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Examination of Vegetation Fire Spread with Numerical Modelling and Simulation Using Fire Dynamic Simulator

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Nowadays, the number of forest and vegetation fires is gradually increasing, which are destroying ever larger areas of the Earth. In order to increase the efficiency of activities aimed at prevention and elimination of the consequences of fires, a scientifically based investigation of vegetation fires is essential. Our goal is to examine vegetation fires in simulation environment. During our research work, a simulation model was created with WFDS program, and the spread and effects of fire in a given area were examined. The analysis of the simulation results can help in understanding the propagation properties of vegetation fires, as well as form a good starting point for further research.

Keywords: *forest and vegetation fire, fire spread, firefighting, numerical simulation, fire prevention*

Introduction

Outdoor fires arising as a result of global climate change, especially forest and vegetation fires depending on location and extent, can cause serious damage to the natural and built environment, and their ecological destruction is slowly regenerated.[5] In the event of a large-scale vegetation fire, not only the vegetation living in the area is damaged, but the environment also suffers a significant load; therefore, accurate knowledge of the fire spread processes plays an important role in prevention and firefighting. One possible way to investigate fire spread is modelling and computer simulations. Modelling forest and vegetation fires is a complex process, as many non-linear interactions take place in space

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5 József Padányi – László Földi: Security Research in the Field of Climate Change. In László Nádai – József Padányi (eds.): *Critical Infrastructure Protection Research. Results of the First Critical Infrastructure Protection Research Project in Hungary.* Zürich, Springer International Publishing, 2016. 79–90.

and time.[6] Physics-based modelling approximates fire behaviour using CFD[7] methods, numerically solving 3D time-based equations.[8] Vegetation fires can be divided into three groups according to the way they spread: ground, surface and canopy fires.[9] According to another grouping, there are also plume-driven and wind-driven vegetation fires.[10] The aim of the authors of this paper is to carry out case studies in simulation environment, taking into account Hungarian parameters, after a theoretical overview of vegetation fires. We consider it important to test a program suitable for the simulation of vegetation fires, as well as to facilitate the practical use of the results.

Examination of vegetation fires

After reviewing the available literature sources, it was found that several studies dealt with the investigation of forest and vegetation fires, which provides a good starting point for our work. The combustion of pine trees of different sizes and moisture content was investigated in a simulation and in a laboratory environment by William Mell et al.[11] Mass loss and changes in heat flux were monitored. The simulation and measurements were similar. In the paper of Chad Hoffman et al., the risk of trees being attacked by bark beetle was investigated in the case of canopy fires.[12] Randomly generated layouts and mortality rates were used. It was shown that the mortality rate had the greatest effect on the burning of trees. Fuel consumption and canopy fire intensity were also investigated. In the publication of Rodman Linn et al., we can read about 5 physics-based simulation models, 4 of which take into account idealised conditions, and the fifth takes into account realistic meteorological conditions and non-homogeneous vegetation.[13] The influence of the environment on fire was investigated using the FIRETEC program. The publication of Nicolas Frangieh et al. deals with grassland fires.[14] The rate of fire spread, and the intensity of fire were examined in the case of different wind speeds. In case of low wind speeds, the simulation approximated the experiment well. It was also shown that fire ignition greatly affects the shape of the fire front without changing the rate of fire spread. It was found that low-speed wind does not significantly affect the spread of the fire. However, a higher wind

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[6] Chad M. Hoffman et al.: Advancing the Science of Wildland Fire Dynamics Using Process-Based Models. *Fire,* 1, no. 2 (2018.

[7] CFD: computational fluid dynamics.

[8] Chad M. Hoffman et al.: Evaluating Crown Fire Rate of Spread Predictions from Physics-Based Models. *Fire Technology,* 52 (2016). 221–237.

[9] William Mell et al.: Numerical Simulation and Experiments of Burning Douglas Fir Trees. *Combustion and Flame,* 156, no. 10 (2009). 2023–2041.

[10] Andrew L. Sullivan: Convective Froude Number and Byram’s Energy Criterion of Australian Experimental Grassland Fires. *Proceedings of the Combustion Institute,* 31, no. 2 (2007). 2557–2564.

[11] Mell et al. (2009): op. cit.

[12] Chad Hoffman et al.: Numerical Simulation of Crown Fire Hazard Immediately after Bark Beetle-Caused Mortality in Lodgepole Pine Forests. *Forest Science,* 58, no. 2 (2012). 178–188.

[13] Rodman Linn et al.: Studying Wildfire Behavior Using FIRETEC. *International Journal of Wildland Fire,* 11, no. 4 (2002). 233–246.

