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ORIGINAL ARTICLE

Spatio-Temporal Forest Fire Spread Modeling Using Cellular Automata, Honey Bee Foraging and GIS

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ABSTRACT
Million hectares of worldwide forests fall victim to disasters either natural or man-made. Providing effective strategies to prevent and manage this complex phenomenon has been an ideal for environmental managers. In this study, an integration of Cellular Automata (CA)is used for modeling the forest fire spread. But, the important issue in cellular automata is calibration. In this study, the Honey Bee Algorithm (HBA) is used for model calibration. The criteria taken in this study are vegetation type and density, topography, velocity and direction of wind. The output of simulation indicates high efficiency of the integrated model comprising of Cellular Automata, Honey Bee Algorithm and GIS. The proposed model was implemented in the forests stretching on the north of Iran. The area under study was divided into two parts: the model was implemented in the first part and a Kappa of 58% was obtained which was enhanced to 92% after calibration by honey bee algorithm. To evaluate the model, the calibrated model was implemented in the second part of the area under study; the results for the overall accuracy and Kappa were 98% and 88% respectively. Total burning time of the real area in the second part was 11 hours and overall burned area was 351.62 ha; simulation outputs showed 11.95 hours of burning time and 365.25 ha of burned area that were an overestimation. The results indicate that the proposed model can be employed for prediction of forest fires and can be used as part of decision support systems.
Keywords:Forest Fire, Cellular Automata, Honey BeeAlgorithm, GIS, Kappaindex.

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INTRODUCTION

Forest fires destroy from six to fourteen million hectares of forests throughout the world every year, thereby causing changes in the structure and composition of forests and even imposing adverse effects on human health, supply of goods and services. Thus, forest fires have gained much public attention throughout the world [1]. It is obvious that designing and developing methods for wildfire control, as a phenomenon occurring with great frequency proves so significant and vital. Repressive policies of fire can generally be classified into preventive and operational policies. Preventive policies that are more strategic in principle are to minimize the chances of successive fire events through organization of existing resources and building fireproof areas for prevention of fire spread. When a fire occurs, the operational interventions such as efficient allocation of defenses and rapid evacuation of the villages are needed. Mathematical models can be used, to some extent, in both strategic and tactical fire fighting for prediction of the spatial and temporal dimensions of the fire spread [2]. Simulation of forest fire is important for two reasons; firstly, it is operational and is used to estimate the spread of fire during the incident as well as management of resources during the crisis. Secondly, the use of a tool to quantify risk of fire by simulation resources during the crisis is possible and this is the most efficient method for authorities for dispatching emergency units to areas with high levels of risk [3].

Geographic Information Systems(GIS)with its capabilities and efficient tool scan facilitate the problem solving process. Cellular Automation (CA) is one of the approaches to increasing the simulation properties of modeling dynamic systems, as well as spatial raster database. As CA can easily be combined with spatial and non-spatial GIS data, it is an appropriate choice for modeling the complex behavior of forest fire [2].

This paper is organized in 4 sections. The first section elaborates on the issue and presents the background information and required definitions. Section 2 defines effective parameters, section 3 discusses about methodology, study area, calibrating and evaluation. Finally section 4 is conclusion and recommendations.

BACKGROUND

Over the past 50years, several scientists researched into the spread of fire; proper understanding of this issue is the most important factor for successful simulation of forest fires [4]. Cellular automata was first employed in 1950 for forest fire modeling [5]. Ulam proposed this method to optimize modeling forest fires and more generally for presenting dynamic phenomena. He proposed general modeling frame work based on cellular spatial models in discrete times [6]. [7,8] are also among the first researchers who studied this subject.

The first forest fire model was developed by [9] in Canada and later[10] in United States worked on similar subject. These models were able to calculate spread rate, intensity of fire front as well as crown fire that were applied in reality.

[11] proposed a semi-experimental model for obtaining the active and passive crown fire spread rate in the cone forests of Canada. He chose this type of vegetation due to its bright classification and low diversity of its combustible materials in comparison with other natural areas. Validation results were acceptable and the model was used in Global Forecasting Systems in North America from then on.

[10] proposed a statistical correlation for spread rate of active crown fire using modified surface fire prediction method introduced by [12]. He applied the model for analysis of eight wild fires in Northern Rocky Mountains. He estimated that the spread rate of active crown fire is3.43times larger than the rate predictedby its model and actual environmental features. In addition, variables influencing fire behavior, such as canopy height, crown, leaf density and moisture content were not used in the model. As per above analysis,it was concluded that this model should be studied with similar wild fires [5].

(13Karafyllidis and Thanailakis, 1997)developed a CA-based model to predict fire spread rate under various scenarios of climate and topography. Although their results were compatible with reality, there were some defects in the model; for example, while the shape of front fire was as expected, its location was erroneous.

[1] used the cellular automata model based on transfer of fractional burned area. This model was an improved model of [13]. They used hexagonal cells with two-dimensional cellular automata. Considered criteria for simulations were topography, wind and fire spread rate. In most models, two kinds of neighboring cells were considered for the central cell, but in reality and under normal circumstances, all cells exert the same impact on the central cell. The proposed model exhibited an efficient performance in several scenarios in hypothetical forests. Outputs were compared with those of [13] model's indicating approximate adaptability of the proposed model.[1] proposed a new model based on [13] model using two-dimensional cellular automata. This model is based on transfer of fractional burned area and square cells. The proposed model yielded a partial rate of fire spread as well as a more accurate fire spread pattern from diagonal neighboring cells to the central cell. In addition, this model proved its efficiency for both homogeneous and heterogeneous environments under different scenarios.

[12] using two-dimensional cellular automata, provided a model based on factors such as type and density of vegetation, wind speed and direction, topography and spot phenomenon to simulate fire spread. Square grids with Moore neighborhood were employed in this model and it was stated that hexagonal cells, while improving the graphical presentation, made calculations more complex. A nonlinear optimization approach based on combined data in GIS and obtained from real fire incidents in Golestan Forest was used for calibration of model parameters. Comparison between simulated and actual results showed that the proposed model predicts the temporal and spatial characteristics of real fire is acceptably.

