires (Ager et al., 2012). The BP is defined as (1):

$$BP = F/n \qquad (1)$$

where F is the number of times a pixel burns and n is the number of simulated fires (10000).

The fireline intensity (FI – kW/m) for a given fuel type and moisture condition can be calculated from the fire spread rate normal to the front (Byram 1959; Catchpole et al. 1982), and then it is converted to flame length (FL – m) based on Byram's (1959) equation (2):

$$FL = 0.0775\ (FI)^{0.46} \qquad (2)$$

Conditional flame length is the probability weighted flame length given a fire occurs and is a measure of wildfire hazard (Ager et al., 2010), while it is calculated by incorporating the flame length distribution generated from multiple fires burning each pixel in equation (3):

$$CFL = \sum_{i=1}^{20} \left(\frac{BP_i}{BP}\right)(Fi) \qquad (3)$$

where *Fi* is the flame length midpoint of the ith category.

Text files containing the size (FS, ha) and ignition coordinates were used to analyze spatial variation in the size of simulated fires.

Six weather scenarios were defined by wind speed, azimuth, and frequency derived from historical observation during fire season (June–September) in the study area (40°, 70°, 100°, 130°, 160° and 190°). Fire ignitions were distributed within the modelling domain according to IP, and then every fire was independently modelled considering the weather scenario.

During fire simulation, weather conditions were held constant, and fire suppression efforts were not considered due to the lack of the information. Although suppression activities have a very limited influence on wildfire growth during peak fire events (Alcasena et al., 2015, 2016).

The wildfire scenarios were created with a fire period of 5 hours, which is the common average duration, and 0.01 spot probability. Output analysis, as well as input data assembling are facilitated by other advanced models and tools as ArcFuel 10 (Ager et al., 2011), implemented for ArcGIS 10.4.1. Spatial variation in BP, CFL and FS were analysed among municipalities of the study area with no-uniform landscape topography, weather condition and land cover to determine the relative wildfire exposure.

3. RESULTS

3.1 Wildfire hazard and exposure

We obtained burn probability (BP), conditional flame length (CFL), and fire size (FS), from fire modelling. BP is a pixel-level wildfire likelihood estimate obtained from the proportion of fires that burned each pixel given a fire occurs under weather conditions within the modelling domain. BP varied both among and within municipalities (Table 2, Figure 3). BPs were arbitrarily categorized for tabular and display purposes in four classes. The highest BP values were observed for Kowsar and Bile Savar (10 percent in burn probability class 4). In contrast, BP for the Khalkhal, and to a lesser extent, Sareyin, Germi, Nir and Ardabil exhibited the lowest burn probabilities. On both a percentage and absolute basis, BPs for the Khalkhal were concentrated in BP classes 1 and 2. The non-burnable fuels present in the study area, mostly related to densely developed areas, as well as agricultural irrigation lands and water bodies were barriers to fire spread and reduced the burn probability in the central and eastern regions such as the city centre of Ardabil.

Wildfire hazard was defined as the average flame length of all simulated fires that burned a given pixel. Hazard was calculated as the probability weighted flame length among the flame length intervals output from the model (Calkin et al., 2010). The outputs were then placed into categories corresponding with the response function flame length categories of Low (L= 0-0.6 m), Moderate (M= 0.6-1.8 m), High (H= 1.8-3.6 m), and Very High (VH= >3.6 m) (adapted from Andrews et al., 2011) (Table 2).

Table 2. Area in Burn Probability (BP) and Fire Size (FZ) classes, and the L, M, H, and VH wildfire hazard categories by municipality. Categories defined as L= 0 to 0.6 m, M= greater than 0.6 to 1.8 m, H= greater than 1.8 to 3.6 m, and VH= greater than 3.6 m. Hazard is defined as the average Conditional Flame Length (CFL) of the simulated fires.

Municipality	Area in burn probability classes (km^2)				Fire hazard categories (km^2)				Area in fire size (ha) classes (km^2)			
	1	2	3	4	L	M	H	VH	1	2	3	4
	0-0.0005	0.0005-0.002	0.002-0.004	0.004-0.013					0.98-160.7	160.7-340.4	340.4-633.2	633.2-1697.9
Sareyn	262.9	117.6	19.4	0.2	300.6	98.8	0.6	-	211.2	116.9	72.1	0.2
Bileh Savar	924.5	446.0	236.5	187.6	1655.3	139.7	0.8	-	294.3	315.6	492.7	692.4
Germi	1275	485.1	194.8	61.6	1949.3	67.4	0	-	793.3	441.2	411.1	370.7
Khalkhal	2065.5	591.05	122.1	15.8	1969.2	823.6	1.5	0.003	2392.2	376.9	25.4	-
Kowsar	496.7	446.1	206.0	130.2	531.6	746.9	1.4	-	435.9	584.8	258.3	-
Meshgin Shahr	2212.1	1132.3	339.8	80.0	2604.6	1136	23.4	0.005	2421.7	1007.1	333.3	2.4
Namin	646.2	215.8	30.3	53.9	794.2	152.2	0.15	-	679.1	163.0	104.4	-
Nir	479.8	508.6	158.3	77.5	632.1	591.6	0.96	-	263.1	334.4	627.0	-
Parsabad	663.5	492.7	235.5	21.6	1156.2	242.3	14.5	-	694.4	328.0	342.1	48.3
Ardabil	1301.2	554.2	154.6	154.6	1615.5	530.7	17.9	-	1212.4	536.3	379.3	36.5
Total	10327.7	4989.7	1697.8	783.4	13209	4529	61.4	0.008	9398.0	4204.6	3046.1	1150.8