[14] Nicolas Frangieh et al.: Numerical Simulation of Grassland Fires Behavior Using an Implicit Physical Multiphase Model. *Fire Safety Journal,* 102 (2018). 37–47.

speed significantly increases the depth of the fire front. Fire intensity was calculated based on Byram's theory taking into account vegetation mass loss and heat release rate. In the publication of Dominique Morvan and Jean-Luc Dupuy, we can read about a multiphase outdoor fire spread in case of a Mediterranean shrubland.[15] A finite number of fuels were defined as a multiphase approach. The 2D calculations were performed in a flat area assuming that the shape of the fire front is straight. In case of wind, the initial line of the fire front changed to a parabolic shape. It was found that the shape of the flame is almost vertical in case of low-speed winds. In case of a stronger wind, the airflow is diluted in the plume, and the hot flames cool down above the combustion zone, thereby reducing the height of the flame. Correlations between flame spread rate and wind speed were also investigated. The Hungarian experience of extinguishing forest and vegetation fires so far[16] and the data of aerial reconnaissance[17] also provide a good starting point for creating the model and determining the boundary conditions of the simulation.

Simulation model

For the simulations, the Wildland Urban Interface Fire Dynamic Simulator (WFDS) program was used, which is an extension of the Fire Dynamic Simulator (FDS). It is primarily used to simulate wildland fires and structural fires.[18] WFDS numerically solves the Navier-Stokes equations for low Mach-number flow and models turbulent dissipation using a large-eddy simulation approach. This approach results in space- and time-dependent predictions of fire behaviour characterised by transient heat flux (radiative and convective) and takes into account heterogeneous fuel complexes and fuel–fire–atmosphere interactions.

WFDS offers different simulation models for wildfires, which are the particle model, the boundary fuel model and the level set model. The program also includes a pyrolysis model developed specifically for vegetation fires. Vegetation is made up of particles with different properties such as surface area/volume ratio, moisture content, density and volume fraction. The model takes into account the interaction between living and dead vegetation. The multiphase reaction includes both the vegetation and the resulting gases. The increase in temperature first causes the evaporation of the water and then of the dry matter, during which combustible gases are produced, and then the remaining solid fuel turns into charcoal. Particles can be described based on the mass percentage of water,

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15 Dominique Morvan – Jean-Luc Dupuy: Modeling the Propagation of a Wildfire through a Mediterranean Shrub Using a Multiphase Formulation. *Combustion and Flame,* 138, no. 3 (2004). 199–210.

16 László Földi – Rajmund Kuti: Characteristics of Forest Fires and their Impact on the Environment. *AARMS,* 15, no. 1 (2016). 5–17.

17 Ágoston Restás: *Az erdőtüzek légi felderítésének és oltásának kutatás-fejlesztése* [Research and Development of the Aerial Reconnaissance and Extinguishing of Forest Fires]. PhD thesis. Budapest, Zrínyi Miklós National Defence University, Bolyai János Faculty of Military Engineering, Doctoral School of Military Technology, 2008.

18 Chad M. Hoffman et al.: Surface Fire Intensity Influences Simulated Crown Fire Behavior in Lodgepole Pine Forests with Recent Mountain Pine Beetle-Caused Tree Mortality. *Forest Science,* 59, no. 4 (2013). 390–399.

dry matter, charcoal and ash. The solid phase thermal decomposition process of general vegetation consists of three reactions:[19]

1. Endothermic moisture evaporation

$$\text{Wet vegetation} \rightarrow \nu_{\text{moisture}} \text{ Moisture} + (1 - \nu_{\text{moisture}})\text{Dry vegetation}$$

$$\nu_{\text{moisture}} = \frac{M}{1 + M}$$

where is the moisture content, ν_{moisture} is the mass fraction of the moisture.

2. Endothermic pyrolysis of dry vegetation

$$\text{Dry vegetation} \rightarrow \nu_{\text{char}}\text{Char} + (1 - \nu_{\text{char}})\text{Fuel gas}$$

where is the mass fraction converted to char during pyrolysis.

3. Exothermic charcoal oxidation

$$\text{Char} + \nu_{O_2,\text{char}} O_2 \rightarrow (1 + \nu_{O_2,\text{char}} - \nu_{\text{ash}})CO_2 + \nu_{\text{ash}} \text{Ash}$$

where is the mass of oxygen consumed per unit mass of char oxidised and is the mass fraction of char that is converted to ash during char oxidation.

The simulation is physical model-based.[20] The particles model foliage and branches of different sizes. The material properties were also given based on the literature.[21] The reaction gas was cellulose. The height of the shrubs is 3 m. The ambient temperature was 20°C. The terrain is flat, there are no slopes. The mesh size was 0.5 × 0.5 × 0.5 m. The moisture content of the wooden materials was 0.49.

Five simulation cases were examined:

1. there are only shrubs, there is no wind
2. there are only shrubs, there is 5 m/s wind
3. there are only shrubs, the height of the shrubs is 1 m
4. there are only shrubs, the moisture content is 0.1
5. there are some trees with random generated placement

The simulation models are shown in the figure below.

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19 Kevin McGrattan et al.: Fire Dynamics Simulator User's Guide. *NIST Special Publication 1019*, 2022.

20 William Mell et al.: A Physics-Based Approach to Modelling Grassland Fires. *International Journal of Wildland Fire*, 16, no. 1 (2007). 1–22.