[14] developed a forest fire behavior model based on CA with intuitive and simple transition rules. This research improved the previous cellular automata-based models using unique and particular transition rules that can accurately calculate fire spread within and between cells and also synchronize fire with wind direction and slope realistically. In addition, these researchers developed a GIS-based modeling tool based on user interface to provide a flexible environment for modeling and facilitating the presentation of simulation results. Also a direct comparison between cellular automata and fire spread wave approach was presented. Among other researches who used CA with intuitive and simple transition rules, [15], [16] and [17] can be mentioned [5].

[18] used a method known as vector or wave propagation model for modeling forest fires. In the vector model, fire front moves as a continuous plane. Each vertex in this plane is considered as a small fire point created by the experimental, semi-experimental or mathematical models in a homogeneous environment and spreading in an oval-shaped manner. [19], [20] and [21], are among the studies that adopted this method.

[22] proposed a new method comprised of fuzzy inference systems and neural networks based on an integration of existing data on actual fire incidents occurred in the past. The main goal of this model was its adoption in a decision support system for allocating facilities and resources to appropriate locations of fire in an optimum time. Criteria influencing the fire were chosen based on experts' opinion, these criteria were the amount of flammable vegetation, vegetation density, slope, temperature and wind speed.
[22]showed that a model that has proved efficient ina certain region may exhibit the same level of efficiency in other regions as well. Therefore, general and spatial-temporal interactions are particularly important for addressing questions pertaining to climate change, forest management and fire.

Geographic Information System
Geographic Information System (GIS) is an essential part ofenvironmentalmodelingtechnologyforenvironmentaldatamanagementand analysis. GIS is designed to collect, retrieve, analyze and present spatial data [16] . However, this system is usually not designed to show temporal dimensions or continuous interactions of variable changes[23]. Therefore, integration of GIS with other methods makes it possible to model most of dynamic phenomena. In this study, GIS plays an important role in the early stages for providing and coding different layers of information and their preparation, while its importance decreases in later stages of this study.

Cellular Automata
Cellular Automata (CA) is based on Systems Theory according to which any complex system is a result of more simple activities between subsystems; that is, a complex system can easily be simulated by means of fraction of the same complex system. CA, following this same approach, having a simple structure, and being compatible with spatial data and intuitive rules, is an efficient candidate for simulation of forest fires [24].
Cellular automata is a discrete dynamic system consisting of a grid network which is usually square. Hexagonal cells have also been employed in several papers [25]. Each of these components is called a cell containing a value in a specific time. The state of cells in discrete time steps are updated based on a series of transition rules. These rules are defined based on neighboring cells. With this interpretation, cellular automata is formulated as:

$$S_{(i,j)}^{(t+1)} = f(S_{(i,j)}^{(t)}, S_{\varphi(i,j)}^{(t)}) \qquad (1)$$

This function shows that the state of (i, j) cell at time t +1 is a function of its own state ($S_{(i,j)}^{(t)}$) and the state of neighboring cells ($S_{\varphi(i,j)}^{(t)}$) at time t. In general cases, cellular automata is a function of four factors:

$$Q = f(C, S, N, f) \qquad (2)$$

C is cellular space that is usually an n*n grid: $C = \{(i,j), 1 \le i \le n, 1 \le j \le n\}$

The state of each cell (S) indicates the state of cell in time step t ($S_{(i,j)}^{(t)}$) Set of S can be finite or infinite [1,26] .
By taking central cell (i, j) into consideration, some types of neighborhood (N) can be defined. The simplest type of neighborhood is the Von Neumann neighborhood. Moore neighborhood is another type of neighborhood which is employed in this study because of compatibility with reality (Fig. 1)[26].
Transition rules (f), as shown above, are important components of CA which, with simple rules, compose the main body of a dynamic phenomenon.

1.1.3Bee Colony Algorithm
Bee Colony Algorithm, which is capable of simulating the behaviorof bees without anyrestrictions, was introducedby [27] for optimization of problems. Bee algorithm belongs to swarm intelligence category. In swarm intelligence, members of a group interchange information locally to reach a global answer. The solving method is not centralized in this method; that is, the responsibility of solving the problem does not rely on a specific member, but onallmember [28].
Honey Bee Foraging (HBF) is an optimization algorithm inspired by the natural optimum-solution-finding behavior of bees while searching for a solution. There arethree types of bees [29]:Follower Bees, Scouts Bees and Explorer Bees.
Figure 2 shows a schematic process of problem solving by HBF algorithm[30].

Components of the Proposed Method

Forest fire spread models have been investigated in various studies and many different methods have been adopted by researchers. most of these proposed models have a good efficiency in studied areas as the data of the studied area is used in the model; the efficiency of the models may decrease with a change in nature, type and coverage of vegetation and climate. This problem is solved, in this study, by calibration of the proposed model using HBF so that the model can simulate forest fires more accurately and efficiently. This model can easily implement layers required for the simulation of forest fire. The proposed model, able to resolve one of the big challenges of natural resource managers and officials that is allocation of resources and facilities in optimum location and time, and can be used as a part of decision support systems in forest fires. This model is of four components: empirical models, GIS, CA and HBF optimization algorithms. Figure 3 shows the four components of the proposed method.

Assessing Effective Parameters

Forest fire is a complex and dynamic phenomenon. The study of such complex behavior demands the study of the governing parameters. The model employed in this paper for modeling forest fire spread is based on the model proposed by(Alexandridisa A. et al., 2008).In this method, a two-dimensional cellular automata has been used for simulation of forest fire spread. By considering this model and HBF algorithm, a new model is proposed that can simulate forest fire more realistically. The proposed model uses several parameters including types of vegetation, vegetation density, wind speed and direction and topography. According to these parameters, the model can simulate fire front at any time and location precisely. For each cell, the probability of being burning is calculated by Eq. 3.

$$P_{burn} = P_h(1 + P_{veg})(1 + P_{den})P_w P_s \qquad (3)$$

In this equation, P_{burn} is burning probability of a cell, P_h is an empirical coefficient that indicates the fire spread probability in one of the neighboring cells. In this formula, P_{veg} indicates vegetation type, P_{den} is density, P_w is impact of velocity and direction of wind and P_s is the topography impact on forest fire spread.

Vegetation Model

In this study, the categorization of vegetation type and density is based on the table 1.These coefficients are according to the model proposed by [2].

