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# Development of Forest Fire Spread Simulation on Up and Down Slope

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Recently, forest fires have caused a serious hazard to forest management and the forest environment in Korea. The development of an accurate forest fire spread prediction method could contribute to supporting fire control operations. A forest fire can rapidly develop into a large–scale forest fire due to topographic characteristics such as slope. Since the development of the GIS system, analyzing a slope on a large scale has become relatively straightforward. However, the legacy algorithm used for calculating slope is problematic as it is not able to distinguish the spread rate between the upslope and the down slope.

Accordingly, in order to solve this problem, a comparative analysis is carried out in this study on the forest fire spread rate for upslope and down slope. When a slope in simulation was calculated using a supposed algorithm, a supple method was used that applied a direction for the spread of forest fire. The proposed method was able to calculate spread rate more accurately. Furthermore, the spread rate of forest fire could be analyzed on each slope, since the method classified upslope (+) and down slope (–). Consequently, the proposed method is able to be used to effectively support the attack of forest fire by providing accurate predictions of fire spread.

## INTRODUCTION

Recently, as information technology has developed, the requirement for information has increased. In the field of GIS (Geographic Information System), information is being processed more rapidly and more accurately. In particular, in a forest fire, the quick analysis of forest fire information (topography, ignition point, weather condition, etc.) over a wide area is essential for minimizing the number of victims, and environmental and economic damage, and for deciding the course of evacuation, estimating a fire spread course, and arranging fire attack resources. In the United States, Canada, and Australia, many researchers have established forest fire management systems that can efficiently protect forests from disaster and can analyze factors related to forest fire (Rothermel, 1972; Bradshaw *et al.*, 1983; Hirsch, 1996; Andrews and Queen, 2001). In Korea, forest fires are usually accidentally ignited by individual persons such as a mountain climber or a farmer. Furthermore, the damage caused by forest fires has recently increased. In an attempt to minimize this damage, research on forest fires began in 1986 and many researchers have variously attempted to research ways to predict forest fire occurrence risk (Cheong *et al.*, 1989; Lee, 1995) and a management system for forest fire using GIS (Jo *et al.*, 2001; Jo *et al.*, 2002, Lee *et al.*, 2004, An *et al.*, 2004). A great deal of research on the prediction of forest fire spread rate has been developed for successful fire attack that is dependent on the burning behavior of the fire front, which affects spread and damage (Chung *et al.*, 2001; Lee *et al.*, 2002).

Since the GIS system has been developed, the analysis of a slope on a large scale has become relatively straightforward. However, the legacy algorithm used for calculating slope is problematic as it is not able to distinguish the spread rate between the upslope and the down slope.

Accordingly, in order to solve this problem, a comparative analysis is carried out in this study on forest fire spread rate for upslope and down slope. A slope calculation algorithm is also suggested for each slope direction and an algorithm is simulated.

## MATERIALS AND METHODS

A 60 cm × 90 cm plate was made with 2 mm deep holes at intervals of 1 cm (Fig. 1) and a spread rate for the angle and aspect of each slope was determined

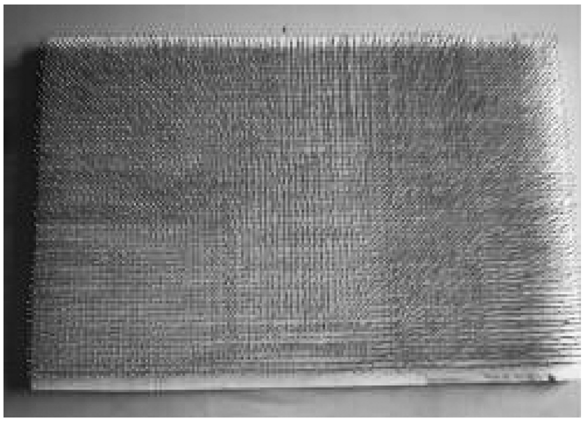

**Fig. 1.** Manufacturing model to measure forest fire spread speed.

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using this plate. Toothpicks were arranged on the plate to provide slopes of 10, 20, 30 and 40 degrees and the experiment was repeated three times. At the ignition point, toothpicks were densely arranged and some gunpowder was added in order to increase the fire intensity. After firing, the distance from the ignition point was measured for each unit time on the flat, the upslope and the down slope. A relative fire spread equation was made for this determination on each slope.

