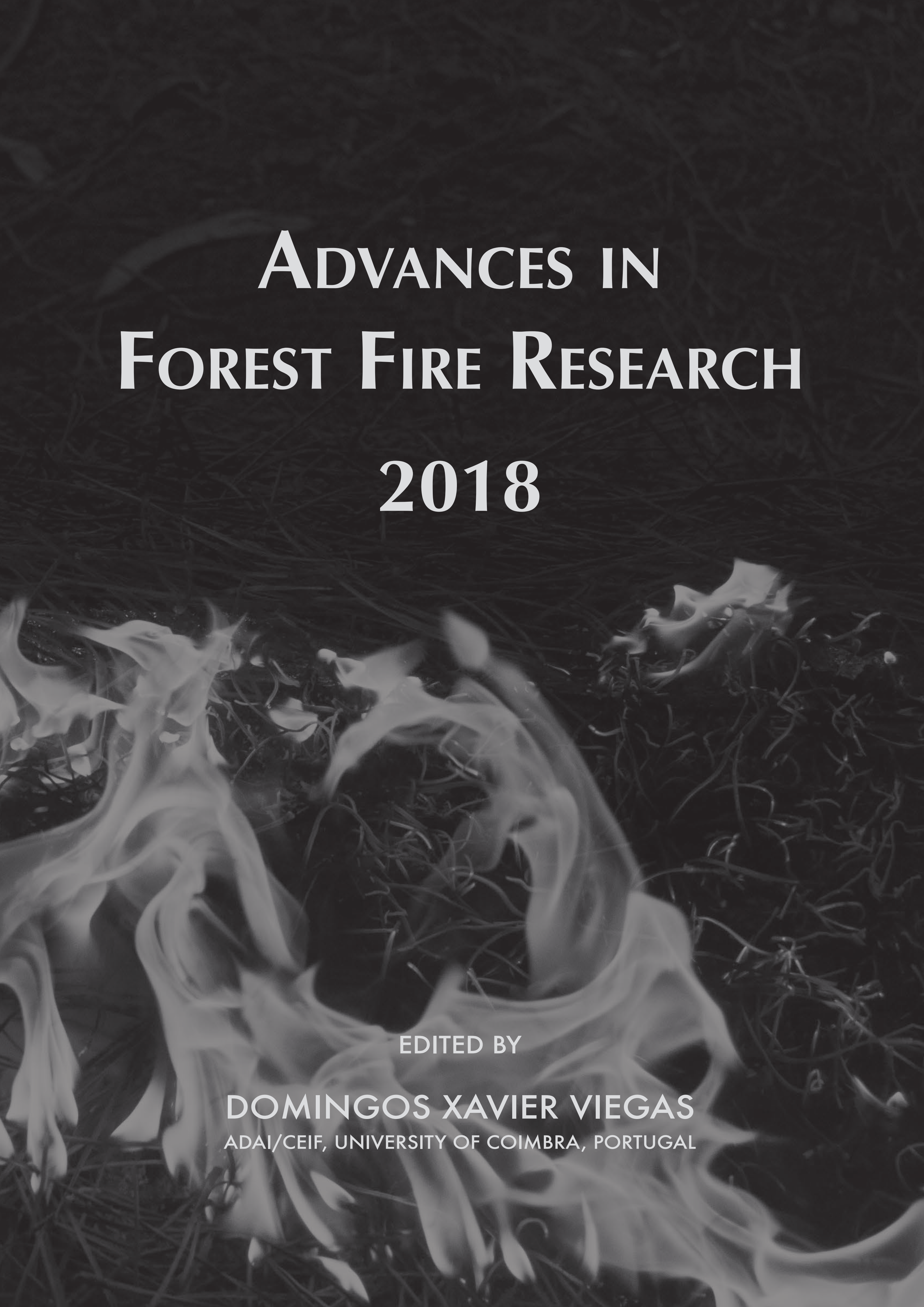

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Fire Risk Assessment of UNESCO Historic Villages by Heat Flux from Forest Fire