21 Mell et al. (2009): op. cit

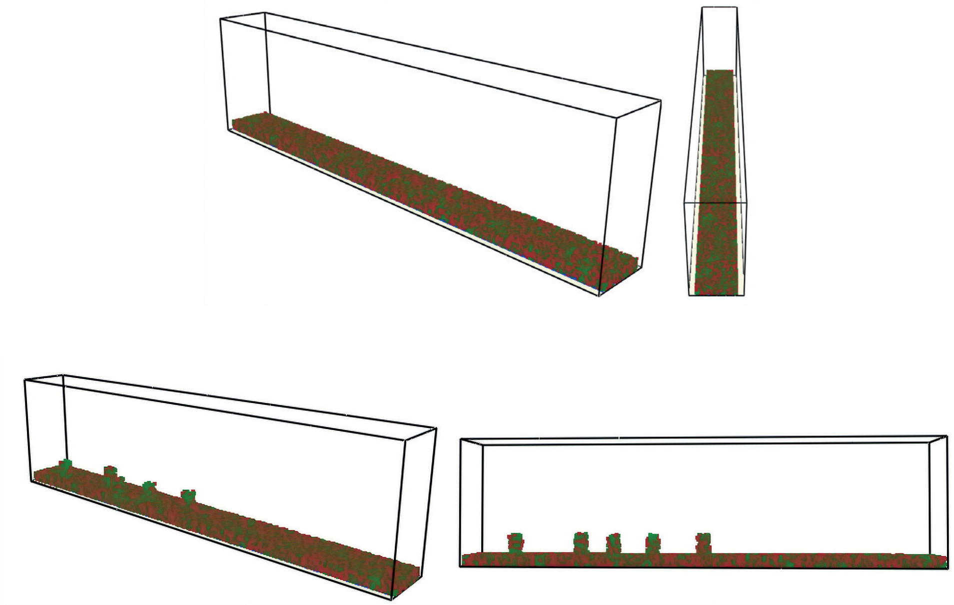

Figure 1: Simulation models (up: shrubs only, down: there are also trees)

Source: Compiled by the authors.

The burnable area is 150 × 18 × 40 m. There is a road on both sides of the area. The speed of the fire spread was determined to be 3 m/min. with starting point 75; 2.1; 0. The heat release rate per unit area (HRRPUA) value of the fire is shown in Figure 2.

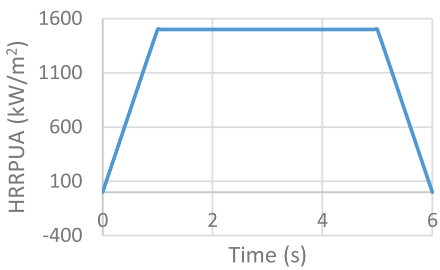

Figure 2: Heat release rate per unit area of the fire

Source: Compiled by the authors.

The simulation time was 900 s. The simulation ran in parallel using MPI and OpenMp.

Results

Before examining the cases, it was analysed how the width of the non-combustible part (road) affects the simulation. The fire spread (HRRPUV[22]) and the heat flux were examined at 200 s, 350 s, and 900 s (Figures 3–5) in case of different road widths.