The fire spread was then simulated with this equation using the GIS Application, ArcView3.1. The slope, which is the most important factor in this simulation, was analyzed using DEM (Digital elevation model) with various algorithms. The various algorithms used to analyze slopes were the Neighborhood algorithm, as suggested by Arc/Info GRID *et al.* (ESRI, 1995), the Quadratic Surface algorithm, as suggested by Zevenbergen *et al.* (1987), the Maximum slope algorithm, as suggested by Shanholtz *et al.* (1990), the Maximum downhill slope algorithm, as suggested by Hickey *et al.* (1994) and the Maximum uphill slope algorithm, which is suitable for forest fires and suggested by An *et al.* (2006). However, all these slope algorithms use a fixed value and are not able to calculate the upslope and down slope, both of which vary depending on fire direction. It is essential to accurately simulate the distinction of a fire spread rate between the upslope and down slope. Therefore, a new fire spread simulation was suggested that could solve this problem and the results of this simulation were compared with the results obtained from a pre–existing algorithm.

## RESULTS AND DISCUSSION

### Fire spread distance for up and down slope

A fire spread distance was determined at each unit time (10 sec) through an experiment on various slope degrees. Distinctions between flat, upslope and down slope were then compared, as shown in Fig. 2. Table 1 shows the results of this experiment. On the upslope, the spread distance at each unit time (10 second) was 1.83 cm (minimum), 4.00 cm (maximum) and 2.47 cm (average) on a 10° slope. On a 20° slope, the spread distance was 2.67 cm (minimum), 7.00 cm (maximum) and 4.43 cm (average) and the rate of increase was about 180% of that on the 10° slope. On a 30° upslope, the spread distance was 3.33 cm (minimum), 12.67 cm (maximum) and 6.87 cm (average) and the rate of increase was about 278% of that on the 10° slope and about 155% of that on the 20° slope. On a 40° upslope, the spread distance was 4.67 cm (minimum), 13.33cm (maximum) and 7.73 cm (average) and the rate of increase was about 313% of that on the 10° slope, 174% of that on the 20° slope, and 112% of that on the 30° slope. For the tests on the 10° slope, the spread distance at each unit time (10 second) was 1.00 cm (minimum), 2.67 cm (maximum) and 1.82 cm (average) in the left and right direction, that is, on a flat slope. For the 20° slope, the spread distance was 1.50 cm (minimum),

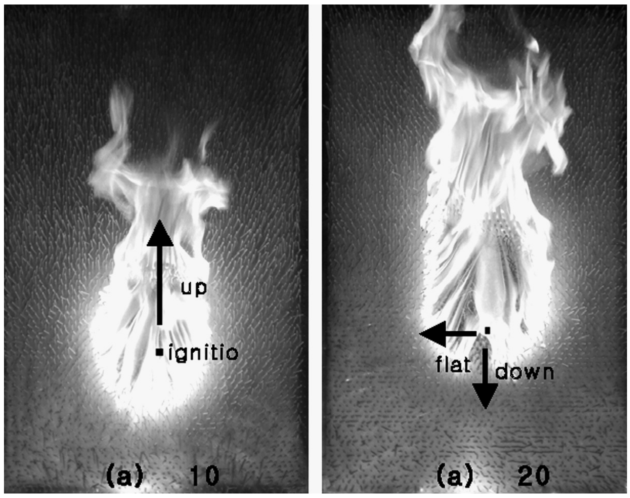



**Fig. 2.** Forest fire spread distance experiment on each slope (60 sec).

**Table 1.** Average distance of fire spread influenced by up and down slope

[Unit: cm]