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Abstract

Most structures in ASIA UNESCO Historic Wooden Villages are timber framed houses with thatched or shingled roofs that are combustible materials; they are thus exposed to the risk of forest fires. The study examined the effect of the heat flux on the houses in Yangdong UNESCO Historic Village as a result of forest fires to evaluate to what degree of risk they are exposed to. After distinguished the tree species of major structural components of wooden buildings. This was done by getting the precise location information on the houses in Yangdong Village with the GIS analysis, collating the information on the construction materials and conducting the numerical analysis on heat flux in case of forest fires. The results showed as follows: around 10% of the houses are directly exposed to the danger of forest fires and 5% of all the houses are expected to be subject to the indirect effects due to the proliferation of the initial forest fires. In conclusion, it was determined that appropriate and effective methods of forest fire prevention and fighting need to be sought, and they should be based on eliminating the possible fuels for forest fires that are nearby the fire-vulnerable houses, securing enough separation distances and installing waterproof facilities.

Keywords: UNESCO Historic Village, WUI (Wildland Urban Interface), Forest Fire, Heat Flux, Fire Risk Map.

1. Introduction

Many of Korea’s historical and cultural properties were lost by fires including forest fires. Local cultural assets as well as national treasures were damaged by arson, forest fires, and other unidentified causes. Most of Korea’s architectural cultural properties were made of wood, which is vulnerable to fires. In the case of a historical and cultural district forming a village, there will be more serious if fire occurs, in addition to danger of wood architectural cultural properties by fire. Between 2004 and 2009, a total of 15 cases of fire occurred in Seongeup Village in Jeju. The causes include short circuit and mishandling of fire arms when repairing thatched roof. Other five cases of fire occurred from 2001 to 2009 in Yangdong Village registered as World Heritage were due to short circuit and mishandling of fire arms, and negligent management of fire source in the construction site. A fire broken out on June 4, 2010 (15:39) in Andong Hahoe Village burnt Beonnam Old House to ashes while Hanju Head House was partially lost by fire occurred on January 25, 2011. In particular, as World Heritage Yangdong Village was surrounded by coniferous forests, which are vulnerable to forest fire, occurrence of fire will expose the entire village formed by wood and straw-roofed structures, to danger of fire when fire breaks out.

This study aims to assess fire risk of heat flux when fire occurs in the current forest environment and placement of residence and create a risk map based on the assessment results, thereby improving fire safety of Yangdong Village

2. Overview of Yangdong Viliage

Below is an example of a picture and respective legend. Use the same formatting for tables. Yangdong Village is a time-honored village formed by two clans: Wolseong Son Clan and Yeogang

Yi Clan. There are Mt. Seolchangsan to the north and Soengjubong Peak of 100m in height to the south, and Yangdong Stream runs in front of the village. Beyond the west mountain unfolded Angang Plain, which was economic source of the village. The village is divided into Hachon and Sangchon as of Angye stream east and west, while Namchon and Bukchon north and south.

Figure 1 - A woodend and straw roof houses of Yangdong Viliage

The total number of houses in Yandong excluding non-residential structures and head houses designated as a cultural asset is 140, out of which straw-roofed houses are 78, approximately 56% of total houses. The 78 houses consist of 49 straw-roofed houses and 29 mixed (straw-roofed and tile-roofed) houses, and the number of individual straw-roofed house buildings is approximately 190 (Fig. 2, Lee and Kim, 2013). Important cultural heritage properties include Tonggam sokpyeon (Supplement to the Comprehensive Mirror for Aid in Government) (National Treasure 283), Mucheomdang House in Yangdong, Gyeongju (Treasure 411), Hyangdan (Treasure 412), Hyangdan House in Yangdong, Gyeongju (Treasure 412), Gwangajeong House in Yangdong, Gyeongju (Treasure 442), Portrait of Son So (Treasure 1216), 12 important folk materials including Seobaekdang (Important Folk Material 23), and 7 cultural assets designated by the province including estate distribution documents of Son So (Gyeongbuk Tangible Cultural Heritage Property 14).