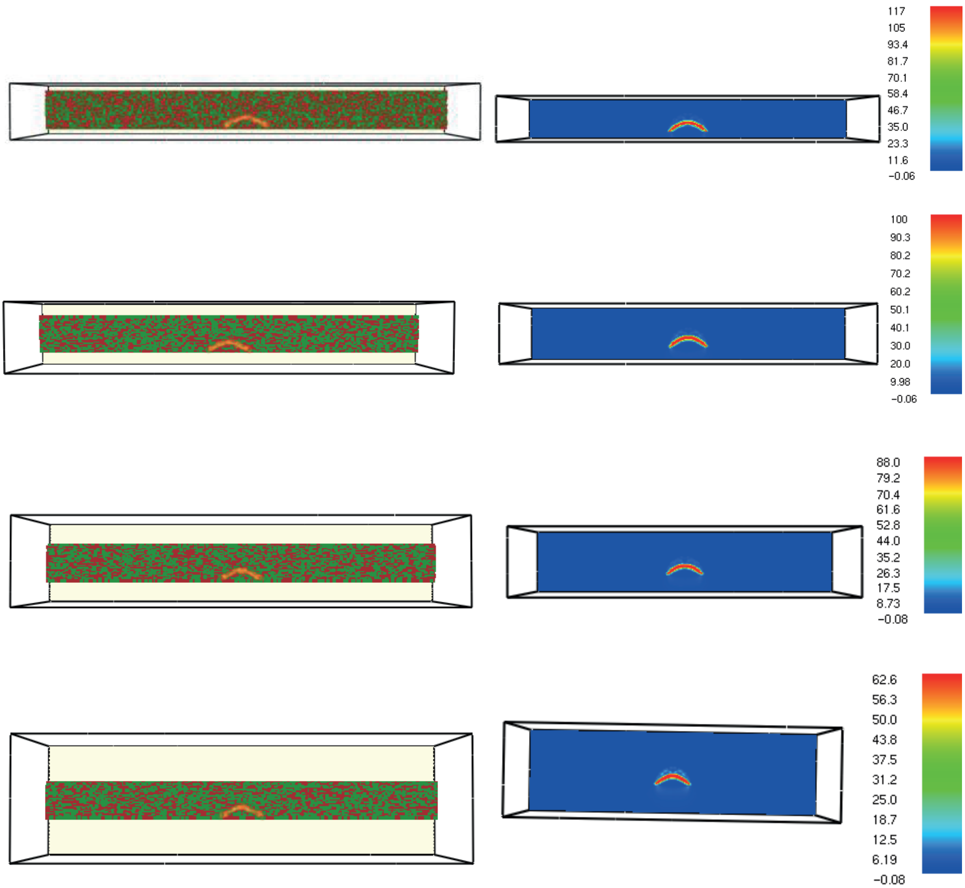

Figure 3: HRRPUV and heat flux (kW/m^2) at 200 s (from top to bottom 2 m, 5 m, 8 m, 16 m)

Source: Compiled by the authors.

[22] HRRPUV: Heat release rate per unit volume.

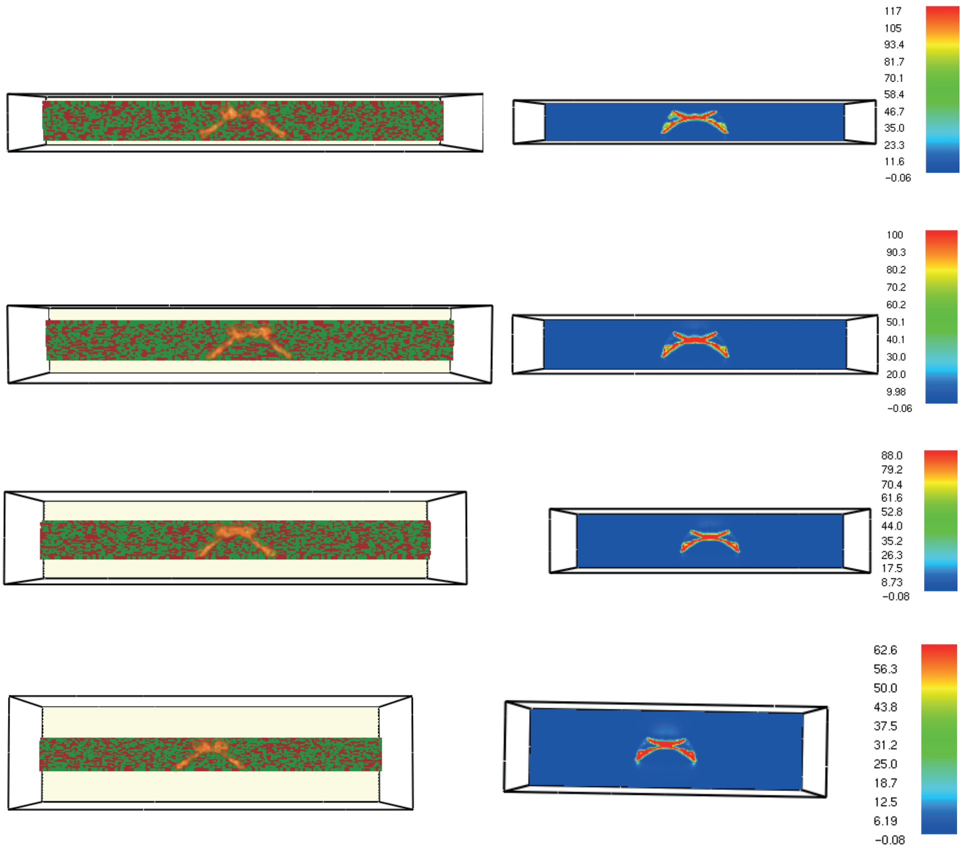

Figure 4: HRRPUV and heat flux (kW/m^2) at 350 s (from top to bottom 2 m, 5 m, 8 m, 16 m)

Source: Compiled by the authors.