| Time | 10° | | | 20° | | | 30° | | | 40° | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Up | Flat | Down | Up | Flat | Down | Up | Flat | Down | Up | Flat | Down |
| 10sec | 3.00 | 2.67 | 2.00 | 3.67 | 2.67 | 2.33 | 3.50 | 2.67 | 1.67 | 4.67 | 2.67 | 2.33 |
| 20sec | 1.83 | 1.00 | 1.00 | 2.67 | 2.17 | 1.83 | 3.50 | 2.00 | 1.33 | 5.00 | 1.67 | 1.00 |
| 30sec | 2.83 | 1.33 | 1.33 | 3.00 | 1.50 | 1.50 | 5.00 | 2.00 | 1.00 | 7.00 | 1.83 | 0.67 |
| 40sec | 2.67 | 1.33 | 0.83 | 4.00 | 1.83 | 1.33 | 3.33 | 2.33 | 1.17 | 10.33 | 1.67 | 0.83 |
| 50sec | 2.33 | 1.33 | 1.50 | 3.33 | 2.00 | 1.00 | 4.67 | 2.00 | 1.00 | 7.67 | 2.67 | 0.83 |
| 60sec | 2.00 | 2.33 | 1.33 | 3.67 | 2.00 | 1.00 | 6.00 | 2.33 | 1.17 | 13.33 | 3.50 | 0.17 |
| 70sec | 2.33 | 2.00 | 1.67 | 5.00 | 2.17 | 1.50 | 9.00 | 2.67 | 1.17 | 9.00 | 3.00 | 0.83 |
| 80sec | 4.00 | 2.00 | 1.50 | 5.00 | 2.00 | 1.00 | 9.00 | 2.00 | 1.17 | 7.00 | 2.17 | 1.00 |
| 90sec | 2.67 | 2.00 | 1.50 | 5.33 | 1.83 | 1.50 | 12.67 | 1.67 | 1.33 | 7.00 | 2.25 | 1.00 |
| 100sec | 3.33 | 2.33 | 2.00 | 5.00 | 2.33 | 1.50 | 12.00 | 2.67 | 2.00 | 7.00 | 1.50 | 1.00 |
| 110sec | 2.33 | 2.33 | 2.33 | 4.00 | 1.83 | 1.50 | | 2.00 | 1.00 | 7.00 | 2.00 | 1.00 |
| 120sec | 2.00 | 2.33 | 1.33 | 5.33 | 2.00 | 1.75 | | 2.50 | 1.00 | | 2.00 | 1.00 |
| 130sec | 3.00 | 1.83 | 1.67 | 5.00 | 2.00 | 1.00 | | | | | | |
| 140sec | 2.67 | 2.50 | 2.33 | 7.00 | 1.50 | 1.00 | | | | | | |
| 150sec | 3.33 | 2.00 | 2.50 | | | | | | | | | |
| Mean | 2.47 | 1.82 | 1.49 | 4.43 | 1.99 | 1.41 | 6.87 | 2.24 | 1.25 | 7.73 | 2.24 | 0.97 |

**Table 2.** Comparative analysis of fire spread speed influenced by uphill and downhill slope

| Time number | slope | | | | |
|---|---|---|---|---|---|
| | 10° | 20° | 30° | 40° | mean |
| | U:D | U:D | U:D | U:D | U:D |
| 1 (min/m) | 6.20:12.06 | 3.96:10.70 | 3.63:12.27 | 2.15:19.13 | 3.98:13.54 |
| 2 (min /m) | 7.66:14.08 | 4.55:15.27 | 3.72:18.28 | 3.36:21.52 | 4.82:17.28 |
| 3 (min /m) | 6.75:11.30 | 4.31:11.80 | 3.13:15.83 | 2.26:23.95 | 4.11:15.72 |
| Mean (min /m) | 6.87:12.48 | 4.27:12.61 | 3.49:15.46 | 2.59:21.54 | 4.30:15.52 |

2.67 cm (maximum) and 1.99 cm (average) on a flat slope. For the 30° slope, the spread distance was 1.67 cm (minimum), 2.67 cm (maximum) and 2.24 cm (average) on a flat slope. For the 40° slope, the spread distance was 1.50 cm (minimum), 3.50 cm (maximum) and 2.24 cm (average) on a flat slope. Even though the right and left directions were the same, the spread distance increased with the angle of the plate. This is because the increased radiant heat on the spreading upslope direction causes an increase in the spread distance in the left and right directions.