Wind Model

Wind has a highly complex behavior, especially in topographic lands. Many empirical models have been adopted in several studies to model the effect of wind speed on fire spread. In this study, a model with a higher flexibility and better simulation results has been used. Equation 4 shows the model employed to calculate the effect of wind on fire spread model [2].

$$P_w = exp(c_1 V) f_t \qquad (4)$$

In this regard, the empirical coefficient c_1 must be calibrated using HBF; V (m/s) in this formula is wind speed.

$$f_t = exp(V c_2 (cos(\theta) - 1)) \qquad (5)$$

In this equation, θ is the angle between direction of fire spread and wind and c_2 is an empirical coefficient that will ultimately be calibrated. In equation (5), the wind direction can be any continuous value between 0 and 360 degrees, whereas in many of the used techniques in other studies, wind can only have a few discrete values.

Topography Model

Topography is another factor influencing forest fire spread. In an upward slope, the angle between terrain and fire flame decreases and thus causes fire to spread faster. While on a downward slope, the opposite happens. The used model to calculate the impact of slope is equation 6; θ_s is the slope angle of a given piece of land and a is an empirical coefficient that will be calibrated in this study.

$$P_s = exp(a\theta_s) \qquad (6)$$

Considering the fact that cells are square, the slope angle calculation depends on the fact whether the two neighboring cells are situated side by side or diagonally adjacent. For side-by-side cells, the slope angle is calculated by equation 7.

$$\theta_s = tan^{-1}\left(\frac{E_1 - E_2}{l}\right) \qquad (7)$$

In this relation, E_1 and E_2 are the height of the two cells and l is the length of square cells. For diagonally adjacent cells, the slope angle is obtained by equation 8.

$$\theta_s = tan^{-1}\left(\frac{E_1 - E_2}{\overline{\theta_s = tan^{-1}\left(\frac{E_1 - E_2}{\sqrt{2}l}\right)2l}}\right) \qquad (8)$$

IMPLEMENTATION

Study Area and data used

The studied area was Golestan forest located in the north of Iran. The forest fire which occurred in 2001 is studied in this paper. The largest forest fire occurred in Minoodasht this year (2001) which resulted in the complete burn-out of nearly 13,000 ha of the forest. The case study was divided into two parts: the first part for calibration of the model and the second part was used for the evaluation of the calibrated model. The first part was located at: φ=37° 07' 16'', λ=55° 27' 32'' southwest and φ=37°10' 16'', λ=55°28' 36'' northeast. Figure 4-a shows a schematic map of the study area.

The second part of the case study was located at φ=37° 06' 00'', λ=55° 30' 39'' southwest and φ=37° 07' 22'', λ=55° 31' 51'' northeast. Figure 4-b shows a schematic map of this region.

Effective Parameters

There are many factors that impact on forest fire, but the most influent factors are vegetation type and density, topography, wind speed and its direction. In this study, vegetation types are encoded, through GIS, into three categories: agricultural areas, shrubs and dense forest trees (usually oak trees). Figure 5 shows the vegetation type for the first and second areas under study. Table 1 also shows the codes considered for each class. These values are experimental data that were considered in the model proposed by [2].

Vegetation density is categorized into three classes: sparse, dense and normal vegetation. Considered values for this vegetation type and density were based on experimental data provided by [2]. Figure 6 shows the vegetation density for each part of the region.

Slope and direction of slope can be derived from digital elevation model (DEM). Figure 7 shows DEM for both parts. Incombustible areas (rivers, residential areas, roads) can also be elicited.

Table 2 shows the weather condition during forest fire incident.

Methodology

Integrating Cellular Automata with mathematical model makes it possible to study forest fire spread moment by moment. In this paper, Moore neighborhood is employed for modeling the forest fire spread.

To simulate forest fire spread using CA, each cell has one state. The four possible states which can be assumed by each cell are:

1: Cells not having any fuels (Incombustible Area). The cells cannot burn at anytime steps; Residential areas, rivers and roads can be mentioned as instances of such cells;

2: Cells containing fuels, but still unburned;

3: Burning cells;

4: Cells completely burnt out.

Each cell can assume one of the above states.

Calculating the state of each cell is possible by using cellular automata. Based on Moore neighborhood and the state of cells, local transition rules are defined for implementation in CA to simulate forest fire spread. The applied transition rules are [2]:

- If cell (i, j) at time t is 1, the state of cell at time step t +1 will be 1. This rule indicates that if one cell has no fuel, it cannot burn (Incombustible Area).
- If cell (i, j) at time t is 3, the state of cell at time step t +1 will be 4. The rule states that if the cell containing fuels in this stage is burning, it will be burnt out completely at the next time step and will be 4.
- If cell (i, j) at time t is 4, the state of cell at time step t +1 will be 4. Burnt cell will remain at the same state.
- If cell (i, j) at time t is 3, the state of cells (i ∓ 1, j ∓ 1) at time t +1 with P_{burn}(Burn Probability) will be 3.

This rule is the most important rule of translation rules. This rule is in fact the foundation of cellular automata which determines the forest fire spread principle. Based on this rule, if a cell is burning (at time t), according to Moore neighborhood, the eight neighboring cells are also exposed to combustion. According to the above, the main transition rule is based on equation 8.

$$P_{burn} = p_h(1 + p_{den})(1 + p_{veg})\,p_s p_w \qquad (9)$$

In equation 9,P_h is an empirical coefficient that indicates probability of fire spread to neighboring cells. This factor applies when there is no wind, no topography and when vegetation is of the same type. P_h must be calibrated in this study. P_{veg} indicates vegetation type, P_{den} is vegetation density, P_w and P_s are effect of wind and topography respectively.

Based on the above discussion, the model proposed by [2] was selected as the main model and was implemented in the first part of the region. Figure 8 shows the output simulation based on the initial model. Initial parameters are shown in Table 3. One of the more efficient ways to evaluate simulation in

comparison with real map is Kappa Index. According to the real fire which occurred in this part, Kappa index was implemented for the calculated of the model.
Comparison of the obtained results with the real incident data yields the Error Matrix of the output. In this study, there are only two states in the error matrix: burned and unburned cells; therefore, it would be a 2×2 matrix. Rows and columns of the matrix contain the real map and simulation results respectively. Two indexes, Total Accuracy and Kappa Index, can be derived from the error matrix. Total accuracy index cannot contain wrong cells but kappa index contains both right and wrong simulated cells; thus, kappa index is more reliable than the total accuracy index.
Table 4 shows that total accuracy equals 65%. Calculations show 58% for kappa index in the first part of the region. It is obvious that the closer to 1 (or 100%) kappa index, the higher the accuracy and precision of the simulation.