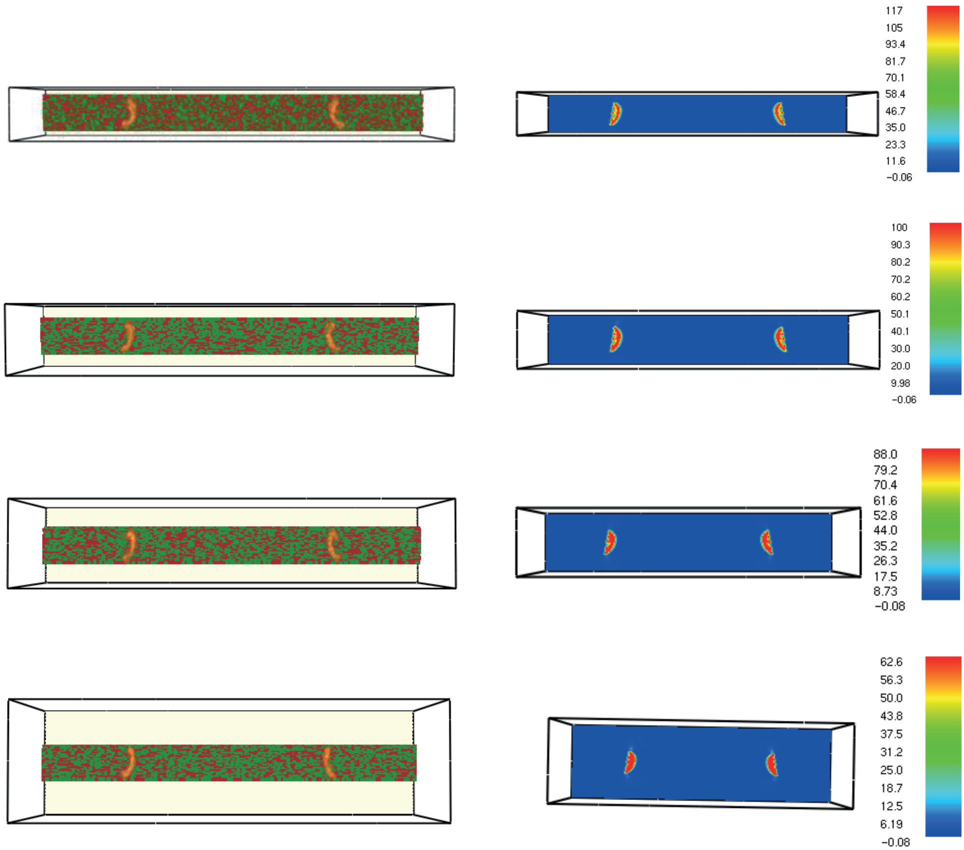

Figure 5: HRRPUV and heat flux (kW/m^2) at 900 s (from top to bottom 2 m, 5 m, 8 m, 16 m)

Source: Compiled by the authors.

It can be seen that the HRRPUV figures developed similarly. However, at 350 s, when the fire plume reaches the other side, there is a difference. There is also a difference in the maximum value of the heat flux. The value of the heat release rate (HRR) was also examined (Figure 6).

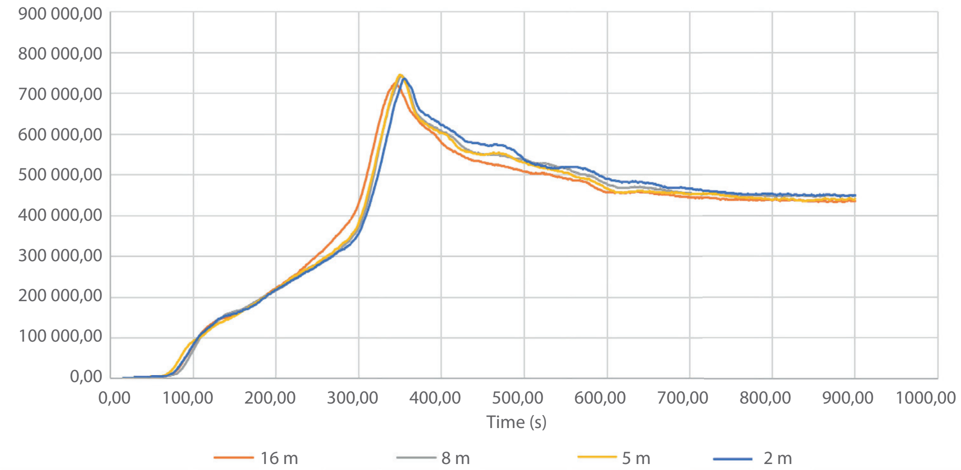

Figure 6: Heat release rate (HRR)

Source: Compiled by the authors.

It can be seen that there is a difference between the individual HRR curves. Between the 8 m and 5 m curves, the difference is minimal. The value of the HRR is initially 0, followed by a rising section, then reaches a maximum and begins to decrease, and finally settles to a constant value. There is a greater difference between the curves in the increasing and decreasing sections.

The calculation time of the simulations was also examined (Table 1).

Table 1: Calculation time of the simulations

Road width	2 m	5 m	8 m	16 m
Calculation time	14 h	17 h	17 h	25 h

Source: Compiled by the authors.

It can be seen that the 5 m and 8 m wide roads do not significantly increase the calculation time of the simulation. However, the 16 m wide road significantly increases the calculation time. Therefore, we performed the simulations with the 8 m wide road.

From Figures 2–4 we can get information about the spread of the fire. At 200 s, the fire front has a parabolic shape, which becomes wider as time goes by. At about 350 s, the fire reaches the other side, and then it splits in two directions. After that, the fire spreads symmetrically in a parabolic shape.

The rate of fire spread (ROS) is calculated as follows.

