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Wind Effect on Wildfire and Simulation of its Spread (Case Study: Siahkal Forest in Northern Iran)

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ABSTRACT

Lack of fire behavior studies and the immediate needs posed by the extent of the fire problem in forests of Iran require that extensive studies be conducted to develop models to predict fire behavior in the region. In this study, FARSITE Fire Area Simulator was applied to simulate spread and behavior of two real fires that had occurred in Northern Forests of Iran during 2010 summer and fall seasons in a spatially and temporally explicit manner taking into account the fuel, topography, and prevailing weather in the area. Spatial data themes of elevation, aspect, slope, canopy cover, and fuel model were prepared and formatted in GIS along with weather and wind files to run FARSITE fire behavior model. The effect of weather conditions on the accuracy of FARSITE simulations was evaluated in order to assess the capabilities of the simulator in accurately predicting the fire spread in the case study. The WindNinja model was used to derive local winds influenced by vegetation and topography. The simulations were validated with the real mapped fire scars by GPS mapping. Kappa Coefficient was used as measure of the accuracy of the simulation. The Kappa statistic was lower for spatially uniform wind data (0.5) as compared to spatially varying wind data (0.8) for the two studied events. The results confirm that the use of accurate wind field data is important in fire spread simulation, and can improve its accuracy and the predictive capabilities of the simulator.

Keywords: FARSITE, Fuel Model, Weather condition, Wildfire spread, WindNinja.

INTRODUCTION

Forest fires are a natural disaster causing a great volume of damage both to environmental systems and infrastructure worldwide (Boboulos and Purvis, 2009). These fires can cause enormous destruction, consuming forests, buildings, and also endangering human life. The impacts of forest fires can have global effects, producing gaseous and particle emissions that impact the composition and functioning of the global atmosphere, exacerbating climate change (Akyürek and Tasel, 2004). Unfortunately, there are no comprehensive data on different attributes of fire, such as fire behavior, burned area, ecological and socio- economic effects of fire, and regeneration status, especially in most developing countries (Safaian *et al*., 2005; Sibanda, 2011). Fire behavior refers to the manner in which a fire reacts to the influences of fuel, weather, and topography (NWCG, 2012). This behavior is a product of the environment in which the fire is burning (Pyne *et al*., 1996). The fire environment is composed of the surrounding conditions, influences, and modifying forces that determine the fire behavior. The interacting forces and influences that constitute the fire environment are represented by topography, weather, fuel, and the fire itself (Countryman, 1972). In many cases, meteorological conditions overcome the other elements of the fire

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environment, so much to determine, alone, the behavior and the dangerousness of a fire (Pyne *et al*., 1996). Wind is one of the primary environmental variables influencing wildfire spread and intensity (Catchpole *et al*., 1998; Rothermel, 1972). The lack of detailed wind speed and direction information is one major source of uncertainty in fire behavior prediction (Butler *et al*., 2005).

Temporal and spatial variations of fire spread and behavior can be predicted using one of the semi-physical or empirical models developed over the past two decades (Andrews and Queen, 2001; Perry, 1998). FARSITE Fire Area Simulator (Finney, 1998) is one of the main fire simulation systems. The simulator is based on the semi empirical fire prediction model developed by Rothermel (1972) and incorporated into BEHAVE Fire Behavior Prediction and Fuel Modeling System (Andrews, 1986). This spatial growth of fire perimeters also is simulated with the elliptical wave propagation technique, applying Huygens' Principle (Finney, 1998). The model was originally developed for simulation of prescribed fires in the national parks and wilderness areas of the United States of America (Arca *et al*., 2007). The model has been widely used and validated in other areas such as Europe and Australia (Arca *et al*., 2006; Andrews *et al*., 2007; Arroyo *et al*., 2008; Carmel *et al*., 2009; Mbow *et al*., 2004; Mutlu *et al*., 2008; Sibanda, 2011). They concluded that the accuracy of fuel models and wind data was important for realistic fire spread simulation using FARSITE model. The simulation of past fires is important for comparison of simulated fires with the real fire scars and validating the model for a given simulation. Therefore, these facts show that the model is well proven and so applicable in this study. To support these modeling capabilities, the simulator requires specific input layers (elevation, slope, aspect, fuels, percent canopy cover, weather, etc.), consisting of geo-referenced digital map data. Two procedures (constant or gridded stream) are applicable to provide more detailed weather condition data files. Fire behavior analysts have traditionally relied on uniform wind speed and direction (from weather station), which do not describe the localized terrain effects on wind (Forthofer and Butler, 2007; Forthofer, 2007). Fire behavior models such as FARSITE incorporate wind in fire behavior prediction. The modeling of wind behavior has been shown to improve the prediction of fire perimeters by fire models (Forthofer *et al*., 2007; Butler *et al*., 2006; Forghani *et al*., 2007). At least three micro-scale wind models have recently been developed to improve fire behavior simulation. These include WindStation (Lopes, 2003) WindWizard (Forthofer, 2007) and WindNinja (Forthofer, 2007). WindNinja is a simple diagnostic model designed for simulating micro-scale, terrain-influenced winds for fire behavior prediction (Forthofer *et al*., 2007). The input data required to run the model are elevation, mean initial wind speed and direction, and specification of the domain vegetation in the study area. The outputs of this model include raster grids of wind speed and direction for use in spatial fire behavior models such as FARSITE and shape files for plotting wind vectors in GIS.