On the down slope, the spread distance was 0.83 cm (minimum), 2.50 cm (maximum) and 1.49 cm (average) on a 10° slope. On a 20° slope, the spread distance was 1.00 cm (minimum), 2.33 cm (maximum), where there was a temporary increase in the strength of fire intensity on the point of ignition, and the average was 1.41 cm, which decreased at a rate of 95%. On a 30° slope, the spread distance was 1.00 cm (minimum), 2.00 cm (maximum) and 1.25 cm (average). On a 40° down slope, the spread distance was 0.17 cm (minimum), 2.33 cm (maximum) and 0.97 cm (average) and the rate of decrease was about 65% of that on the 10° slope, 69% of that on the 20° slope and 78% of that on the 30° slope. In contrast with the upslope, as the slope increased, the distance of spread decreased.

**Modeling of forest fire spread rate**

The fire spread rates of the upslope and downslope were used as the converted times of arrival, which is the arrival time from the ignition point to the specific point. These times of arrival were then compared. The results of this comparison are shown in Table 2. These results show that, on the upslope, the mean time of arrival is 6.87 min on the 10° slope, 4.27 min on the 20° slope, 3.49 min on the 30° slope and 2.59 min on the 40° slope. For both cases of from the 10° slope to the 20° slope and from 20 to 40, the time of arrival decreased by about 40% from 6.87 min to 4.27 min and from 4.27 min to 2.59 min.

We classified a time of arrival (from the ignition point to a 10 m specific point), according to the upslope (U) and down slope (D) using the results obtained from this experiment, as presented in Table 2.

A regression analysis was then performed using the time calculated. From the regression analysis, for the equation calculated from the results on the first time experiment, $y=7.0059e^{-0.0251}$ and $R^2$ was 95.2%. For the equation on the second time experiment, $y=8.8267e^{-0.0254x}$ and $R^2$ was 97.16%. Finally, for the equation on the third time experiment, $y=7.5361e^{-0.0281x}$ and $R^2$ was 98.41%. The final equation average was $y=7.8138e^{-0.0262x}$ and $R^2$ was 97.99%.

**Forest fire spread simulation on each slope**

While the pre–existing algorithm has useful characteristics, it is intended to be used simply as a one–way method to calculate slope. For this reason, it is essentially problematic, since it cannot distinguish between the up and the down slopes. The fire spread rates of forest fires respectively vary depending on the up and down slope in each forest fire case. In order to identify this problem, each algorithm was applied on a simple inclined plane. 5×5 squares on a 7×7 DEM were used to measure results of slope calculation using the pre–existing algorithm. For convenience, the size of the squares was assumed to be 10 m. Fig. 3(a) shows a sample DEM used for analyzing the results of slope calculation using the pr–existing algorithm. The ①–⑧ direction in Fig. 3(b) indicates the fire spread direction when the forest fire was ignited.

A slope value of ①–⑧ direction was calculated from Fig. 3(b) using the preexistence slope calculation algorithm and the real slope was measured through a fire spread path. Table 4 shows the results obtained of the slope calculation.

**Table 3.** Computation of fire spread speed influenced by slope

| Time number | Fire spread speed (y: time, x: slope) | |
|---|---|---|
| 1 (s/m) | $y=7.0059e^{-0.0251x}$ | $R^2=0.9520$ |
| 2 (s/m) | $y=8.8267e^{-0.0254x}$ | $R^2=0.9716$ |
| 3 (s/m) | $y=7.5361e^{-0.0281x}$ | $R^2=0.9841$ |
| mean(s/m) | $y=7.8138e^{-0.0262x}$ | $R^2=0.9799$ |