Before splitting in y direction:

$$ROS = \frac{y}{t} = \frac{14}{358} = 0.039\ m/s$$

Before splitting in x direction:

$$ROS = \frac{x}{t} = \frac{15}{358} = 0.042\ m/s$$

After splitting in x direction:

$$ROS = \frac{x_2 - x_1}{t_2 - t_1} = \frac{44 - 15}{900 - 358} = 0.05\ m/s$$

ROS can be calculated similarly in the other cases as well. A summary of ROS is shown in Table 2.

The fire spread and heat flux in the second case is shown in Figure 7.

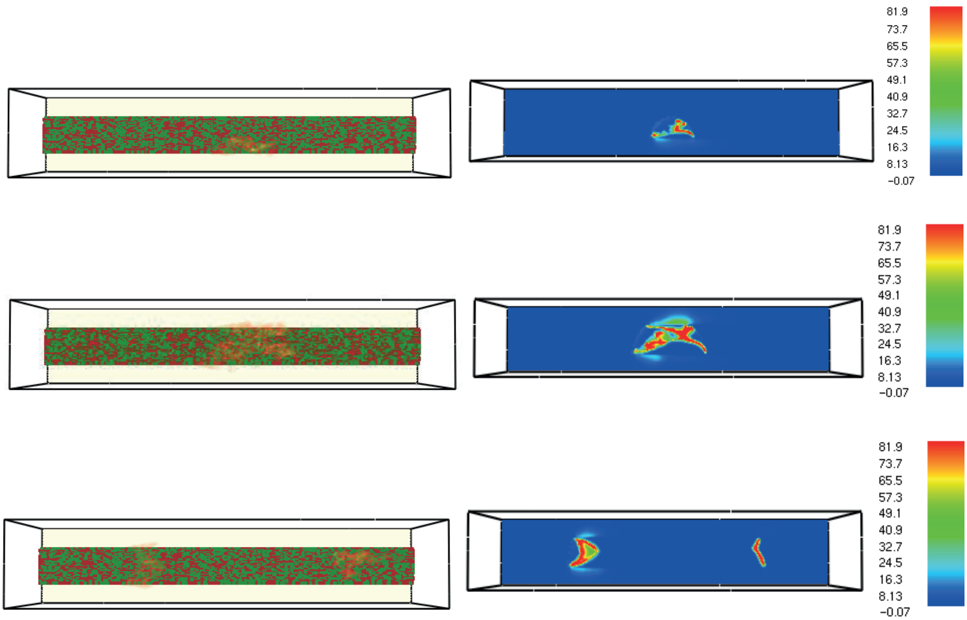

Figure 7: HRRPUV and heat flux (kW/m^2) in the second case (top: 200 s, middle: 350 s, bottom: 900 s)

Source: Compiled by the authors.

It can be seen that the fire spreads more in the direction of the wind. After separation, it primarily spreads in the direction of the wind, but it also spreads in the other direction as well. The direction of the wind can also be observed on the heat flux: a wider flux can be seen on the left side, and a narrow but more intense flux can be observed on the right side.

The fire spread and heat flux in the third case is shown in Figure 8.

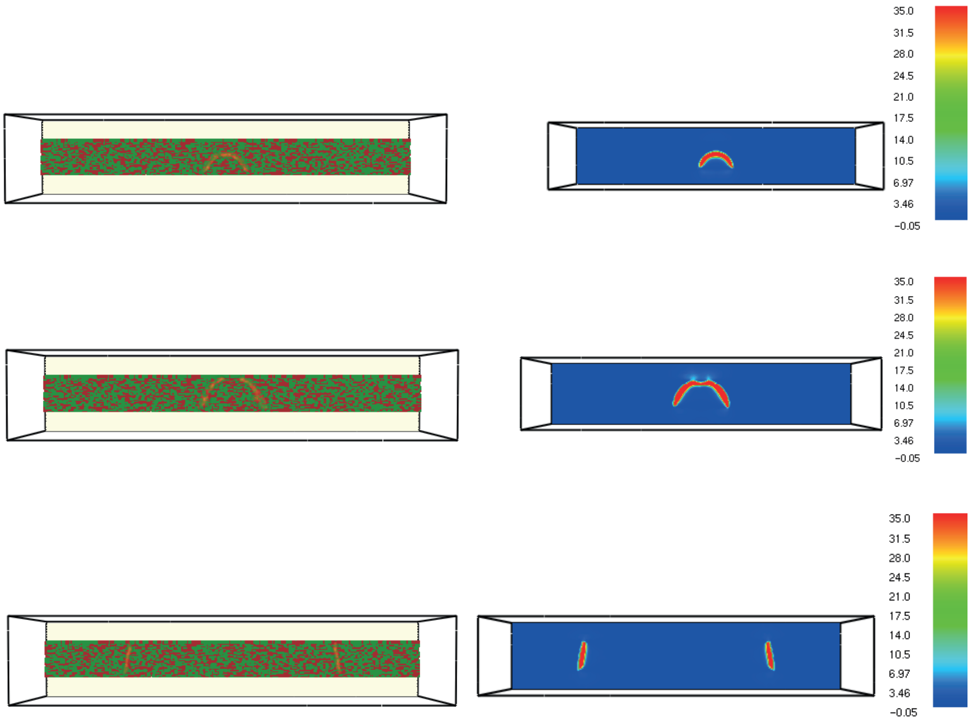

Figure 8: HRRPUV and heat flux (kW/m²) in the third case (top: 200 s, middle: 295 s, bottom: 900 s)

Source: Compiled by the authors.