Northern Iran has a total of 1.2 million ha temperate forest where fire occurs around 300-400 ha annually (Anonymous, 2002). These are mostly surface fire and affect mainly undergrowth and young trees. Despite such fires, there are unfortunately limited scientific studies or published papers about the fires (Banj Shafiei *et al*., 2006). The study of the fire spread and behavior in Northern Forests of Iran with the use of fire simulation systems is important in order to improve our knowledge on this problem and to help the fire management. In addition, it is also important to calibrate the real field data as the parameters of the fire model with simulation tools in order to acquire the real situation of the fire area and to find the accuracy and reliability of the model by comparing the extracted and simulated burned area in the study area. The main aims

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of this study were: (1) to evaluate the capabilities of FARSITE simulator in accurately modeling the fire spread on historical wildfires in Siahkal Forests that burned the areas, and (2) to assess using uniform and also spatially varying wind data in explaining fire spread. FARSITE simulated burnt areas were validated with real burnt scar maps. The area was selected for study due to the availability of information on the fire events. Besides, the topographic heterogeneity of the area allowed for testing the effect of incorporating spatial variation in wind in fire simulation.

MATERIALS AND METHODS

Study Area and Input Data

FARSITE was employed to simulate spread of two surface fires that had occurred in Siahkal Forests of Hyrcanian Forests, in Guilan Province (Figure 1), during 2010 summer and fall seasons. The area is sensitive to fires particularly during fall due to hot winds and high temperatures. These wildfires were selected because burnt area map was easily prepared for model validation. These fires burned areas mainly covered by the typical Hyrcanian vegetation. Both of these wildfires were located near the Caspian Coast, with similar climate and vegetation characteristics. The two sites had areas of about 300 ha and 250 ha corresponding to, respectively, Toshi and Malekroud wildfires, which included fire scars and their surroundings, were studied for the simulation of the past fires.

Wildfire Case Studies

Toshi Case Study

The first fire occurred near the village of Toshi, Koldemsara district (Lat. 37º 11´ N, Long. 49º 88´ E), on August 14, 2010. It burned an area of about 34 ha covered by a relatively mixed, medium density forests with nearly heterogeneous structural characteristics and mainly composed of *Carpinus betulus*, *Quercus castaneaefolia*, *Alnus subcordata*, *Parrotia persica*, *Acer insign*, *Gleditshia caspica*, *Zelkova carpinifolia*, *Diospyros lotus*.

The fire started at 4:00 PM and lasted

Figure 1. The location map of Siahkal Forests within Guilan Province in the northern part of Iran.

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approximately 25 hours. The ignition point was located near an agricultural area (Figure 2). The weather was relatively severe, with air temperature around 35ºC and relative humidity around 38%. Based on the report of firefighters, the fire moved towards south-east driven by a north-east wind (30º). The topographic situation facilitated the spread of fire towards south-east (Figure 2). The fire was not completely successfully controlled by forest firefighters.

Malekroud Case Study

Malekroud wildfire occurred near the town of Malekroud (Lat. 37º 03´ N, Long. 49º 84´ E), in December 2010. This site is located in a low slope area with an elevation of about 250 m (Figure 2).

The fire occurred on December 17, 2010, at 5.00 PM. The burned area was about 24 ha. The day was characterized by a high wind and it was very hot, the maximum temperature recorded in the closest meteorological station was 25ºC and it was reached at 3.00 PM. the minimum was 7ºC at 3.00 AM. The vegetation type was mainly plantation forest with dominant species included *Acer insign*, *Quercus castaneaefolia*, *Alnus subcordata*, *Populus spp*.

The ignition point was located near the road along the southern boundary of the area (Figure 2). The fire moved towards north driven by mild slope and southern wind (160º). Forest firefighters extinguished the fire with relatively good success near the road. The fire stopped its spread approximately at 8.00 AM, after about 15 hours.

The fire spread simulation in FARSITE model was based on fuel, topography, and weather conditions. The model also uses an ignition point for the fire. The model required five spatial raster layers, namely, slope, aspect, elevation, fuel model, and canopy cover percentage (Finney, 1998). Non spatial data, which is also required by the model, include records of temperature, relative humidity, precipitation, wind speed and direction, cloud cover during the fire event, and geographic coordinate of the region and dates for simulation.