In particular, tree species of pillar, beam, and girder members of Mucheomdang House and Gwangajeong House in Yangdong designated as World Heritage was revealed to be pine tree (P. denstiflora), which was analyzed to have significant potential risk (Lee, J. H. et al., 2013).

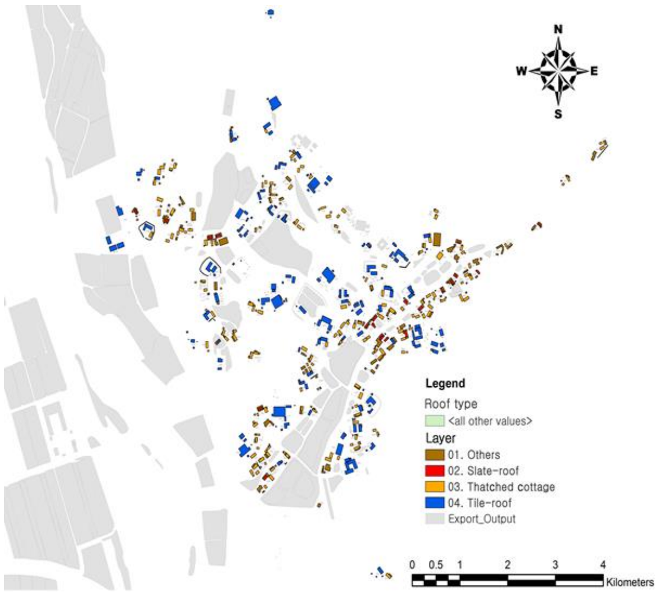


Figure 2 - Arrangement map of Yangdong Viliage

3. Theory Analysis of Forest Fire Flames

3.1. Flames of Forest Fire

Spread of forest fire undergoes the pyrolysis process of unburned fuel by heat flux emitted through flames. Then, when the surface temperature of the burning substance reaches the igniting temperature, the process of creating flames causes the expansion of the forest fire. To assess heat flux emitted from flames, height of flames should be considered. First, to calculate the height of flames, heat release rate (HRR, kW) should be estimated using Effective Heat of Combustion (kJ/kg) and Mass Loss Rate (MLR, kg/s). HRR can be calculated from Equation (1) and is proportional to MLR and Effective Heat of Combustion changed by energy equivalent, water content, combustion diameter, and density.

$$HRR(\mathrm{kW}) = \Delta h_c \times MLR \tag{1}$$

Flame height calculation models were proposed by McCaffrey (1995) and Heskestad (1998) for horizontal-plane fire of liquid flammable materials under the condition of no wind. The calculation Equation of fire flame height was presented by Albini (1981) as $H \propto IB/U$, which is an estimation Equation for one dimensional flame height, and Nelson (1986) suggested Equation (2). However, when wind velocity is 0, it is not possible to calculate flame height with the Equation.

$$H = \frac{aI_B}{U} \tag{2}$$

where, I_B is Byram' fire intensity (kW/m^2) and a is 1/360 and U is wind velocity (m/s). Kim (2009 a) suggested a calculation Equation of flame height of solid fuel such as surface fire fuel materials as the following Equation (3):

$$H = 0.027(\dot{Q}')^{2/3} \tag{3}$$

where, $\dot{Q}'$ (kW/m) is HRR in length, and unit length, which is an experiment setting of Q calculated by Equation (1) was applied. Equations (2) and (3) are to calculate flame height under the condition of no wind and flat area, and flame height changed by wind and slope can be calculated with Equation (4).

$$H\_ws = H \times \sin(\theta) \tag{4}$$

where, θ (°) is angle between ground surface and the flame changed by wind and slope and it is obtained by subtracting flame angle (∅) from 90°. Calculation of flame angle can be conducted using Equation (5), which represents correlation between Froude Number (Fr) and wind velocity under the condition of uniform wind (Kim, 2009b, 2009c).

$$Fr = \frac{U_\infty}{\sqrt{gH}} \tag{5}$$

$$tan\emptyset_{ws} sin\emptyset_{ws} = 1.2\frac{U_{ws}^2}{gH} \tag{6}$$

where, g is acceleration of gravity (m/s^2), H is initial flame height (m), and U_{ws} is air entrainment rate (m/s).

