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Numerical Examination of a Forest Area Fire

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An important task of sustainability is the protection of Earth's forests and the prevention of forest fires. In this paper, the numerical examination of a typical Hungarian ash forest fire is presented. The connection between sustainability and forest fire simulations is also discussed. For the simulation, a Fire Dynamics Simulator was selected, and a particle-based model was used. The simulation setup, which includes a random location of trees following Poisson distribution, is also explained. Then, the simulation of a 10x10 m area of ash forest is presented. It was found that in case of arson, the fire spreads rapidly among the trees, and there will be a high-intensity fire in which the forest area burns down in 4 min. The mass loss rate, the temperature, and the heat release rate also increased fast (above 50 kg/s, above 2,000 °C and above 800,000 kW). The aerosol concentration reached a high pollutant concentration ($1.3x10^{-6}$), and the carbon dioxide concentration also increased significantly (above 14,000 ppm). These changes have a direct effect on climate change. Therefore, it is important to examine them in a simulation environment. The simulation was compared to a pine tree forest simulation, and it could be observed that in the case of the pine tree, the values are similar, but phenomena occur faster. With the computer simulation, it is easier to determine the areas affected by the fire, which also helps fire prevention and firefighting. The aim of the research is to contribute to the prevention and more efficient extinguishment of wildfires and the sustainability of the Earth.

1. Introduction

The consequence of global warming and human activity is the increasing number of forest and vegetation fires (Tyukavina et al., 2022). Globally, over 400 Mha of vegetation are affected by fire every year (Robinne, 2020). Fires are occurring more frequently and severely in places like tropical forests. Because of climate change, there will be a longer dry season, more extreme droughts, and an increase in global aridity, which results in drier vegetation and a longer fire season (International Union of Forest Research Organizations (IUFRO), 2018). The other cause of wildfires is human activity, which includes generating ignition sources, modifying land use, and using fire to manage agriculture. 70-90 % of the fires are started by humans. This increase in wildfires affects biodiversity, human well-being, and national economies. Wildfires have economic, social, and ecological impacts (Lang and Moeini-Meybodi, 2021). For example, a high amount of CO_2 is released, which contributes to climate change, as the increase in CO_2 emissions increases the greenhouse effect. With the destruction of forests, oxygen production decreases, the water cycle is affected, and habitats are lost, resulting in a negative effect on biodiversity and even erosion damage. Forest fires also affect air quality. For example, smoke from the Canadian wildfires in 2023 severely deteriorated air quality ratings even in more distant places (NPR, 2023). For sustainable development, it is important to pay attention to sustainable land use and forest and fire management. One way to develop sustainable forest and fire management is to use computer simulation (Peng,

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2000). In the literature, there are several studies dealing with sustainable forest management (Peng, 2000) and fire safety in sustainable buildings (Ivanov et al., 2021), but there are fewer papers dealing with the connection between sustainability and forest fire simulations (Baranovskiy and Malinin, 2020). Forest fire simulations are an important aspect of sustainable development. There are several opportunities to simulate wildfires. One of the most common methods is using physical-based models (Hoffman et al., 2012). Other opportunities include empirical models (El Ezz et al., 2022), statistical models (Hansen et al., 2022), and artificial intelligence-based models (Khanmohammadi et al., 2023). In this research, the physical-based model was selected.

In this research, a case study, the simulation of a typical Hungarian ash (Fraxinus ornus) forest area of 10x10 m was carried out in the case of arson. Forest fires are becoming more common throughout Europe. According to our knowledge, there is no scientific literature that typically deals with the fire simulation of Hungarian wood species and forests. Most of the literature deals with the simulation of pine forests (Hoffman et al., 2012) or shrublands (Morvan and Dupuy, 2004). Comparing the simulation of an ash forest and a pine forest, it can be stated that the tree geometry is different. Comparing a forest fire simulation to a shrubland fire simulation, it can be stated that a shrubland is lower in height. From a simulation point of view, shrublands can be entirely modelled as connected particles (Hajdu et al., 2022), while the trees have to be modelled separately. In this paper, it is presented how a typically Hungarian species behaves in the case of fire. The results are reviewed from a sustainability point of view. The aim of the research is to contribute to the prevention and more efficient extinguishment of wildfires and the sustainability of the Earth.