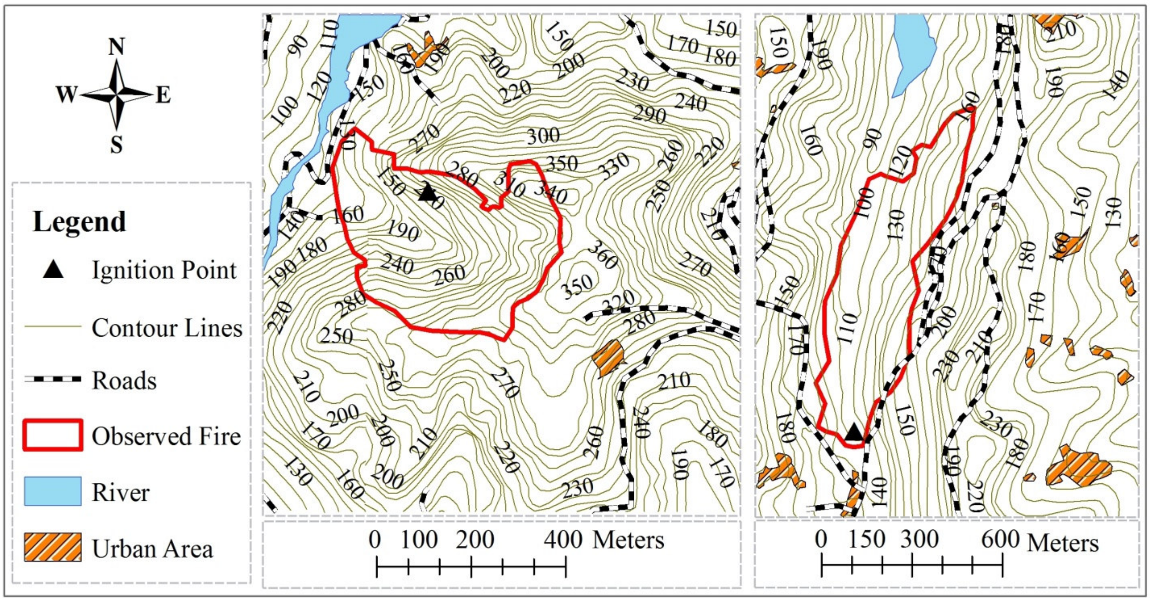

Figure 2. Toshi (left) and Malekroud (right) wildfire case studies, with contour line, roads, and urban areas.

Topography

Topography is a static element that strongly influences winds and vegetation, besides the fire behavior (Pyne *et al*., 1996). Topographic data of the area were derived from a digital elevation model (DEM) (15 m) of the area using ArcGIS9.3. DEM was derived from the 1: 25,000 scale topographic digital maps. The layers were converted to ASCII format for input into FARSITE model.

Weather Data

The weather constitutes, if combined with some physiological conditions of fuel, the factor which mainly influences the fire behavior (Salis, 2008). In order to build meteorological conditions of the wildfire days, hourly meteorological data (air temperature, relative humidity, wind speed and direction, and rainfall) were obtained from the closest weather station (Lahijan Station) located 15 km away from the Siahkal Forests. It was assumed that there was no significant variation in weather conditions between the study area and the weather station since both of them lie on the same seaward facing side and at a comparable altitude. Meteorological data were input as hourly values for wind speed and direction and for cloud covers, whereas rainfall, the maximum and minimum temperature, and relative humidity were input as daily data.

Fuel Model Selection

Since the description of fuel proprieties is usually very complex, fire managers have tried to summarize the physical parameters and spatial distribution of fuel in different classes also known as ‘‘fuel models’’ (Anderson, 1982; Burgan and Rothermal, 1984). More specifically, a fuel model has been defined as ‘‘an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions’’ (Merrill and Alexander, 1987). The spatial distribution of the fuel characteristics can be displayed as fuel type maps. The different classification systems are often used to group vegetation types together according to their fire behavior. Fifty three standard fuel models have been developed for the Rothermel (1972) fire spread model. According to Nyatondo (2010), these include the original 13 fuel models described by Anderson (1982) and the recent 40, which were described by Scott and Burgan (2005). In this study, selection of suitable fuel models was done based on the similarities between the vegetation characteristics observed within the study areas during fieldwork and the description of the standard fuel models (Anderson, 1982; Scott and Burgan, 2005). The vegetation cover types classified through fieldwork were reclassified according to the selected fuel models based on the fuel status as observed in the field (Table 1, Figure 3).

Canopy Cover

During the fieldwork for forest type mapping, canopy cover percentage was determined for each cover type unit. Within each one, four readings in different directions (N, S, E, and W) were taken and averaged for that unit. This was done to reduce bias. Moreover, shrub and herb cover percentages were visually estimated for each cover type unit.

Fire Spread Simulation

The vegetation and topography datasets were converted to ASCII grid files and incorporated into the development of FARSITE model. Weather data were input as text stream. FARSITE has the ability to incorporate gridded wind fields. Comparison of wildfire spread simulations with and without simulated gridded winds have demonstrated that the accuracy of fire spread