Calibration of the Proposed Model

Initial coefficients at Table 3 are calibrated by Honey Bee Foraging Algorithm (HBF). In this method, each series of coefficients is considered as one bee. In this study, 20 bees are considered that include 3 scouts bees, 15 following bees and 2 explorer bees.
After 2000 iterations in HBF, the maximum kappa index was 95%. Table5shows the coefficients obtained from calibration process. Figure9illustrates the HBF algorithm convergence diagram. Table6 shows the results obtained from error matrix using the calibrated model. The calibrated coefficients were applied on the simulation (in the first part) for the calculation of the new kappa; asshowninTable7,kappaindex reached 92% and the calibrated model could simulate the forest fire front spread correctly. Considering the initial kappa, it is obvious that the obtained kappa is an ideal result. The result also indicates a good calibration by HBF. Figure 10 shows the simulated forest fire front in the first part (calibration area) using the calibrated model.

Evaluation of the Calibrated Model

Most of the models proposed in various studies were usually applied on hypothetical and simulated regions first, and if results were satisfactory, then they would be implemented on a real region. In this study, both calibration and evaluation were carried out on real regions separately; this can improve the evaluation of the model. The implementation of the initial and calibrated model, and then the calibrated model on the second region is to see and evaluate calibrated model. Figure11 shows real fire in the second part of the region and Figure 12 shows the simulated fire front at the second part by initial coefficients [2]. According to these parameters, Table8 shows the error matrix in the second part. By considering error matrix and Table 9, calculated kappa is 81%.
To study the efficiency and accuracy of the proposed model, the model calibrated by HBF must be implemented in the second part of the region. Figure13shows the outputin the second part.Table10 shows the error matrix under these conditions. According to the error matrix and Table 11, final kappa for the second part of the region increased from 81% up to 88%. This kappa value indicates that the calibrated model has more efficiency than the initial model and can be used as a new model for a more realistic simulation of forest fire fronts.