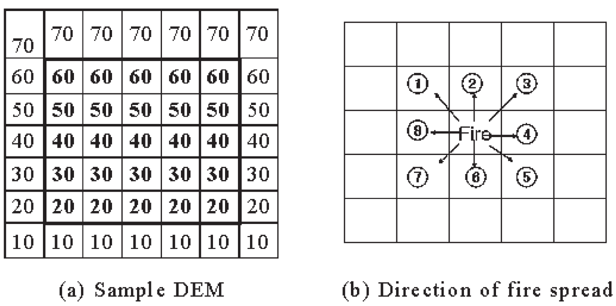



**Fig. 3.** The result of slope calculation using preexistence algorithm.

**Table 4.** Analysis of slope value by slope calculation algorithm

| Number | Preexistence algorithm | Fire spread paths |
|---|---|---|
| ① | 45° | 35° |
| ② | 45° | 45° |
| ③ | 45° | 35° |
| ④ | 45° | 0° |
| ⑤ | 45° | −35° |
| ⑥ | 45° | −45° |
| ⑦ | 45° | −35° |
| ⑧ | 45° | 0° |

The obtained result for direction ② (upslope) in Table 4 corresponds with the real slope on the real forest fire spread paths. However, from the results calculated by the pre–existing slope calculation algorithm for direction ①, ③ on the upslope did not correspond with the real slope. For the fire spread paths for ④, the ⑧ direction was 0° and for ⑤, the ⑦ direction was 35° on the down slope. The result for ⑥ corresponded with the fire spread path on the down slope.

In this study, the slope for the direction of fire spread was calculated in order to accurately estimate the fire spread pattern on the up and down slopes in this simulation. The procedure for the method used is presented in Fig. 4. The simulation of the forest fire spread was tested on a simple slope plane in order to compare results with those obtained using the pre–existing algorithm. The forest fire spread was simulated on respective slopes of 0, 10, 20, 30, and 40° slope similarly to the forest fire spread experiment.

The following equation for the time of arrival of forest fire spread was estimated by using a mean equation that was obtained from the repeated experiments:

$$y=7.8138e^{-0.0262x} \qquad R^2=0.9799 \qquad (1)$$

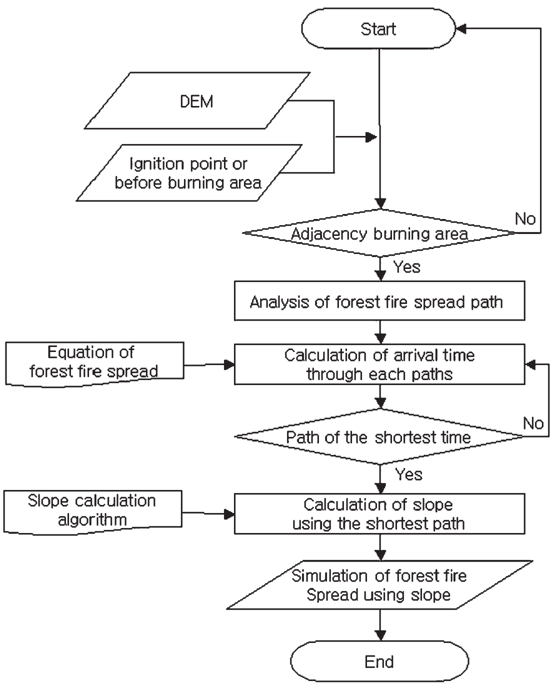



**Fig. 4.** Flow chart for simulation of forest fire spread using slope calculation algorithm.

y : time of arrival of forest fire for particular point.
x : slope

The forest fire spread path from the ignition point or immediately before the burning point (Fire) to the specific point (target) was ①, ②, and ③, as shown in Fig. 5. It was assumed that the cell size was 10 m ×10 m and the slope was 10°. For the calculation of the time of arrival using equation (1) through each path, the time of arrival to the upper cell through path ① was 6.013 min, the time of arrival from the upper cell to the target cell was 7.814 min on a 0° slope and the total time was 13.827 min. On path ②, the time of arrival to the target cell was 9.19 min on a 7.035° slope. On the ③ path, the time of arrival to the flank cell was 7.814 min on a 0° slope, with an additional 6.013 min, which was the time of arrival to the target cell, and the total time was 13.827 min, similarly to the time of arrival on path ①.

Consequently, using the pre–existing algorithm, the forest fire arrived at a specific point (target) through path ② on a 7.035° slope (the shortest time) rather than on a 10° slope. For the simulation, a check mark was added at each 10m and its color was changed every 5 minutes.