2. Methods

The aim of the investigation is to develop a simulation framework for the assessment of the damages of forest fires. In the first step, a small area of ash forest was investigated for degradation of air quality, rise in ambient temperature, time of burning and fire intensity. For the numerical simulation, FDS (Fire Dynamics Simulator) was used, which is a computational fluid dynamics (CFD) software (Ez-zahra El Hamraa et al, 2023), that uses large-eddy simulation to solve low Mach-number Navier-Stokes equations. The program offers 3 models for forest fire simulation: the particle model, the boundary fuel model, and the level set model. The numerical simulation used a physical-based model where actual physical properties of the burning material were used in the software to simulate the fire. The program includes a solid-phase thermal degradation model, which can be used for vegetation fires. There are 3 reactions in the case of the burning vegetation, which are endothermic moisture evaporation, endothermic pyrolysis of dry vegetation, and exothermic charcoal oxidation respectively. The following equations describe the above-mentioned reactions:

$$WV \rightarrow \nu_m M + (1-\nu_m)DV \quad (1)$$

$$DV \rightarrow \nu_c CH + (1-\nu_c)FG \quad (2)$$

$$CH + \nu_{o_2,ch} O_2 \rightarrow \left(1 + \nu_{o_2,ch} - \nu_{ash}\right) CO_2 + \nu_{ash} ASH \quad (3)$$

In the equations, WV, M, DV, CH, FG, and ASH are the chemical amounts of the wet vegetation, moisture, dry vegetation, char, fuel gas, and ash respectively. The stoichiometric coefficients ν_m, ν_c, and ν_{ash} are the mass fractions of the moisture in wet vegetation, dry vegetation converted to char, and char converted to ash. Also, $\nu_{o_2,ch}$ is the mass of oxygen consumed per unit mass of char oxidised (McGrattan et al., 2022).

In the output CO_2, $PM_{2.5}$ and PM_{10} aerosol concentrations were measured for the assessment of air quality, temperature sampling locations and planes were investigated, fire intensity was characterised by the overall heat release rate (HRR), time of burning was measured using mass loss rate (MLR) and mass loss of trees.

The generation parameters were based on various parameters that were well-established in the literature. The foliage and the branches of the trees were modelled by particles (Mell et al., 2009). The simulation area was 10x10 m with 5 ash trees. The height of the ash trees was around 5 m, the crown diameter was around 6 m, and the crown base height was around 2 m (Profi Faiskola, 2023). The descriptive tree parameters are stored in a semantic structure, enabling the parameterisation of probabilistic distributions with typical measured values. The tree positions were sampled from a random Poisson distribution (Hoffman et al., 2012) with parameters derived from the presumed density of the ash cluster. The variation of other parameters (e.g., foliage diameter, stump height, base diameter) was sampled for each ash tree from a normal distribution, with a variation factor derived from tree-specific parameters (Kara, 2021).

The simulation setup is shown in Figure 1.

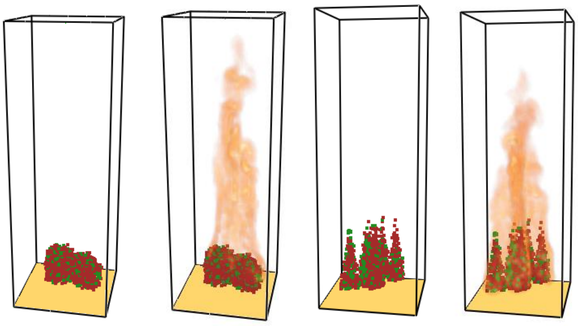

Figure 1: Simulation setup (from left to right: ash forest initial setup, ash forest burning, pine forest initial setup, pine forest burning)

The simulation area was 20x20x60 m with a 0.5x0.5x0.5 m mesh size. The ignition source was a circular burner below the middle tree (xyz = 9, 12, 1.9) and a temperature of 1,500 ˚C to model arson. The moisture content of the trees was 20 %. The simulation time was 6 minutes. The sensors were placed at the top of the middle tree (xyz=9, 12, 5), and the slice for measuring the temperature field was placed on y=12 plane.
A simulation of a pine tree forest in the same area was also carried out. The height of the pine trees was around 15 m (Raptis et al., 2018), the crown base diameter was around 4 m (Pyataev and Vais, 2019), and the crown base height was around 2.4 m (Riano et al., 2004)

3. Results and discussion

The results are shown in Figure 2.