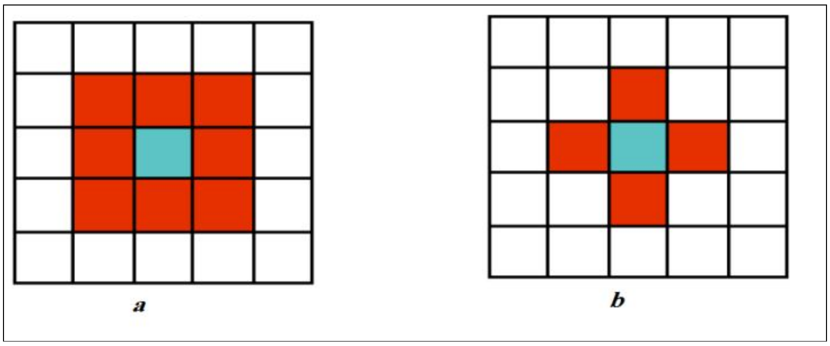

Fig 1. (a) Moore neighborhood (b) Von Neumann neighborhood

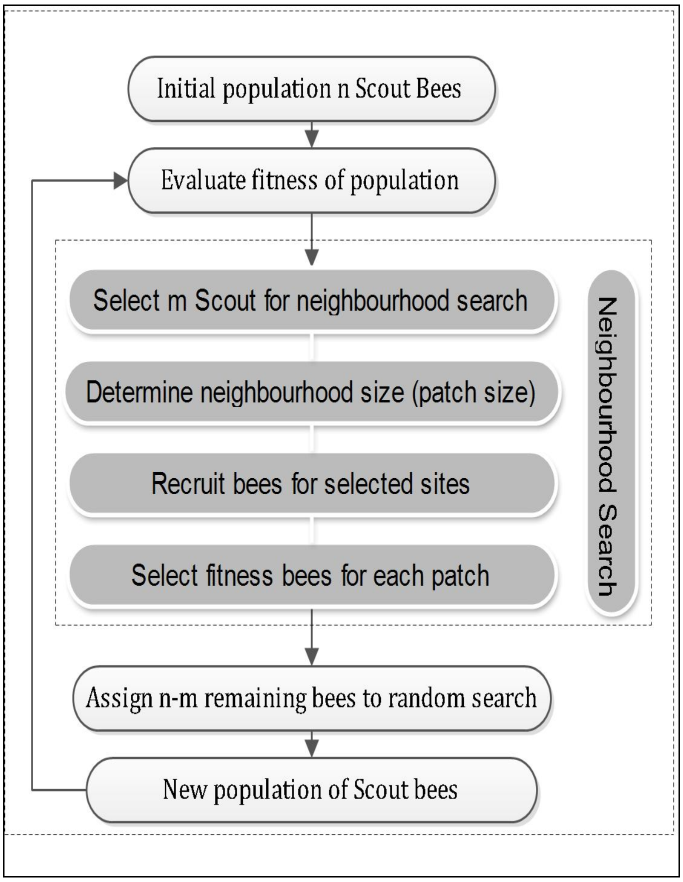

Fig 2. Problem solving using HBF algorithm

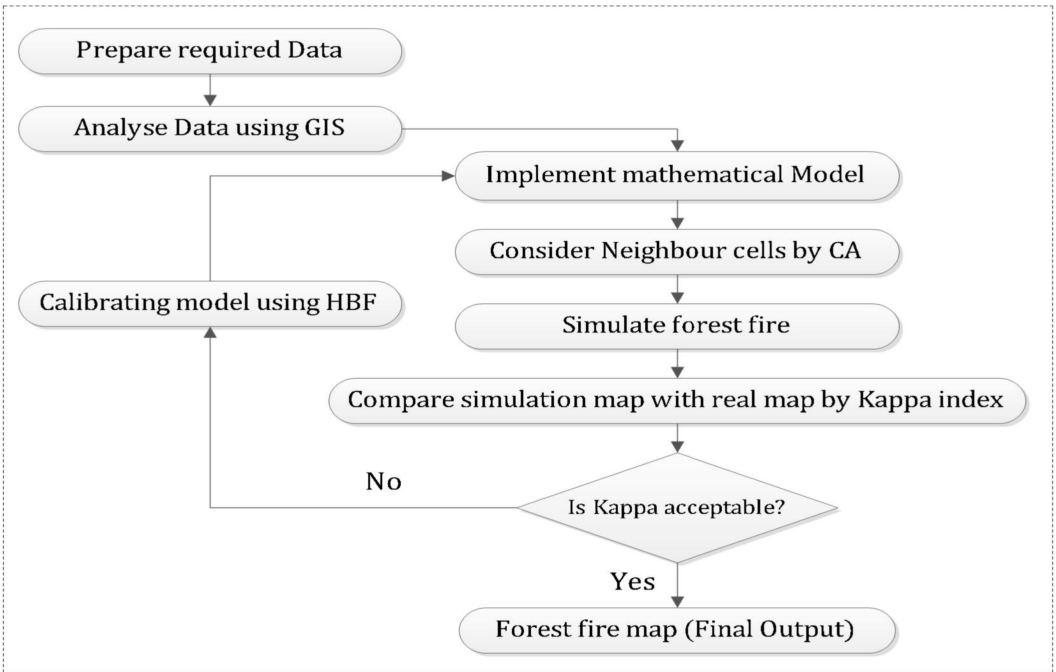

Fig 3. Components of the proposed model for forest fire mapping

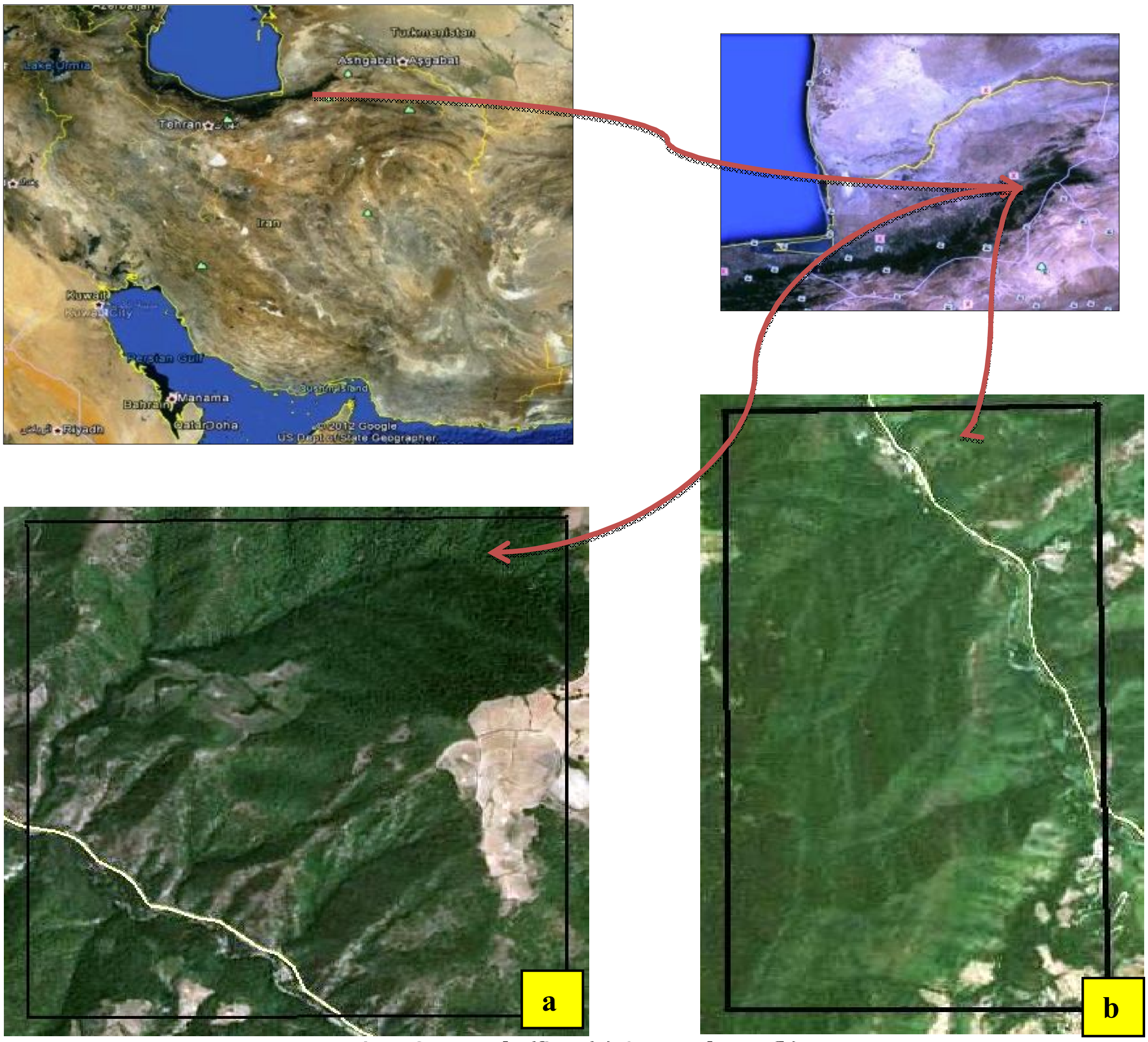

Fig 4. Case study (first (a) & second part (b)