3.2. Heat Flux of Forest Fires

Radiation heat transfer by surface fire flame is conducted through calculation of total radiant heat flux received by unburned section from individual flame for the grid defined as follows (Figure 3), where three-dimensional position values against the center point of flame obtained by Equation (3) are x_f, y_f, and z_f. To calculate heat energy per unit area emitted from flames, PSM (Point Source Model) in Equation (7) was used. With the PSM can be used when calculating radiant heat flux per unit area and unit time delivered target distant by r from emitting flame. Therefore, when the total heat flux reaches ignition energy, flame combustion is conducted and expanded.

$$\dot{q}'' = \frac{\dot{Q}_r}{4\pi r^2} cos\theta' \qquad (7)$$

where, $\dot{Q}_r$ is radiant flux, r is radius of flame depth (m), and θ' is angle between the center of flame and z_f vector and expressed as Equation (8). Location coordinates of the center of flame (x_f, y_f, z_f) needed to calculate heat flux transfer from flame can be moved by slopes and wind, which can be represented as the following Equation (9).

$$cos\theta' = \frac{Z_f - Z}{r} \qquad (8)$$

where, $r = \sqrt{(x_f - x)^2 + (y_f - y)^2 + (z_f - z)^2}$

$$\overrightarrow{P_f} = \begin{pmatrix} x_f \\ y_f \\ z_f \end{pmatrix} = \begin{pmatrix} x_0 + \frac{1}{2} L_f cos\emptyset cos\alpha \\ y_0 + \frac{1}{2} L_f cos\emptyset sin\alpha \\ z_0 + \frac{1}{2} L_f sin\emptyset \end{pmatrix} \qquad (9)$$

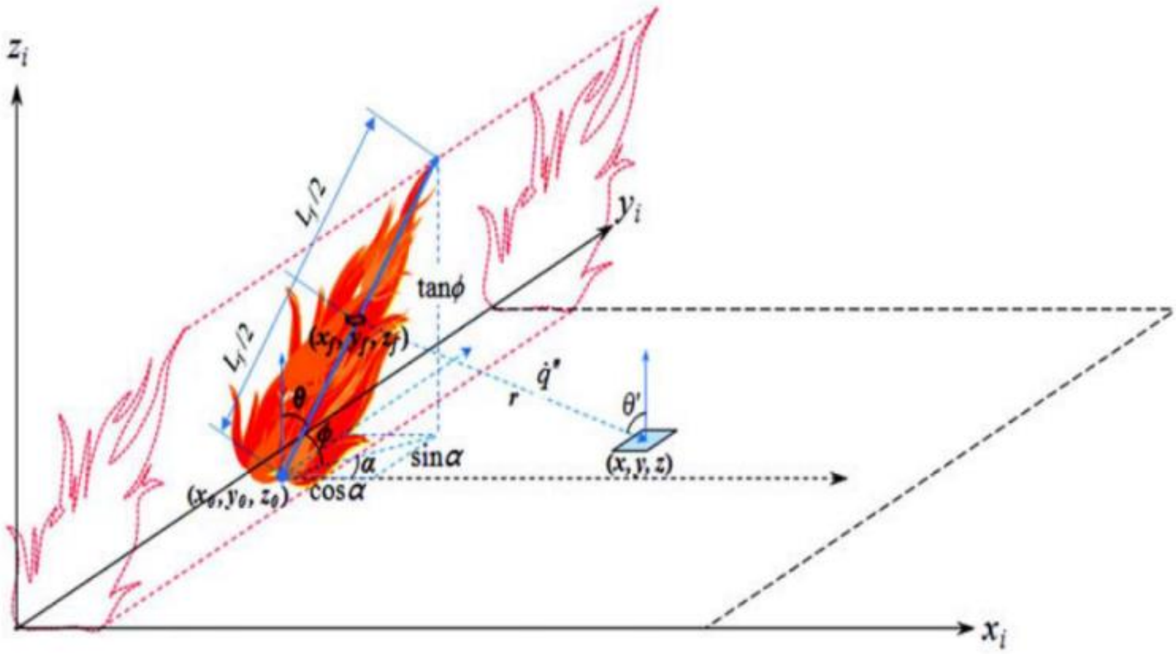
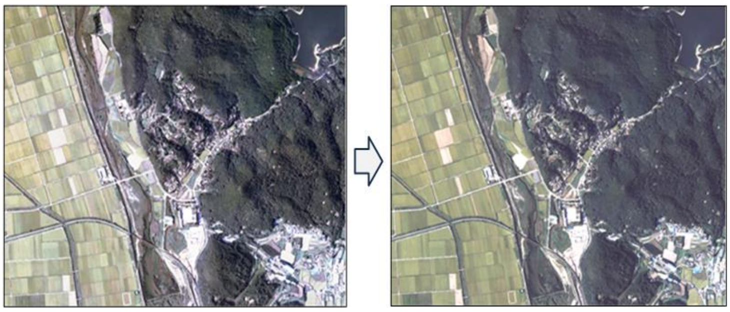