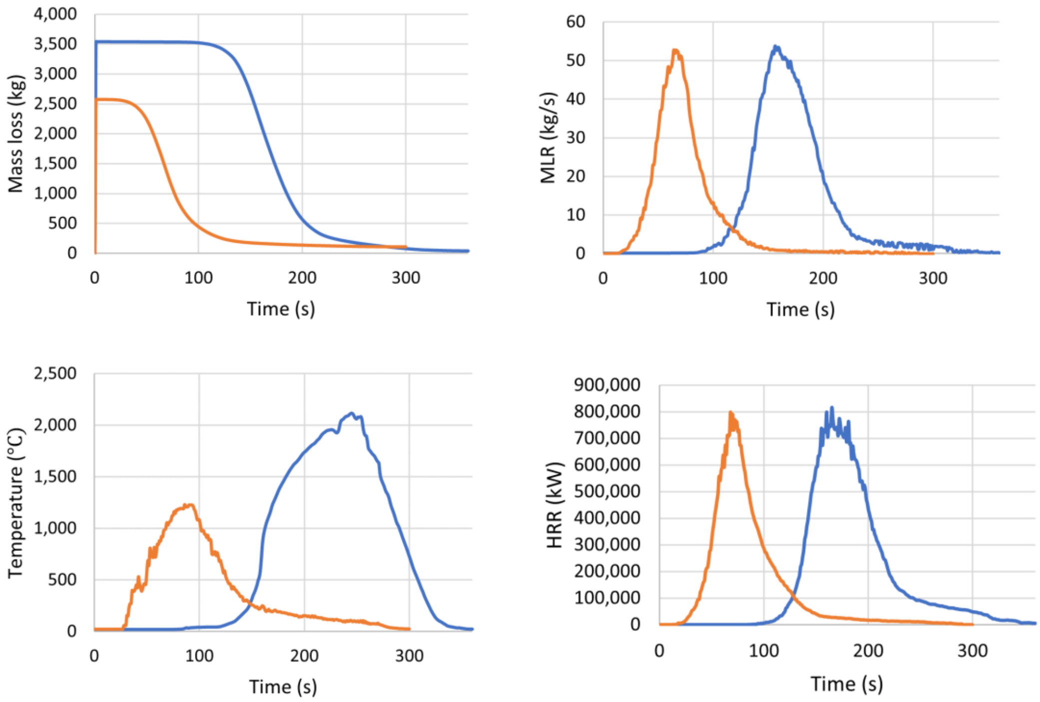

Figure 2: Mass of the trees (top left), mass loss rate (top right), temperature at the top of the middle tree (bottom left) and heat release rate (bottom right), (blue: ash, orange: pine)

It can be stated that fire spreads fast from one tree to another. Therefore, the mass loss is fast. The trees are first ignited slowly, therefore, the fire started at 115 s. From the mass loss rate, it can be concluded that all the trees burned down in 4 minutes. After the ignition of the first tree, the mass loss rate increased fast, then reached a peak at around 170 s and then it decreased fast when all trees burned down. The temperature at the top of

the middle tree first increased fast after the first tree ignited, then reached a peak at 2,119 ˚C, then decreased fast, and then became constant. The heat release rate (HRR) first increased fast, reached a peak value (816,342.05 kW), and then decreased fast. It also can be observed that the burning was faster in the case of a pine forest as the diagrams reached their peak in a shorter time.
The intensity of the fire can be calculated from the HRR with the following equation (Frangieh et al., 2018):

$$I \approx \frac{HRR_{average}}{w} = \frac{155247.68}{100} = 1552.4768\ \frac{kW}{m^2} \tag{4}$$

which is a high-intensity fire. The intensity of the fire in the case of pine was $1310.105\ \frac{kW}{m^2}$. It is interesting to observe that the intensity of the fire was almost the same. The cause of it was that the trees were located densely, and the ignition source was large. The temperature field in the middle plane (y=12) can be seen in Figure 3.

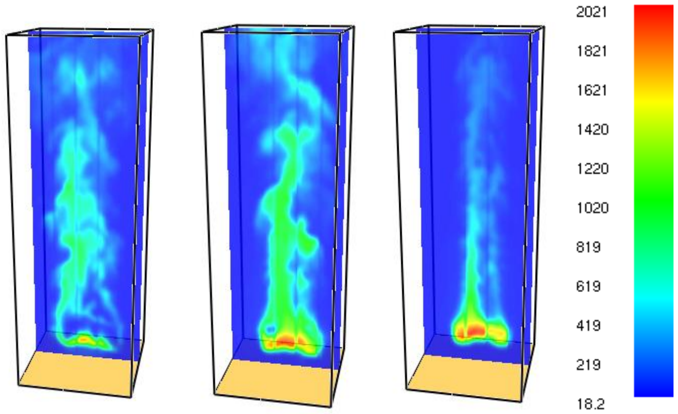

Figure 3: Temperature field in the middle plane (150 s, 200 s and 250 s) in the case of the ash

It can be seen that the temperature rise was high. The average temperature was above 1,000 °C at the entire middle plane. The temperature was the highest at 200 s when the trees were ignited completely. Then, the temperature started to decrease.
Aerosol ($PM_{2.5}$, PM_{10}) is one of the main pollutants in the air (Liua et al., 2018). The concentration of the aerosol and CO_2 at the top of the middle tree and at 59 m high is shown in Figure 4.