In general, moderate hazard values were observed within all municipalities and were associated with the continuity of wildland vegetation and relatively dry climate in the southern part and because of the concentrated farming activities in the northern part. Across all municipalities, less than 1 percent of the total burnable area was assigned to the H hazard category, 26 percent to the M category, and 74 percent to the L category. Negligible areas of the burnable area in Khalkhal and Meshgin Shahr were in the VH hazard category. Kowsar and Nir contained the largest area on both a percentage and total area basis in the M category (58 and 48 percent, respectively, table 2). Bile Savar and Germi show relatively minor area within the M hazard category (7.7 and 3 percent, respectively). Nearly all the burnable area in the Bile Savar, and Germi were in L category (92 and 96 percent, respectively). Other largest percentage of area in the L hazard category, were estimated in Namin, Ardabli and Sareyn.

The fire size (FS) output assigned a value (ha) to every fire ignition coordinates on a fire list file. Large differences in FS among the municipalities were obtained, especially between the northern municipalities and others. The highest FS values were observed in Bile Savar (38 percentage in FS class 4). FS for Khalkhal, Namin and Meshgin Shahr exhibited the lowest values (83, 72 and 64 percent in FS class 1, respectively).

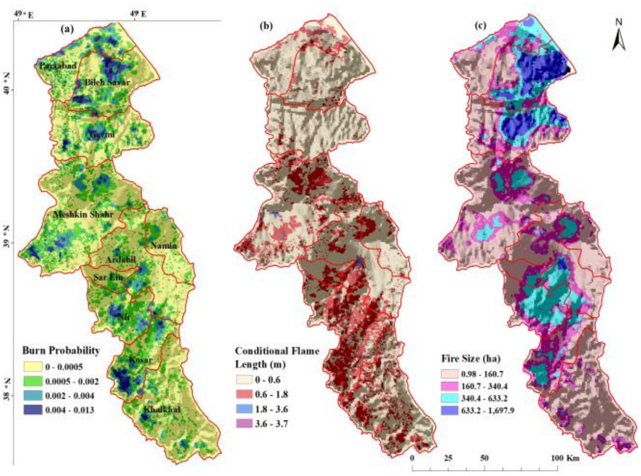

Figure 3. Output maps of BP (a), CFL (b), and FS (c), considering the historical fires and weather condition in the study area for the period 2005–2018.

4. CONCLUSIONS

The MTT fire spread algorithm coupled with advanced geospatial tools can be useful for quantifying exposure profiles and identifying landscapes able to support large and severe fires. Fire likelihood and intensity maps, as well as fire exposure profiles are substantial to landscape managers and policy makers for prevention, mitigation and monitoring strategies. The modelling approach presented in this study has many applications for fire risk assessment and management in the fire-prone landscapes in Iran, where most fire ignitions are linked to anthropic activities and few long-distance-spreading large wildfires cause most of the damage. Although the method should be carefully evaluated and modified accordingly (if needed) prior to adopting in other areas.

Analyses of wildfire exposure were conducted at municipality level and results were developed for the 10 municipalities included in Ardabil. The work allows discriminating areas that should be targeted for mitigation and prevention planning. BP and FS values across all municipalities (Figure 3a-c) can suggest different prevention and management strategies, as for instance planning fuel treatments on burnable areas characterized by highest fire intensity values.

Variation in CFL among simulated fires is caused by a number of factors, including wind speed, fuel moisture, and the direction of fire arrival relative to the maximum spread direction. Bile Savar, and Germi, Namin, Ardabli and Sareyn were almost entirely in the L and M hazard categories (CFL<1.8m) reflecting relatively moderate weather and fuel moisture conditions. In contrast, Parsabad, Ardabil and Meshgin Shahr presented the highest percentage of burnable area in the H hazard category (with very small area). CFL spatial variation was completely affected by the spatial distributions of the historic ignition point densities.

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REFERENCES

Ager, A.A., Vaillant, N.M., Finney, M.A., 2010. A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management*, 259, 1556–1570.

Ager, A.A., Vaillant, N.M., Finney, M.A., 2011. Integrating fire behavior models and geospatial analysis for wildland fire risk assessment and fuel management planning. *Journal of Combustion*. doi:10.1155/2011/572452.

Ager, A.A., Vaillant, N.M., Finney, M.A., Preisler, H.K., 2012. Analyzing wildfire exposure and source–sink relationships on a fire prone forest landscape. *Forest Ecology and Management*, 267, 271-283.