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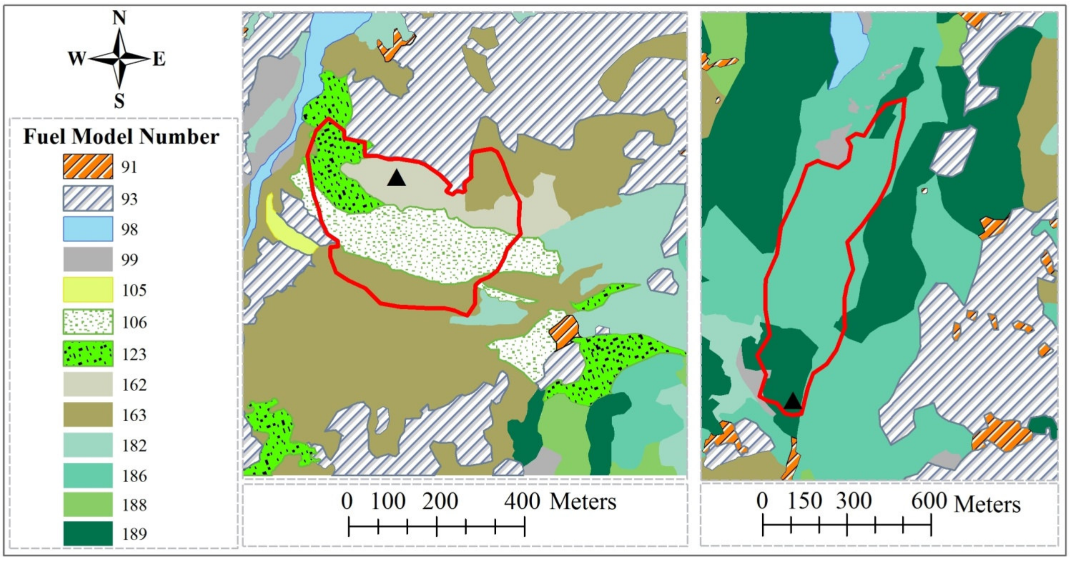

Figure 3. Prepared fuel models map for the wildfire case studies (Fuel model numbers of legend are described in Table 1).

predictions is significantly higher using gridded wind data than without it (Forthofer, 2007; Nyatondo, 2010). The topographic heterogeneity of the area allowed for testing the effect of incorporating spatial variation in wind in fire simulation. Therefore, in this research, the WindNinja model was used to generate gridded wind data, which then was incorporated in FARSITE. The other parameters were kept constant to determine the effect of spatially varying wind data on the fire spread and behavior. The simulation durations were two days 14-15 August, and 17-18 December, 2010, respectively, for Toshi and Malekroud wildfires. This date correspond to days on which fire was reported to have occurred in the area.

Time step of model simulations was set to 1 hour. A time step is the longest time that the environmental conditions are assumed constant. Perimeter and distance resolution were both set to 30 and 60 m, respectively. The same model parameters were used with and without simulated gridded winds.

FARSITE assumes that the spread of fire is dependent on fuel type and load, hence, the model does not have a function to extinguish fire automatically (Ryu *et al.*, 2007). As long as there is surface fuel, the model assumes that the fire is spreading (Nyatondo, 2010; Sibanda, 2011; Ryu *et al.*, 2007). Wildfire growth also depends on the fuel moisture content change during the fire propagation. The change in moisture content of dead and downed woody surface fuels in response to changing weather conditions is critical to calculating the changes in fire behavior (Finney, 1998). Undoubtedly, a high level of fuel moisture can cause the extinction of the fire spread. Moisture contents of live fuels are assumed to remain constant in FARSITE throughout the simulation (but these can be changed in the .FMS file during the simulation). Dead fuel moisture is an important input to two sub-models used in FARSITE: (1) the surface fire behavior model (Rothermel, 1972) for determining spread rate and intensity of surface fires, and (2) the "Burnup" model (Albini and Reinhardt, 1995) for determining fuel consumption and emissions during flaming and after the passage of the flaming front (Finney, 1998). In this study, roads were used as barriers to fire spread. The simulation needs an ignition point as a starting point of the fire spread. Based on the

Table 1. Description of the standard fuel models used for simulation in the wildfire case studies from 53 standard fuel models (Anderson, 1982; Scott and Burgan, 2005).

Observed vegetation	Fire carrying fuel type, model name and code	Fuel model number	Fuel model description
Buildings	Insufficient wildland fuel to carry wildland fire under any condition (Nonburnable, NB1)	91	Land covered by urban and suburban development. The area under consideration must not support wildland fire spread.
Agriculture	Insufficient wildland fuel to carry wildland fire under any condition (Non-burnable, NB3)	93	Agricultural land maintained in a nonburnable condition; examples include irrigated annual crops
River	Insufficient wildland fuel to carry wildland fire under any condition (Non-burnable, NB8)	98	Land covered by open bodies of water such as lakes, rivers and oceans
Bare	Insufficient wildland fuel to carry wildland fire under any condition (Nonburnable, NB9)	99	Include areas of exposed soil surface, settlements and rocky areas.
Grass (Low density)	Humid-climate grass (Grass, GR5)	105	Grass and herb fuel load is light; fuelbed depth is about 1 to 2 feet.
Grass (Medium density)	Continuous humid-climate grass (Grass, GR6)	106	Load is greater than GR5 but depth is about the same.
Grass-shrub	Grass and shrubs combined (Grass-Shrub, GS3)	123	Moderate grass/shrub load, average grass/shrub depth less than 2 feet.
Natural Forest (Medium density and timber-shrub)	Moderate litter load with shrub component (Timber-Understory, TU2)	162	High extinction moisture. Spread rate is moderate; flame length low.
Natural forest/Mixed forest (Medium density and timber-grass-shrub)	Grass and shrub mixed with litter from forest canopy (Timber-Understory, TU3)	163	Extinction moisture is high. Spread rate is high; flame length moderate.
Hardwood Plantation (Low density)	Broadleaf (hardwood) litter (Timber Litter, TL2)	182	Low load, compact broadleaf litter. Spread rate is very low; flame length very low.
Hardwood plantation (Medium density)	Moderate load broadleaf litter (Timber Litter, TL6)	186	Less compact than TL2. Spread rate is moderate; flame length low.
Softwood Plantation (Relatively dense pine forest with very little or no shrub layer)	Moderate load long-needle pin litter (Timber Litter, TL8)	188	May include small amount of herbaceous load. Spread rate is moderate; flame length low.
Hardwood plantation (High density)	Very high load, fluffy broadleaf litter (Timber Litter, TL9)	189	Spread rate is moderate; flame length moderate.