Figure 3 - The concept of heat flux transfer

4. Identification and Analysis of Forest Fire Risk Range

4.1. Digital Aerial Photo-Based Analysis

In this study, digital aerial photograph was used to increase visibility of identified scope of risk caused by forest fires and accurately identify relevant information. As its final purpose is to provide almost real environment information, orthometric correction must be performed in displaying location information including identification of forest fire risk range. In this research, satellite image was corrected for orthometric correction by using Image Enhancement method, which improves the brightness environment of image materials and Spatial Enhancement method, which eliminates noise in the image and improves its clarity. In addition, in the case of Image Enhancement, Histogram Stretch was applied while utilizing a method that increases contrast of images by reorganizing the area of image brightness into that represented by computer (Figure 4).



(a) *(b)*

Figure 4 - Histogram stretch of a aerial photograph in Yangdong Viliage; Image Enhancement (a) to (b)

In this study, GIS (Geographic Information System) was applied to identify the scope of heat flux for Yangdong Village in case of forest fire. Risk intensity of forest fire was represented to a functional relation according to distance between forest and the structure, and GRID file was created so as to easily handle modeling work in which cumulative values of risk intensity cells should be applied to each cell of the coverage. GRID file was structured in grid pattern (width (1m) x length (1m)) and in selecting the scope for GRID, the creating scope was set to Polygon with 1,230m in width and 1,000m in length so that it was possible to analyze the entire Yangdong Village in Gyeongju, and 1m-resolution GRID was created by using AutoCAD Tool to identify the scope of forest fire heat flux based on the created Polygon.

4.2. Creating Buffer Line to Analize the Scope Identification of HRR

To identify the scope of forest fire heat flux in Yangdong Village, GIS buffer analysis, which is an operation method to calculate certain area adjacent to a specific space object, was conducted. Buffer for buffering analysis was based on a digital stock map (1:5,000). However, as forest boundaries on the map were not accurate, digitizing was performed based on aerial photograph, and buffer line was extracted based on the accurately extracted forest boundaries. A total of 25 buffer lines were created at intervals of 1m using the multiple ring buffer method. Since the acquired forest data was classified based on polygon according to tree species, it was difficult to identify the risk scope of forest fires depending on forest boundaries, so this research adopted Dissolve method, which is a GIS analysis method integrating spatial data for the same attributes based on the attributes of vector data, in order to extract forest boundaries and for the extracted boundaries, hills and pastureland in and around Yangdong Village were added and the forest was accurately partitioned off.