Ager, A.A. Day, M.A., McHugh, C.W., Short, K., Gilbertson-Day, J., Finney, M.A., Calkin, D.E., 2014. Wildfire exposure and fuel management on western US national forests. *Journal of Environmental Management*, 145: 54-70.

Ahmed, M.R., Rahaman, K.R., Hassan, Q.K., 2018. Remote Sensing of Wildland Fire-Induced Risk Assessment at the Community Level. *Sensors* 2018, 18, 1570.

Alcasena, F.J., Salis, M., Ager, A.A., Arca, B., Molina, D., Spano, D., 2015. Assessing landscape scale wildfire exposure for highly valued resources in a Mediterranean area. *Environ. Manag*. 55, 1200–1216.

Alcasena, F.J., Salis, M., Vega-García, C., 2016. A fire modeling approach to assess wildfire exposure of valued resources in central Navarra, Spain. *Eur. J. For. Res*. 135, 87–107.

Alcasena, F.J., Salis, M., Ager, A.A., Castell, R., Vega-García, C., 2017. Assessing wildland fire risk transmission to communities in Northern Spain. *Forests*, 8, 30; doi:10.3390/f8020030.

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behaviour. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-GTR-122. (Ogden, UT)

Andrews, P.L., Heinsch, F.A., Schelvan, L., 2011. How to generate and interpret fire characteristics charts for surface and crown fire behavior. General Technical Report RMRS- GTR-253. USDA Forest Service, Rocky Mountain Research Station, Fort Collins.

Barnett, K., Miller, C., Venn, T.J., 2016. Using risk analysis to reveal opportunities for the management of unplanned ignitions in wilderness. *J. For.* 114.

Calkin, D.E., Ager, A.A., Gilbertson-Day, J., Scott, J.H., Finney, M.A., Schrader-Patton, C., Quigley, T.M., Strittholt, J.R., Kaiden, J.D., 2010. Wildfire risk and hazard: procedures for the first approximation. General Technical Report RMRS-GTR-235. USDA Forest Service, Rocky Mountain Research Station, Fort Collins.

Calkin, D.E., Ager, A.A., Thompson, M.P., 2011. A comparative risk assessment framework for wildland fire management: the 2010 cohesive strategy science report. General Technical Report RMRS-GTR-262. USDA Forest Service, Rocky Mountain Research Station, Fort Collins.

Chuvieco, E., Aguado, I., Jurdao, S., Pettinari, M.L., Yebra, M., Salas, J., Hantson, S., de la Riva, J., Ibarra, P., Rodrigues, M., Echeverrı´a, M., Azqueta, D., Roma´n, M.V., Bastarrika, A., Martı´nez, S., Recondo, C., Zapico, E., Martı´nez-Vega, F.J., 2012. Integrating geospatial information into fire risk assessment. *Int J Wildl Fire*. doi:10. 1071/wf12052

Finney, M.A., 2002. Fire growth using minimum travel time methods. *Can J For Res*. 32(8):1420–1424. doi:10.1139/x02-068.

Finney, M.A. 2006. An overview of FlamMap fire modeling capabilities. In: Andrews, P.L., Butler, B.W. (Eds.), Fuels Management – How to Measure Success, Conference proceedings, 28–30 March 2006, Portland, OR, USDA Forest Service, Rocky Mountain Research Station Proceedings RMRS-P-41. Fort Collins, Colorado, pp. 213–220.

Hurley, M.J., Bukowski, R.W., 2008. Fire Hazard Analysis Techniques, in fire protection handbook, 20thedn, National Fire Protection Association, Gaithersburg, MD, Sect.3, ch.7, 3-122.

Palaiologou, P., Ager, A.A., Nielsen-Pincus, M., Evers, C.R., Kalabokidis, K., 2018. Using transboundary wildfire exposure assessments to improve fire management programs: a case study in Greece. *International Journal of Wildland Fire*, 27, 501-513

Salis, M., Ager, A., Arca, B., Finney, M.A., Bacciu, V., Duce, P., Spano, D., 2013. Assessing exposure of human and ecological values to wildfire in Sardinia, Italy. *Int. J. Wildland Fire*, 22, 549–565.

Salis, M., Ager, A. A., Alcasena, F., Arca, B., Finney, M., Pellizzaro, G., and Spano, D., 2015. Analyzing seasonal patterns of wildfire exposure factors in Sardinia, Italy. *Environmental Monitoring and Assessment*, 187:4175.

Scott, J.H., Burgan, R., 2005. Standard fire behaviour fuel models: a comprehensive set for use with Rothermel's Surface Fire Spread Model. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-153. (Fort Collins, CO)

Scott, J.H., Thompson M.P., Calkin, D.E., 2013. A wildfire risk assessment framework for land and resource management. Gen. Tech. Rep. RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p.

Taber, M.A., Elenz, L.M., Langowski, P.G., 2013. Decision making for wildfires: a guide for applying a risk management process at the incident level. Gen. Tech. Rep. RMRS-GTR-298WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

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