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report of firefighters, during the fieldwork, locations which were considered to be the likely ignition points were determined and recorded using GPS. The accuracy of the simulations was determined by the level of similarity between the simulated and the observed fire scars. The observed fire scar maps were generated by GPS a year after wildfires occurred. An error matrix was calculated between the simulated and observed fire area to determine the frequency of absence or presence of burned areas (Nyatondo, 2010; Sibanda, 2009). The percentage agreement and Kappa Coefficient (Congalton, 1991) were derived from error matrix used as measures of the accuracy of the simulation. It is important to take note that the percentage agreement refers to the proportion of the observed fire scar which was simulated as burned. Furthermore, Kappa Coefficient derived from the error matrix indicates the level of similarity between the observed and simulated fire scars and takes into account the over- and under estimations of the simulation.

RESULTS AND DISCUSSION

In this study, FARSITE simulations of the burnt areas in August and December 2010 fires were based on standard fuel models. The simulations were done using spatially uniform and spatially varying (gridded) wind data. The maps in Figure 4 represent the fire growth outputs.

Fire Simulation for Toshi Wildfire

The first simulation using uniform wind data with the observed fire duration (14-15 August) indicated that the percentage agreement was only 36%. This was an underestimation of the observed fire scar, with 1% overestimation. The simulated fire growth areas from uniform and spatially varying wind data were 12.24 and 25.55 ha, respectively. The level of agreement increased from 36 to 73% after incorporation of gridded wind. In this case, the extent of underestimation decreased to 27%, whilst the overestimation increased only to 6%. The Kappa Coefficient

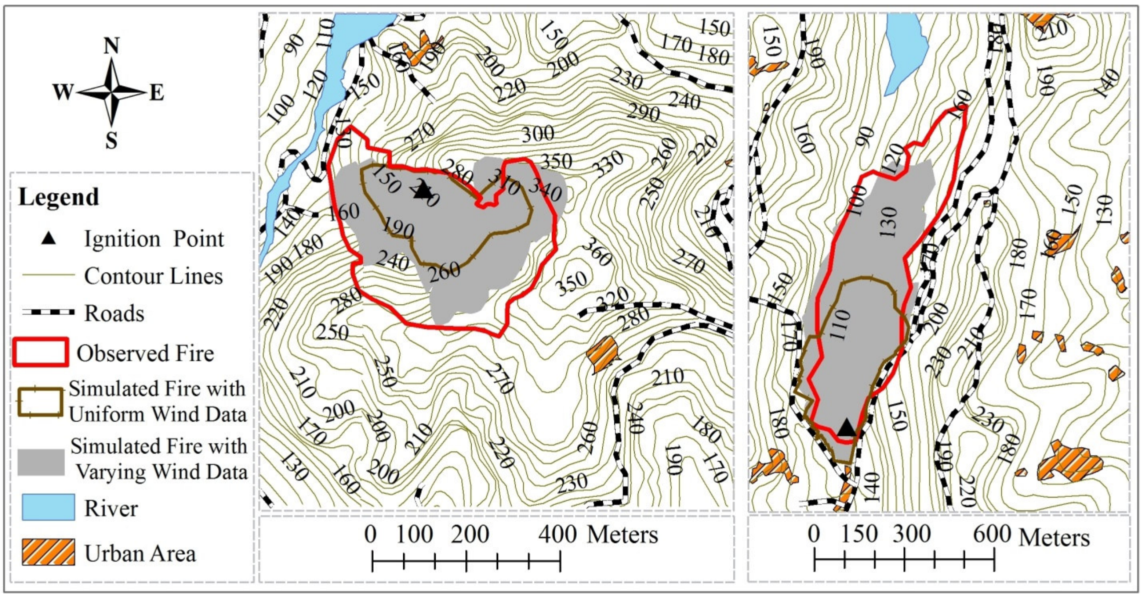

Figure 4. Comparison between observed and simulated fire areas obtained with spatially uniform and spatially varying (gridded) wind data.

increased significantly during the use of spatially varying wind data from 0.50 to 0.81.