The fire reaches the other side at about 295 s. It can be seen that the fire spreads faster, but the fire plume is much narrower. The maximum value of the heat flux is also lower.

The fire spread and heat flux in the fourth case is shown in Figure 9.

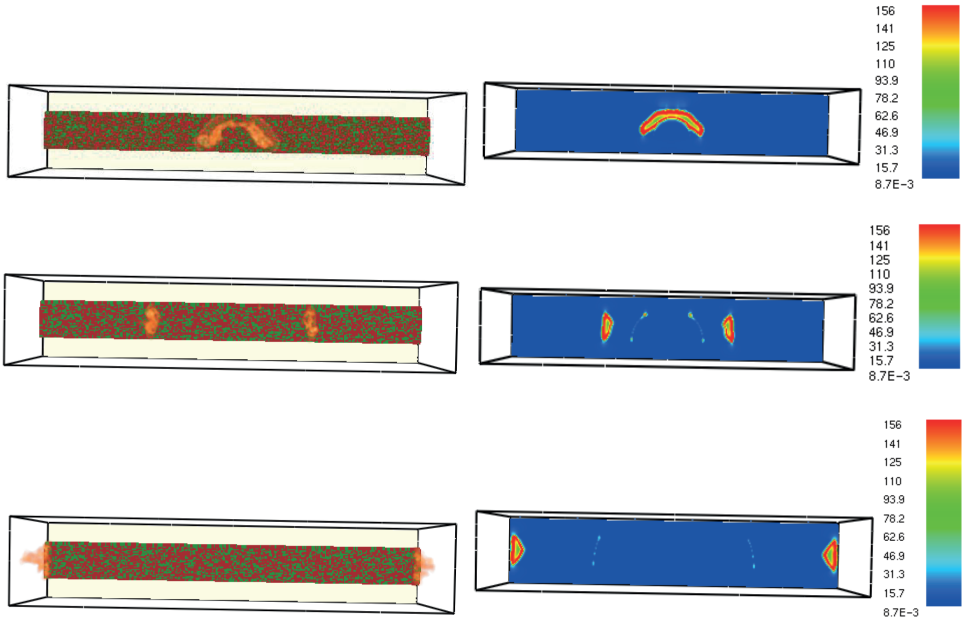

Figure 9: HRRPUV and heat flux (kW/m²) in the fourth case (top: 177 s, middle: 350 s, bottom: 739 s)

Source: Compiled by the authors.

It can be seen that the fire spreads faster and the intensity of the fire is also greater. Accordingly, the fire plume is wider. The maximum value of the heat flux is also higher.

The fire spread and heat flux in the fifth case is shown in Figure 10.

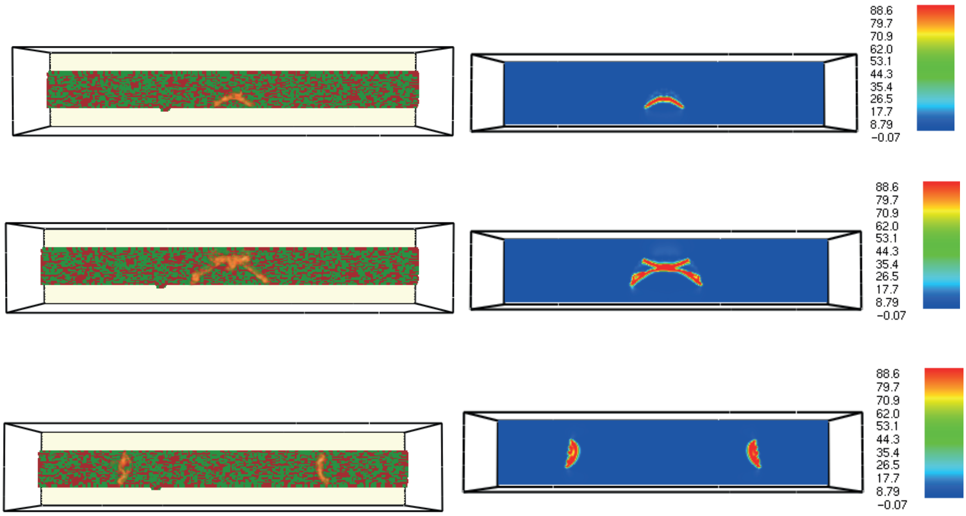

Figure 10: HRRPUV and heat flux (kW/m^2) in the fifth case (top: 200 s, middle: 350 s, bottom: 900 s)

Source: Compiled by the authors.

It can be seen that the spread of the fire is similar to the first case. The maximum value of the heat flux is also similar. However, the shape of the fire plume changed on the side where the trees are. This change can also be observed in the heat flux.

The ROS is shown in Table 2.