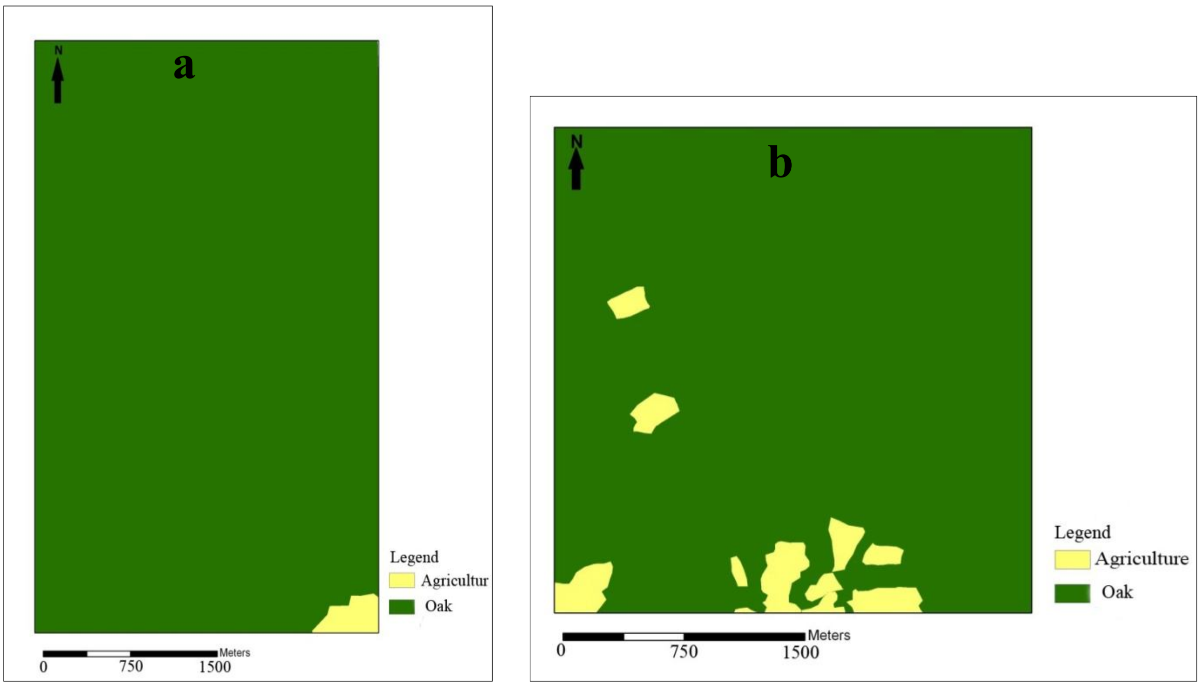

Fig 5. Vegetation type in the first (a) and second part (b)

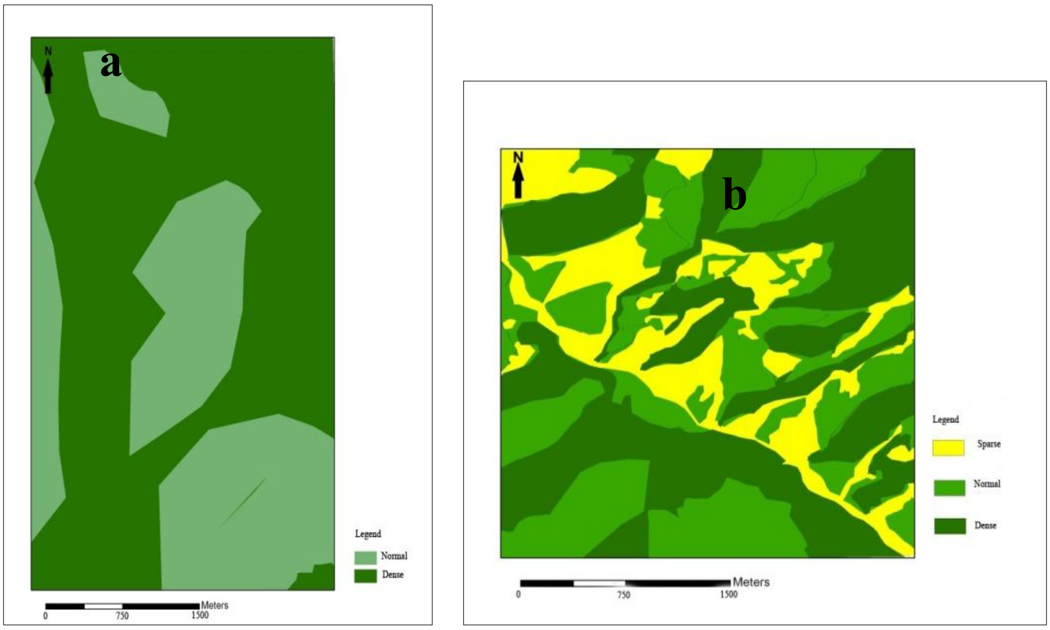

Fig 6. Vegetation density at first (a) and second part (b)

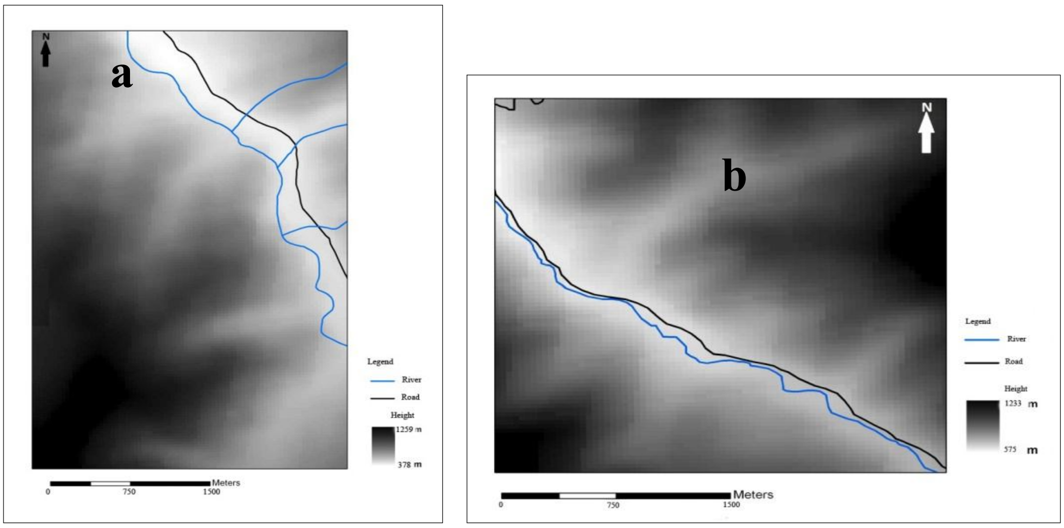

Fig 7. Terrain model in first (a) and second part (b)