Fire Simulation for Malekroud Wildfire

The estimated fire growth areas from uniform and spatially varying wind data were 12.09 and 23.63 ha, respectively. There was a significant difference between the two outputs. Using spatially uniform wind data, the simulated fire spread covered 42% of the observed fire scar, which was almost low, whilst overestimation was 8%. After the incorporation of spatially varying winds, 98% of the observed fire scar was simulated as burned with overestimation of 15%. The Kappa Coefficient was lower for uniform wind data (0.53) as compared to gridded wind data (0.82).

The summary of accuracy assessment of the simulated fire scars from the two different scenarios (with and without gridded winds) is presented in Table 2.

CONCLUSIONS

Wildfire spread and behavior prediction is important to bring the fire under control. This study validated the use of the FARSITE model in Northern Forests of Iran. The direction of spread and the shape of the simulated fire scars highlighted the potential applicability of the FARSITE model in the study areas. It should be noticed that fire behavior models can only approximate the reality. The simulated fire growth areas did not completely agree with the observed wildfire scars. The observed differences between the simulated fire spread areas and the real wildfire areas may be due to inaccurate input into the fuel models, or wind and weather data. The simulation results obtained by spatially varying wind data indicated a better accuracy than the uniform wind, because the complexity of the terrain greatly affected local wind condition (Salis, 2008). The level of agreement and Kappa Coefficient increased as the output gridded wind from WindNinja was input into FARSITE. In summary, the results of the study highlight the importance of the use of wind field data to obtain reasonable fire spread simulations in the areas. Further studies may simulate the spatial variation of wind speed and direction with different methods for computing wind vectors as using a different wind model such as WindWizard (Forthofer, 2007) or WindStation (Lopes, 2003).The wind data used in this study was acquired from a weather station outside the area where the fires occurred. The underestimation of the fire scar may be associated with the improper representation of local winds (Finney, 1998; Forthofer and Butler, 2007). The overestimation could also be attributed to the absence of fire suppression activities to stop the spread of fire during the simulation. This information was not available during the time of the study. The

Table 2 Accuracy assessment of the simulated fire scars.

Wildfires	Toshi		Malekroud	
Scenarios	Uniform Wind	Gridded Wind	Uniform Wind	Gridded Wind
% Agreement	36	73	42	98
%Underestimation	64	27	58	2
% Overestimation	1	6	8	15
Kappa Coefficient	0.5	0.81	0.53	0.82

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incorporation of such information in the fire spread modeling could result in more accurate simulations (Arca *et al*., 2007; Arroyo *et al*., 2008). Due to lack of information and impossibility of field measurement of larger historical fires, the two fires studied were rather small (24 and 34 ha). Access to the documented information about fire behavior of larger fires, however, allows for testing larger change in fire spread.

The fuel models applied in this study have been developed in the United States. Although the fuel models selected closely resembled the conditions in the study area, direct measurement of the fuel parameter (such as fuel load, fuel moisture, etc) may result in more realistic fuel models. There is, therefore, need for development of fuel models specific for temperate conditions in northern forests of Iran. The development of custom fuel models involves adjustment of fuel parameters as observed in the field (Nyatondo, 2010). In several researchworks, it is stated that the accuracy of FARSITE can be improved using custom fuel model, designed and developed with the purpose of simulating the fire spread and behavior on a particular type of vegetation (Fernandes, 2009; Salis, 2008; Bacciu, 2009).

Further researches based on actual fire behavior in the area are necessary for the validation of the FARSITE model and could improve the accuracy of estimates by an extensive calibration. Since there is a strong database of wildfires in Siahkal Forests, several simulations can be done in other areas and comparison of the results can help to provide a significantly better assessment of this approach. The simulation of the wildfires can be improved by constructing fuel models and collecting weather data on a local and regional forest scale.

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REFERENCES

1. Akyürek, Z. and Taşel, E. 2004. Wildfire Simulation Modeling Using RS and GIS Integration for Marmaris-Çetibeli Wildfire, Turkey. "24th EARSel Symposium", 1, (2004), p.69-79.
2. Albini, F. A. and Reinhardt, E. D. 1995. Modeling Ignition and Burning Rate of Llarge Woody Natural Fuels. *Int. J. Wildland Fire*, **5**(2): 81-91.
3. Anderson, H. E. 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. General Technical Report INT-122, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah.
4. Andrews, P. L., Finney, M. and Fischetti, M. 2007. Predicting Wildfires. *Scientific American,* **297(2):** 46–55.
5. Andrews, P. L. and Queen, L. P. 2001. Fire Modeling and Information System Technology. *Int. J. Wild*, **10(3-4):** 343-352.
6. Andrews, P. L. 1986. BEHAVE: Fire Behavior Prediction and Fuel Modeling System-BURN Subsystem. Part 1. General Technical Report INT-194, USDA Forest Service.
7. Anonymous. 2002. *Statistical Yearly Report*. Management and Planning Organization of Mazandran, Iran, 156 PP.(In Persian)
8. Arca, B., Duce, P., Laconi, M., Pellizzaro, G., Salis, M. and Spano, D. 2007. Evaluation of FARSITE Simulator in Mediterranean Maquis. *Int. J. Wild*, **16**: 563-572.
9. Arca, B., Duce, P., Pellizzaro, G., Laconi, M., Salis, M. and Spano, D. 2006. Evaluation of FARSITE Simulator in Mediterranean Shrubland. *Forest Ecol. Manage.*, **234**: S110-S110.