Since it is necessary to create a stock map or forest boundary information, which represents the scope of forest to identify risk scope of forest fire heat flux, Heads-up digitizing was performed based on aerial photograph. To input the following heat flux result values in the extracted buffer line, Split method was used and the buffer lines were classified per distance. The input value according to distance was entered to 25m in the unit of 1m (Figure 5)

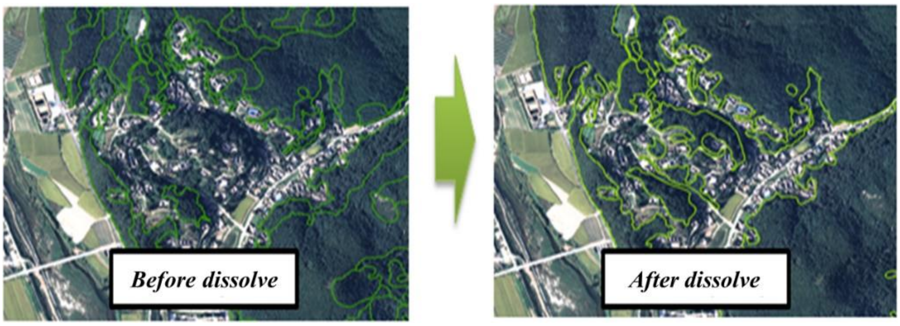


Figure 5 - Result of buffer line protection by 1m unit

4.3. Heat Flux Distribution and Risk Assessment

Heat flux to ignite wood composed of cellulose is 12.7kW/m^2. In other words, if heat flux is at least 12.7kW/m^2, wood is ignited. Therefore, heat flux of coniferous forest fire by distance obtained from Equation 7 is shown in Figure 6 and wood house distant by approximately 4.2m from the fire occurrence boundary was highly likely to ignite.

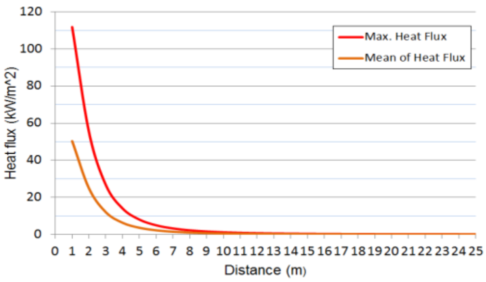


Figure 6 –- Heat flux from forest fire in Yangdong village

To identify heat flux distribution values for forest fire risk in grid pattern with the overlap method of GRID and buffer line, the buffer line should be established in the same format as the existing 1m-unit grid (Figure 7). For making the buffer line into grid, the format of the data was converted from vector to raster and reconverted to vector in the state where it was not simplified. The result values of the converted data were overlapped with aerial photograph that underwent orthometric correction to identify forest fire risk figures using transparency function of ARC GIS. As a result, heat flux distribution around forest-adjacent areas in Yangdong Village was revealed as the following Figure 8.