Table 2: ROS (rate of spread) (m/s)

	Before splitting in y direction	**Before splitting in x direction**	**After splitting in x direction**
Case 1	0.039	0.042	0.05
Case 2	0.043	0.093	0.053
Case 3	0.049	0.042	0.052
Case 4	0.08	0.075	0.11
Case 5	0.04	0.04	0.053

Source: Compiled by the authors.

It can be seen that compared to the original setting, ROS increased in all cases. It can be seen that the ROS in the x direction increased significantly when there was wind or when the vegetation was dry. Trees and low vegetation only minimally increased ROS.

The heat release rate (HRR) curves are shown in the following figure.

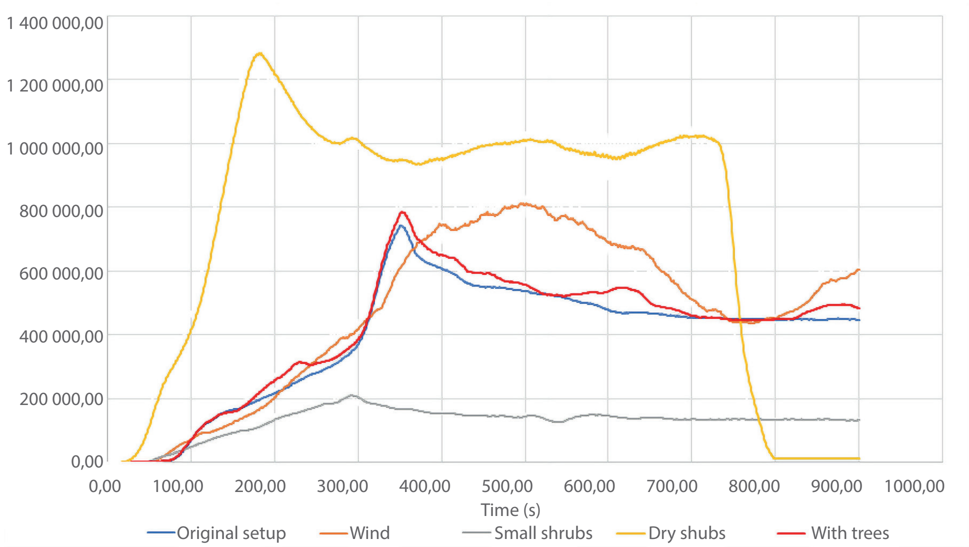

Figure 11: Heat release rate

Source: Compiled by the authors.

At the original settings, the HRR curve first increases almost linearly, then when it reaches the other side it rises rapidly, after that it starts to decrease and finally settles to a constant. The HRR curve developed similarly when there were a few trees in the field. The HRR curve differs in that its maximum is higher and when the fire reaches a tree, there is a jump in the curve. In case of low shrubs, the curve rises more slowly. It reaches its maximum at about 280 s, then decreases, and then becomes constant. In case of wind, the curve first increases linearly. It rises faster at about 310 s till about 400 s, at which point the rise decreases. It reaches its maximum at 500 s, then starts to decrease. It reaches a local minimum at about 750 s, after which it starts to increase again. This can be explained by the fact that the fire started to spread on the other side as well. In case of dry shrubs, the HRR increases rapidly, reaches a maximum at 160 s, starts to decrease, then becomes constant, and finally drops to 0 at 800 s, when the fire front reaches the edge of the field.

The intensity of the fire can be calculated using the following formula[23].

$$I \approx \frac{HRR_{avg}}{w}$$

where is the average value of the HRR, when the fire is fully developed, and w is the width of the field. The intensity of the fire is shown in the following table.

[23] Frangieh et al. (2018): op. cit

Table 3: Intensity of fire

	Case 1	Case 2	Case 3	Case 4	Case 5
HRR_{avg} (kW)	392582.34	471874.82	128682.39	741782.70	414929.03
I (kW/m)	2617.22	3145.83	857.88	4945.22	2766.19

Source: Compiled by the authors.

It can be seen that compared to the original setting, the intensity of the fire increased a little when there were trees in the field. The intensity of the fire also increased when there was wind. The intensity of the fire increased significantly in case of dry vegetation but decreased significantly in case of low shrubs.

Conclusion

In the course of our research work, a simulation model was created and ran related to the spread of fire in a shrubby area (vegetation) with the parameters we determined. We presented the applied simulation model, and also examined how the size of the non-combustible area affects the simulation results. It was found that considering a non-burnable area corresponding to half of the shrubby area led to a suitable result in terms of calculation time and accuracy as well. After that, 5 different settings were examined. It was found that the dryness of the shrubs and the wind significantly increase the spread of the fire. In case of low shrubs, the speed of fire spread increased, but at the same time, its intensity decreased. When there were a few trees in the terrain, it increased the intensity of the fire minimally. The aim of the research is to investigate vegetation fires in a simulation environment, for which detailed knowledge and testing of the applied WFDS program is essential. According to our experience, the WFDS program can also be suitable for investigating fires in forests and vegetation with variable settings, which we intend to carry out in the future.

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