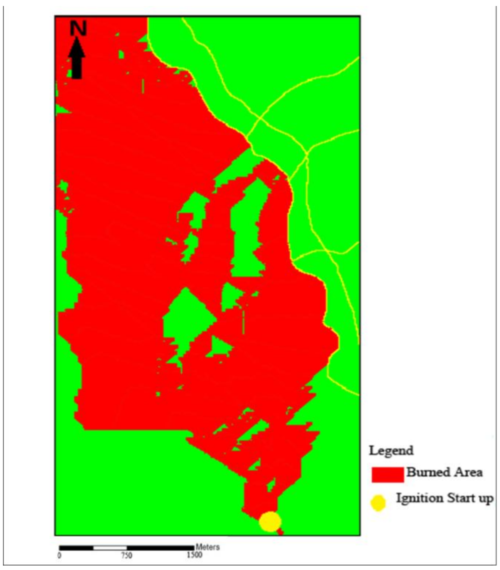

Fig 8. Simulation of forest fire in the first part using initial model

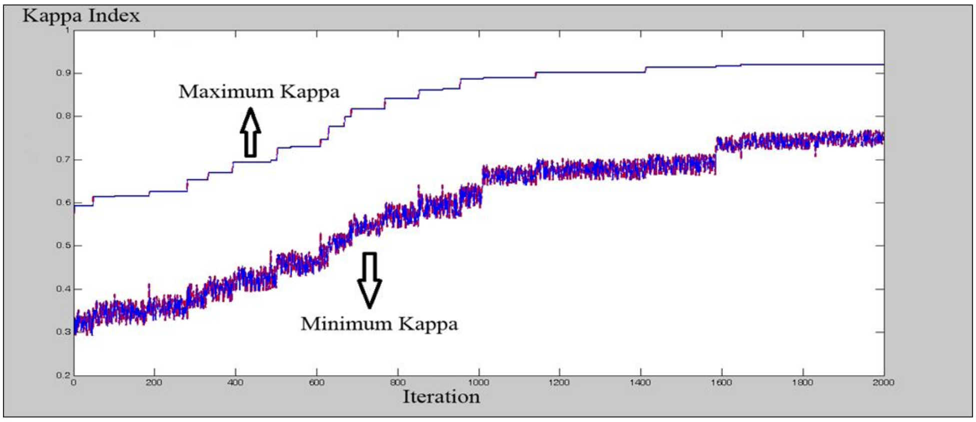

Fig 9. HBF convergence diagram

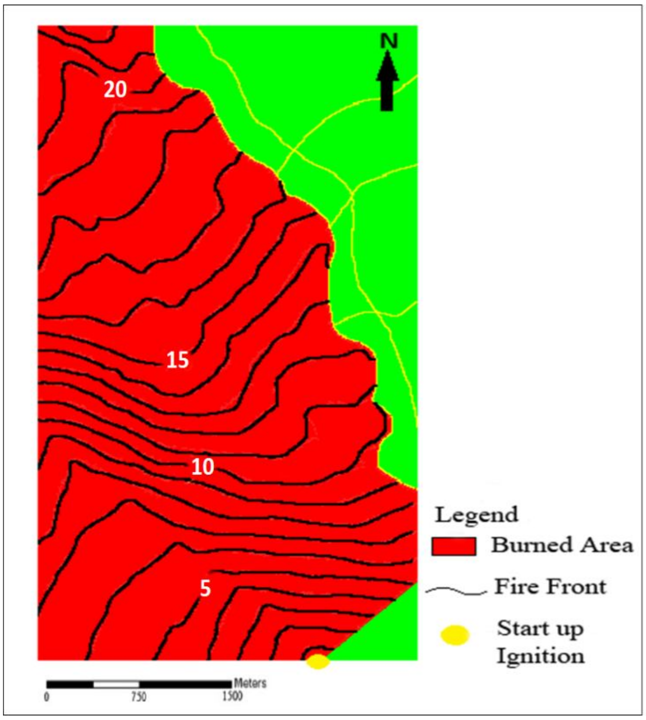

Fig 10. Simulation results in the first part using the calibrated model

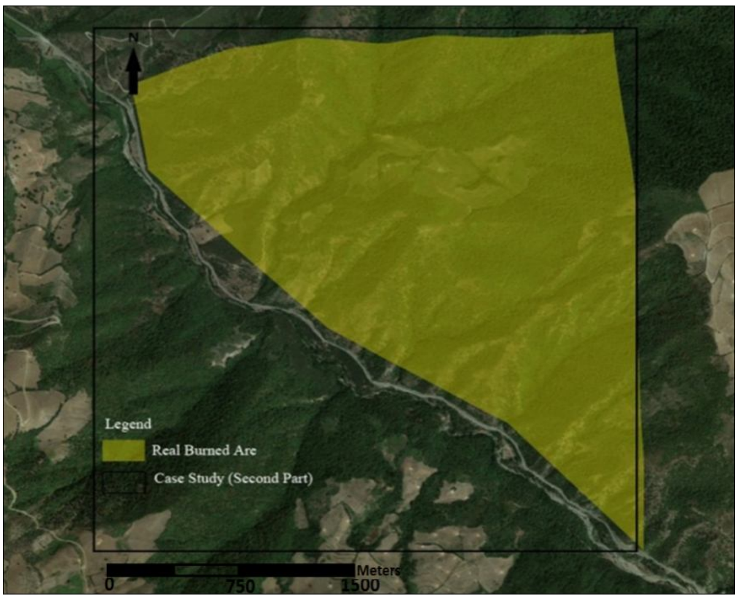

Fig 11. Real forest fire in the second part

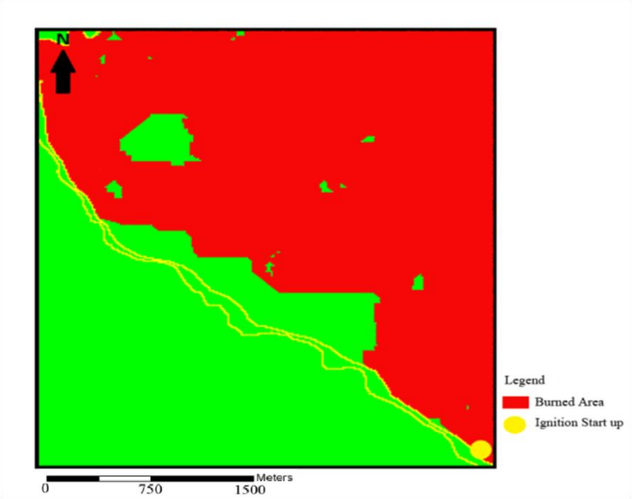

Fig 12. Simulation result in the second part using the initial model

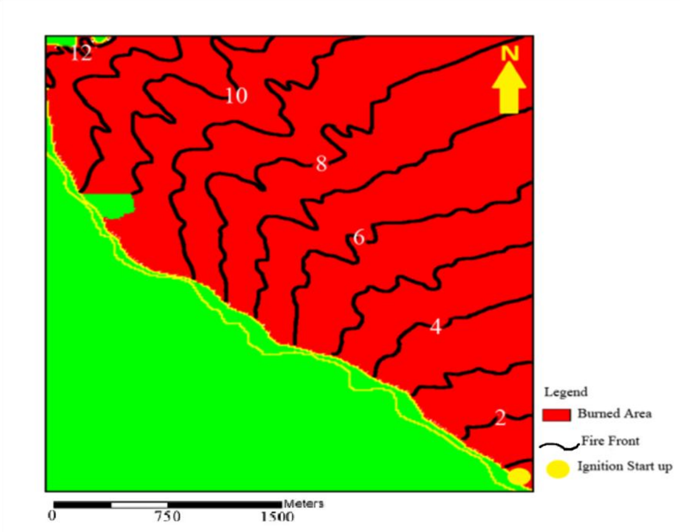

Fig 13. Simulation forest fire in the second part using the calibrated model

Table 1. Density and vegetation type

Vegetation Type	P_{veg}
Agriculture	-0.3
Shrub	0
Oak	0.4
Density	P_{den}
Sparse	-0.4
Normal	0
Dense	0.3

Table 2. Climate conditions at burning time (First Part)

Temperature (˚c)	Relative Humidity (%)	Rain (mm)	Wind velocity (m/s)	Wind direction
2.9	62	50.7	5	North

Table 3. Initial parameters in (Alexandridisa A. et al., 2008)

a	c_1	c_2	P_h
0.078	0.045	0.131	0.58

Table 4. Statistic data of the first part (Initial model)

Total Accuracy	Kappa Index	Burning Time (h)	Real burned Area (ha)	Simulated burned Area
0.65	0.58	26.4	857.59	525.27

Table 5. Calibrated parameters using HBF

a	c_1	c_2	P_h
0.02	0.0219	0.004	0.6003

Table 6. Error matrix in the first part (calibrated model)

		Simulation		Sum
		Burned	Unburned	
Real	Burned	95035	8	95043
	Unburned	3915	28801	32716
Sum		98950	28809	127759

Table 7. Output statistics in the first part using the calibrated model

Total Accuracy	Kappa Index	Burning Time (h)	Real burned Area (ha)	Simulated burned Area
0.95	0.92	22	857.59	796.85

Table 8. Error matrix in the second part (initial model)

		Simulation		Sum
		Burned	Unburned	
Real	Burned	39077	2305	41382
	Unburned	4333	27295	31628
Sum		43410	29600	73010

Table 9. Output statistics in the second part using the initial model

Total Accuracy	Kappa Index	Burning Time (h)	Real burned Area (ha)	Simulated burned Area
0.90	0.81	12.9	351.9	335.2

Table 10. Error matrix in the second part using the calibrated model

		Simulation		Sum
		Burned	Unburned	
Real	Burned	49428	3399	52827
	Unburned	482	26201	26683
Sum		49910	29600	79510

Table. 11. Output statistic in the second part using the calibrated model

Total Accuracy	Kappa Index	Burning Time (h)	Real burned Area (ha)	Simulated burned Area
0.99	0.88	11.95	351.9	365.25

CONCLUSION AND RECOMMENDATIONS

In this study, the model proposed by [2] was used as the base model. This model was integrated with GIS and applied on the case study. The Case study was an area in Golestan province in Iran and was divided into two parts. The proposed model was implemented in the first part and the obtained results were analyzed, then the model was calibrated using HBF and, to evaluate the model, it was implemented in the second part of the region. The obtained results indicated that the calibrated model has a better precision and accuracy in modeling the forest fire spread. This model can be used as a support decision system to predict forest fires in advance; thus, managers can manage and distribute facilities and fire fighters in optimum time to optimum locations.