Fig. 6 shows the results of a comparison between the pre–existing slope calculation algorithm and the proposed algorithm on a 10° slope. Scheme (a) represents the application of the pre–existing slope calculation algorithm. For scheme (a), because every calculated slope was 10°, regardless of the ignition point, it took about 30 minutes for the fire to arrive at both the right and the left of the 50m end. However, in scheme (b), using the shortest path, it took about 30 minutes to arrive at the 50 m end on the upslope (10°), about 50

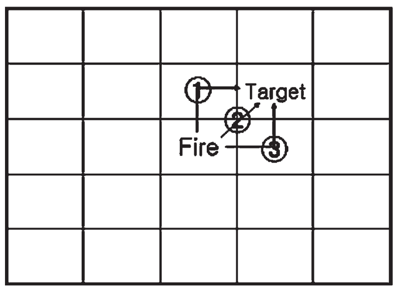
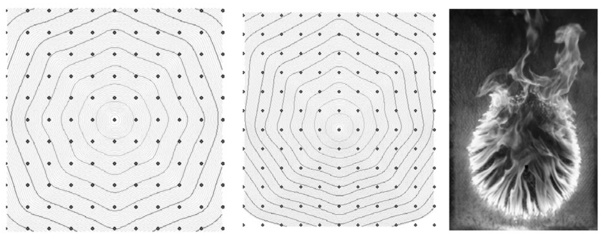



**Fig. 5.** The route of forest fire spread using raster DEM.

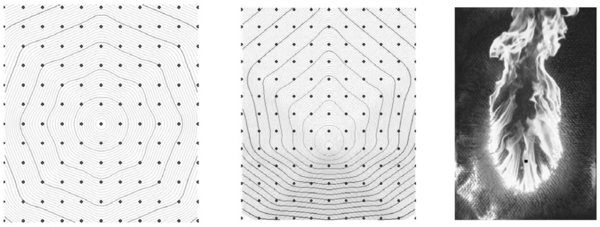


(a) Pre-existing slope calculation algorithm (b) New slope calculation algorithm (c) Fire spread experiment

**Fig. 6.** Comparison of slope calculation algorithm simulation (10°).

**Table 5.** Fire spread time by the process route of fire spread

| Path | Equation for calculating time of arrival | Time of arrival |
|---|---|---|
| ① | $y=7.8138e^{-0.0262}\times 10° + 7.8138e^{-0.0262}\times 0°$ | 13.827 min |
| ② | $y=7.8138e^{-0.0262}\times 7.035°$ | 9.19 min |
| ③ | $y=7.8138e^{-0.0262}\times 0° + 7.8138e^{-0.0262}\times 10°$ | 13.827 min |



(a) Existent slope calculation algorithm (b) New slope calculation algorithm (c) Fire spread experiment

**Fig. 7.** Comparison of slope calculation algorithm simulation (30°).

minutes on the down slope (–10°) and about 39 minutes in the flank direction.

As mentioned above, Fig. 7 shows the results of simulation on a 30° slope using the pre–existing algorithm and proposed algorithm. Because the entire calculated slope was 30°, regardless of slope direction, the same time was taken for all directions. It took 17.8 minutes for the fire to spread to 50 m in both the left and the right directions. However, when the proposed algorithm was applied, (scheme (b)) it took 17.8 minutes for the fire to spread to 50 m on the upslope (30°), 85.7 minutes on the down slope (−30°) and 39 minutes in the flank direction.

Because the pre–existing algorithm for slope calculation could not distinguish between the upslope and the down slope, the calculated fire spread rates were the same when simulated on a simple slope. However, the results obtained by using the proposed algorithm were similar to the results of the real experiment.

For calculating a simulated slope using the proposed algorithm, a supple method was applied that used a direction of the spread of forest fire. This method was able to provide more accurate calculations. Furthermore, since the method was able to classify the upslope (+) and the down slope (–), the spread rate of forest fire on each slope was able to be analyzed. Consequently, the proposed method is able to effectively support the attack of forest fire by accurately predicting the spread of fire.

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