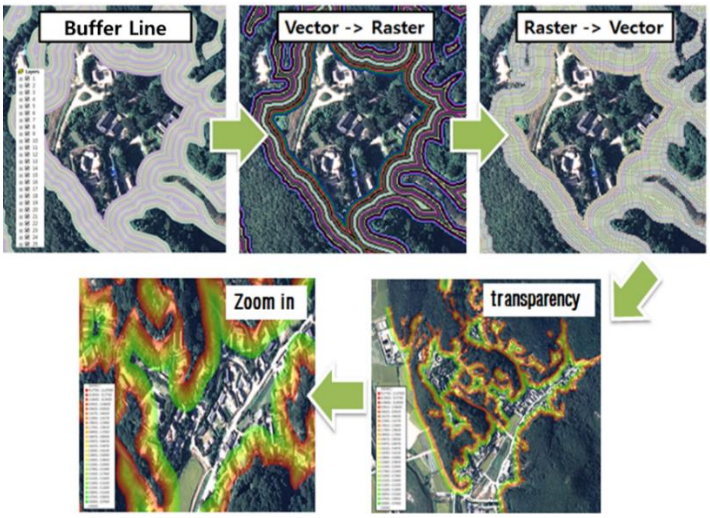


Figure 7 - The process of heat flux distribution for forest fires

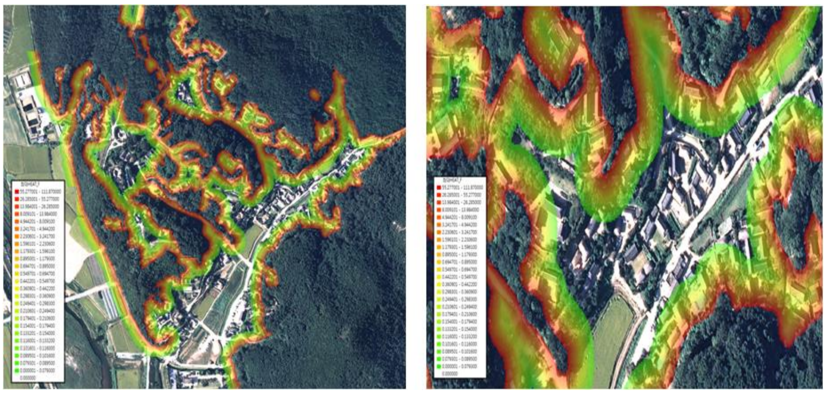


Figure 8 - Risk assessment map of Yangdong village from forest fires

5. Considerations

Roof types of houses in Yangdong Village registered as World Heritage include thatched roof and tile roof, and tree species of pillar, beam, and girder members of Mucheomdang House and Gwangajeong House was revealed to be pine tree (*P. denstiflora*) and most houses in the village were wood structures. In expecting fire behavior with individual combustion property, it is highly important to identify which type of wood composing the combustible materials of the wood structure. In addition, as wood is a complex material consisting of cellulose, hemicellulose, lignin, other extracts (alcohol, ester, and resin), combined water, and compound cell structures, it undergoes a pyrolysis process when it is heated, and heat flux required for ignition energy, which can lead to flames, is known to be approximately 12.7kW/$m^{2.}$ Ignition energy varies by type and water content of wood. However, as experimental studies on those various variables have yet to be conducted, this study applied ignition energy measured within water content of 10% of architectural wood in the dry season where forest fire occurs, as standard value of ignition energy. As for possibility of wood structure ignition from forest fire revealed in this study, wood structures distant by 4.2m from forest was highly likely to ignite as shown in Figure 6 and applicable houses were 10% of the all houses in Yangdong Village.

In this research, expansion of forest fires by spot fires was not considered. In the case of spot fire materials, small embers become a direct cause of fire and leads to fire expansion. Spot fire distance measured in Korea is 2km, and since the entire Yangdong Village is within 2km from forests, the village also deemed to be at danger if a forest fire occurs.

6. Conclusion

Assessment of fire expansion risk when a forest fire breaks out in forest adjacent to Yangdong Village, which is World Heritage, revealed that wood structures distant by about 4.2m from forest fire were highly likely to ignite due to radiant heat. According to analysis conducted based on forest boundaries of the entire Yangdong Village, about 10% of the all houses in the village was evaluated that fire is transferred. In conclusion, to secure safety of village from forest fires, first, preventive measures should be used, for example replacing the coniferous trees with fire-resistance trees or eliminating fuels to secure safety zone, and second is to install water sprays or sprinklers in the houses to extinguish fire. As this research is restricted to wood structures, it is deemed that following research should be conducted including research on the risk with heat release rate of thatched roof and research on the effect of fire on adjacent houses in case of a fire breaks out in a house

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