The proposed approach includes four key components including mathematical model, GIS, CA and HBF algorithm. The data were first collected, then incombustible areas were also elicited. These are as included roads, rivers and residential areas. Then each parameter was categorized using GIS. The parameters were vegetation type, vegetation density, wind speed, wind direction, slope and aspect. Then, through integration of mathematical model with CA, the state of each cell as well as fire spread in each time step for each part of the region was calculated.

Finally, the results from the previous step (simulation results) were compared with the real forest fire. Then, the empirical coefficients were calibrated in the mathematical model using the obtained kappa index. This optimization was carried out through HBF method. To verify and evaluate the proposed model, it was implemented in the second part of the region. In fact, the first part of the region was used for implementation and verification of the outputs as well as calibration of the model; the second part was used for the evaluation of the calibrated model.

Results showed that kappa index was 58% in the first part; after calibration of the model and 2000 iterations using HBF, kappa index reached 92%. To evaluate the proposed model, it was implemented in another real forest fire incident. The total accuracy and kappa index were 98% and 88% respectively in the second part. Total burning time in real forest firewasapproximately11 hours and the burnt area was 351.9hectares of the area and the simulation resultswere11.95 hours and burnt area of 365.25hectares. According to the obtained results, the simulation of forest fire using calibrated model seems accurate in comparison with real incident data. Therefore, this model can be used as a part of decision support system for predicting forest fires.

Following recommendations are presented for further research on the complex phenomena of forest fires:

Availability of time-related data regarding fire spread makes the calibration of the model more accurate. In this paper, HBF algorithm was used for the calibration of the model. Other artificial intelligence algorithms such as Particle Swarm Optimization and Genetic Algorithm can be used in further studies on this subject and the results can also be compared with the ones obtained in this paper. Wind is one of the most influencing factors in forest fire spread. The current models are not of great efficiency for modeling wind and wind twists. Integrating heat-based models with the ones implemented in this study can yield models of greater strength.

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