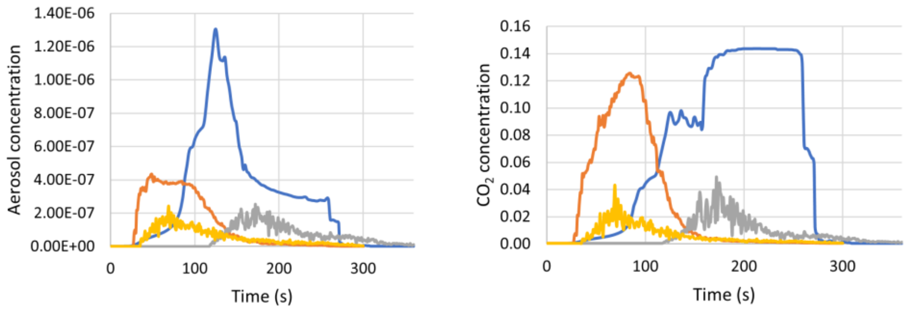

Figure 4: Aerosol concentration (left) and CO2 concentration (right) (blue: ash tree top, grey: ash tree at 59 m, orange: pine tree top, yellow: pine tree at 59 m)

It can be seen that the aerosol concentration was 0 in the first 30 seconds, then it started increasing fast to $1.3x10^{-6}$ above the tree and $2.6x10^{-8}$ at 59 m high. The recommended concentration in urban areas is 5x10-10. Therefore, it is a high pollutant concentration (MacLeod et al., 2010). After 125 s, it started to decrease when there remained less burnable material. The CO_2 concentration increased significantly, especially above the tree (above 14,000 ppm), which has a direct effect on climate change as a greenhouse gas (News European Parliament, 2023). It increased to 4,900 ppm at 59 m high. It is a concentration that might be harmful to people and might cause, for example, headaches and increased heart rate (Kane, 2023). Both the aerosol concentration and the CO_2 concentration were less in the case of the pine at the top of the tree, but it was more

or less the same at 59 m high. This can be explained by the conical shape of the pine tree, providing a decreasing amount of burning material as height increases.
To summarise the results, it can be concluded that all the trees burned down in a high-intensity fire. Burned trees generate ash, which has effects on the soil and the living world. Also, tree burning generates firebrands, which can ignite forests and buildings at a high distance (Wickramasinghe et al., 2022). The temperature reached 2,000 °C at the top of the middle tree and was above 1,000 °C in the entire middle plane. High temperature also has effects on the living world and allows fire to spread faster. The aerosol concentration reached a high pollutant value, which reduces the quality of the air. The CO_2 concentration also increased significantly, which contributes to climate change as a greenhouse gas.
As forest fires cause large environmental damage, as was concluded by this research, it is important to prevent them. With forest fire simulations, the spread of fire and the environmental damage can be analysed without dangerous and expensive field experiments. Thus, they can contribute to more effective fire prevention and firefighting. For example, with the help of fire spread simulation, a more effective firefighting strategy can be established. Simulation forecasts can help to prepare for a real forest fire and eliminate the caused damage more effectively. Moreover, sustainable forest management can be aided by prescribed fire simulations. Variables can be calculated in hardly measurable places. Therefore, a broader examination is also possible. The limitation of the simulation is that it is never exactly the same as the real world. Also, the computational cost of CFD simulations can be high, which means it takes much time to get accurate results. The mesh size also can affect the simulation results.
The novelty of the paper is that, according to our knowledge, it was the first paper that dealt with ash forest fire simulation. In most of the scientific literature, the numerical simulation of pine forests (Hoffman et al., 2012) or shrublands (Morvan and Dupuy, 2004) was carried out.

4. Conclusions

In this paper, the numerical simulation of an ash forest area was carried out. It was found that in the case of arson, the fire spreads quickly among the trees, and a high-intensity fire occurs. Therefore, the mass of the trees decreased fast, and the forest area was burned down in 4 minutes. The mass loss rate and the heat release rate increased fast after the first tree ignited, and after that, it decreased fast. The temperature at the top of the middle tree increased fast above 2,000 °C after the first tree ignited. The aerosol concentration was much higher, which is recommended in the urban area. Therefore, it is a high pollutant concentration. CO_2 concentration also increased significantly, which has a direct effect on climate change. The results were compared to a pine tree simulation, too. It could be observed that in the case of pine trees, phenomena occur faster, but the values are similar.
Forest fire modelling and computer simulation help to more precisely determine the environmental damage of forest fires. Therefore, the requirements of sustainability are also met. The results can be used during sustainable forest management. By planting more drought-tolerant tree species and vegetation, the spread of fire can be slowed down, and the environmental burden can be reduced.The rise in average temperature caused by global climate change affects the moisture content of forests and vegetation. Plants dry out more during sunny periods in the summer, so the fire spreads faster in certain vegetation areas. With the computer simulation, it is easier to determine the areas affected by the fire, which also helps fire prevention and firefighting. The further research task is to carry out the numerical simulation of a larger forest and to compare the results with real fire cases.

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