10. Arca, B., Laconi, M., Maccioni, A., Pellizzaro, G. and Salis, M. 2005. Validation of FARSITE Model in Mediterranean Area. Proceedings of the "6th Symposium on Fire and Forest Meteorology and 19th Interior West Fire Council Meeting", Canmore, Alberta, Canada, 25-27 October 2005.
11. Arroyo, L. A., Pascual, C. and Manzanera, J. A. 2008. Fire Models and Methods to Map Fuel Types: the Role of Remote Sensing. *Forest Ecol. Manage.,* **256**: 1239-1252.
12. Bacciu, V. M. 2009. Maquis Fuel Model Development to Support Spatially-Explicit Fire Modeling Applications. Doctoral Thesis, Universita' Degli Studi Di Sassari, 277 PP.
13. Banj Shafiei, A., Akbarinia, M., Jalali, S. G., Azizi, P. and Hosseini, S. M. 2006. Effect of Fire on Herbal Layer Biodiversity in a Temperate Forest of Northern Iran. *Pak. J. Biol. Sci,* **9(12):** 2273-2277.
14. Boboulos, M. and Purvis, M. R. I. 2009. Wind and Slope Effects on ROS during the Fire Propagation in East-Mediterranean Pine Forest Litter. *Fire Safety J.*, **44**: 764–769.
15. Burgan, R. E. and Rothermel, R. C. 1984. BEHAVE: Fire Behavior Prediction and Fuel Modeling System-FUEL Subsystem. General Technical Report INT-167, USDA Forest Service.
16. Butler, B., Forthofer, J., Finney, M., Mchugh, C., Stratton, R. and Bradshaw, L. 2006. The Impact of High Resolution Wind Field Simulations on the Accuracy of Fire Growth Predictions. *Forest Ecol. Manage.,* **234:** S85-S85.
17. Butler, B., Stratton, R., Finney, M., Forthofer, J., Bradshaw, L. and Jimenez, D. 2005. Detailed Wind Information and at Its Application to Improved Firefighter Safety, Eight International Wildland Fire Safety Summit, April 26-28, 2005 Missoula, MT.
18. Carmel, Y., Paz, S., Jahashan, F. and Shoshany, M. 2009. Assessing Fire Risk Using Monte Carlo Simulations of Fire Spread. *Forest Ecol. Manage.*, **257**: 370–377.
19. Catchpole, W. R., Catchpole, E. A., Butler, B. W., Rothermel, R. C., Morris, G. A. and Latham, D. J. 1998. Rate of Spread of Free-burning Fires in Woody Fuels in a Wind Tunnel. *Comb. Sci. Tech.,* **131**: 1-37.
20. Congalton, R. G. 1991. A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data. *Remote Sens. Environ.*, **37**: 35-46.
21. Countryman, C. M. 1972. The Fire Environment Concept. USDA, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 12 pp.
22. Fernandes, P. M. 2009. Combining Forest Structure Data and Fuel Modeling to Classify Fire Hazard in Portugal. *Ann. Forest Sci.,* **66**: 415–423.
23. Finney, M. A., Bradshaw, L. and Butler, B. 2009. Delivery and Demonstration of Surface Wind Simulation Tool for Fire Management Decision Support: Final Report to the Joint Fire Science Program. JFSP Project No. 06-1-1-09, Missoula Fire Sciences Laboratory, Rocky Mountain Research Station, USDA Forest Service, Missoula, MT, 9 PP.
24. Finney, M. A. 1998. FARSITE: Fire Area Simulator-Model Development and Evaluation. Res. Pap. RMRS-RP-4, Forest Service, US Department of Agriculture, Rocky Mountain Research Station, Ogden, UT.
25. Forghani, A., Cechet, B., Radke, J., Finney, M. and Butler, B. 2007. Applying Fire Spread Simulation over Two Study Sites in California: Lessons Learned and Future Plans. *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2007*, 23-27 July, 2007, Barcelona, Spain, PP.1-6.
26. Forthofer, J. M. 2007. Modeling Wind in Complex Terrain for Use in Fire Spread Prediction. Master's Thesis, Colorado State University, Fort Collins, Colorado.
27. Forthofer, J. and Butler, B. 2007. Differences in Simulated Fire Spread over Askervein Hill Using Two Advanced Wind Models and a Traditional Uniform Wind Field. *USDA Forest Service Proceedings RMRS-P-46.*
28. Forthofer, J., Shannon, K. and Butler, B. 2007. Simulating Diurnally Driven Slope Winds with WindNinja. USDA Forest Service, Rocky Mountain Research Station, Missoula, MT.
29. Lasaponara, R. and Lanorte, A. 2007. *Fuel Type Mapping from Hyperspectral MIVIS and Multispectral Landsat TM Data in the Fragmented Ecosystems of Southern Italy.* (Ed.): Gomarsca, M. A.. ISBN 9789059660618, Geo-Information in

Europe, 2007 Millpress, Netherlands, PP. 219- 225.

30. Lopes, A. M. G. 2003. WindStation: A Software for the Simulation of Atmospheric Flows over Complex Topography. *Environ. Modell. Softw.*, **18**: 81-96.
31. Mbow, C., Goita, K. and Benie, G. B. 2004. Spatial Indices and Fire Behavior Simulation for Fire Risk Assessment in Savannah Ecosystems. *Remote Sens. Environ.*, **91**: 1-13.
32. Merrill, D. F. and Alexander, M. E. 1987. *Glossary of Forest Fire Management Terms*. Fourth Edition, Publication NRCC No. 26516, Natural Resources Council Canada, Ottawa, Ontario.
33. Mutlu, M., Popescu, S. C. and Zhao, K. 2008. Sensitivity Analysis of fire Behavior Modeling with LIDAR-derived Surface Fuel Maps. *Forest Ecol. Manage.*, **256(3):** 289-294.
34. NWCG (The National Wildfire Coordinating Group). 2012. *Glossary of Wildland Fire Terminology.* From http://www.nwcg.gov/pms/pubs/pubs.html., 190 PP.
35. Nyatondo, U. N. 2010. Fire Spread Modeling in Majella National Parks, Italy. MSc., International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands.
36. Perry, G. L. W. 1998. Current Approaches to Modeling the Spread of Wildland Fire: A Review. *Prog. Phys. Geog.*, **22**: 222-245.
37. Pyne, S. J., Andrews, P. L. and Laven, A. R. 1996. *Introduction to Wildfire*. 2nd Edition, John Wiley and Sons Edition. New York, 769 PP.
38. Rothermel, R. C. 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Res. Pap. INT-115, USDA For. Serv. Intermt., For. Range Exp. Stn., Ogden, Utah.
39. Ryu, S. R., Chen, J., Zheng, D. and Lacroix, J. J. 2007. Relating Surface fire Spread to Landscape Structure: An Application of FARSITE in a Managed Forest Landscape. *Landscape Urban Plan.*, **83(4):** 275-283.
40. Safaian, N., Shokri, M., Ziatabar Ahmadi, M., Atrakchali. A. and Tavili, A. 2005. Fire Influence on the Grassland Vegetation in Golestan National Park (Alborz Mts. Iran). *Ekol. Pol-Pol. J. Ecol.*, **53**: 435-443.
41. Salis, M. 2008. Fire Behavior Simulation in Mediterranean Maquis Using FARSITE (Fire Area Simulator). PhD. Doctoral Thesis, Universita ´Degli Studi Di Sassari.
42. Scott, J. and Burgan, R. 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
43. Sibanda, C. 2011. Modeling Forest Fire Behavior and Carbon Emission in the Ludikhola Watershed, Gorkha District, Nepal. MSc., Natural Resource Management, Faculty of Geo-information Science and Earth Observation, University of Twente, Enschede, The Netherlands , 70 PP.

شبیه‌سازی گسترش آتش و اثر باد روی آن (مطالعه موردی: جنگل سیاهکل در شمال ایران)

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چکیده

با توجه به فقدان مطالعات رفتار آتش و نیازهای ضروری ناشی از وسعت مشکل آتش سوزی در جنگل‌های ایران، نیاز بر این است که مطالعات گسترده ای برای توسعه مدل‌ها برای پیش‌بینی رفتار آتش در این منطقه انجام شود. در این مطالعه، شبیه‌ساز سطح آتش FARSITE برای شبیه‌سازی

گسترش و رفتار دو آتش‌سوزی واقعی رخ داده در جنگل‌های شمالی ایران در طول فصل‌های تابستان و پائیز ۱۳۸۹ در یک روش مشخص زمانی و مکانی با در نظر گرفتن ماده سوختنی، توپوگرافی و آب و هوای غالب در منطقه بکار برده شد. نقشه‌های اطلاعات مکانی ارتفاع، شیب، جهت، تاج پوشش و مدل ماده سوختنی در GIS همراه با فایل‌های آب و هوا و باد برای اجرای مدل رفتار آتش FARSITE آماده و به فرمت در آمد. تاثیر شرایط آب و هوایی روی صحت شبیه‌سازی‌های FARSITE در جهت تعیین قابلیت‌های این شبیه‌ساز در پیش‌بینی دقیق گسترش آتش در این مطالعه ارزیابی شد. مدل WindNinja برای بدست آوردن بادهای محلی تحت تاثیر پوشش گیاهی و توپوگرافی استفاده شد. شبیه‌سازی‌ها بوسیله لکه‌های آتش‌سوزی نقشه‌برداری شده با استفاده از GPS اعتبارسنجی شد. ضریب کاپا به عنوان معیار صحت شبیه‌سازی استفاده شد. آماره کاپا برای داده باد یکنواخت مکانی (۰.۵) در مقایسه با داده باد متغیر مکانی (۰.۸) برای دو حادثه مطالعه شده، کمتر بود. نتایج تائید می‌کنند که استفاده از داده میدان بادی دقیق در شبیه‌سازی گسترش آتش مهم است، و می‌تواند صحت آن، و سپس قابلیت‌های پیش‌بینی شبیه‌ساز را بهبود ببخشد.