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NUMERICAL SIMULATIONS OF FLAMMABILITY EXPERIMENTS IN LITTER FUELS IN THE BRAZILIAN AMAZON

Paulo Bufacchi
Laboratory of Thermal and Environmental Engineering, Polytechnic School of the University of São Paulo, Av. Prof. Mello de Morais 2231, 05508-030, São Paulo, SP, Brazil
paulo_bufacchi@hotmail.com; paulo.bufacchi@usp.br

Guenther Carlos Krieger Filho
Laboratory of Thermal and Environmental Engineering, Polytechnic School of the University of São Paulo, Av. Prof. Mello de Morais 2231, 05508-030, São Paulo, SP, Brazil
guenther@usp.br

Abstract. *Numerical simulations of flammability experiments in litter fuels in the Brazilian Amazon are used to better understand the conditions under which surface fires spread or not. This is an important issue for those working with fire management and fire behavior modeling. There is a gap that needs to be filled, regarding a numerical model that is capable of representing the flammability of vegetative fuels. Surface fires, as natural phenomena, have intrinsic high variability. To study surface fires regarding their spread / no-spread condition, two scenarios were evaluated through the use of numerical simulation softwares. The fire spread scenario was well resolved by the two softwares used, although they have different ways to represent the natural phenomena. When simulating numerically the no-spread fire, both softwares misrepresent reality. To identify the reasons that directed to a numerical spread in a no-spread scenario, numerical simulations were carried out varying the input parameters by their standard deviation. From the point of view of spread / no-spread scenarios, numerically simulated fires are more likely to not spread if spatial non-homogeneities in litter distribution are taken into account, but more research is needed to confirm this hypothesis.*

Keywords: *Litter, Flammability, Numerical simulation, Heat release rate, Parametric variation*

1. INTRODUCTION

Wildland fire ignition has been debated for different fuels and weather conditions. Through the years, there have been many experimental fire behavior studies, accompanied by their own statistical model to predict if the fire spreads or not. Some studies refer to the probability of fire spreading in different vegetation types and configurations such as porous beds of woody fuels (Wilson Jr, 1985), while others are related to the fire ignition itself (Dimitrakopoulos and Papaioannou, 2001). There are also important works on live chaparral shrub fuels (Weise *et al.*, 2005; Zhou *et al.*, 2005), maritime pine stands (Fernandes *et al.*, 2008), mixed wood boreal forest surface fuels (Dickinson *et al.*, 2013) and the Brazilian rainforest litter (Krieger Filho *et al.*, 2017). The resulting statistical models fit specific fire environments. These models can adeptly represent data collected from a few types of vegetation under certain fuel and weather conditions, but they fail to represent fire propagation in different scenarios.

The question then is to answer if the fire spreads or not, given a fuel-weather condition. This answer is important for those working with fire management and fire behavior modeling. To the authors' knowledge, there is a gap that needs to be filled, regarding a numerical model that is capable of representing the flammability of vegetative fuels.

Surface fires in the Brazilian Amazon ecosystem are characterized by the burning of dead and undergrowth vegetation, such as herbs, leaf litter layer and twigs. Litters are a challenge for numerical simulation softwares, as the amount of fuel in the forest floor is usually low. To validate the numerical simulation software, laboratory and field experiments can provide reliable input data. Field experiments carried out by Krieger Filho *et al.* (2017) in the Brazilian Amazon collected a large amount of data that is used in this work as input information to the numerical simulations.

Therefore, the goal of this work is to use numerical simulation softwares to assess the fire spread / no-spread conditions in the Brazilian Amazon. Also, through the parametric variation of field measured variables, to contribute to the understanding of this complex phenomena.

2. FIELD EXPERIMENT

Details of the field experiment on which these simulations are based can be found in Krieger Filho *et al.* (2017). One of the major goals of the experimental work was to gather field information to be the input data to computer simulations. Therefore, the planning of the field experiment took into account all the important variables for numerical simulations.

Numerical models typically require a certain number of thermo-physical properties for the fuel bed. They need accurate measurement of litter variables, specifically height, bulk density, moisture content, initial temperature, and residue fraction. Litter bulk density ($LBD=m_{dry}/V_{litter}$) is estimated from the mass of dry vegetation and the volume of the litter, while dry basis litter moisture content ($LMC=(m_{wet}-m_{dry})/m_{dry}$) is estimated from the wet and dry litter masses. Mass of dry litter was obtained by drying the litter samples in an oven at temperatures around 60°C. Litter residue fraction is calculated by $LRF=m_{residue}/m_{dry}$, where $m_{residue}$ is the mass of residue after burning the litter.

Other important variables were also measured, such as ambient wind speed and time of fire spread. Four vane anemometers indicated a zero-wind speed in each experiment. Their range of measurement was from 0.4 to 30 $m.s^{-1}$. They were positioned 1.90 m from the center of the site, along each cardinal direction, at a height of 0.7 m. The height was chosen to avoid the influence of the in-draft air movement caused by the approximately 0.2 to 0.3 m high fire front. After the fire started, the ambient wind speed was taken at time intervals of 3 minutes by the four anemometers.

To measure the time of fire spread between two marks, type K thermocouples were installed in each mark. The first one was installed along a 0.4 m diameter circle from the ignition point, and the other at the experiment boundary (1.5 m). Fire rate of spread (ROS) was calculated based on the elapsed time for the fire to propagate outwards the ignition point, between the respective pairs of temperature sensors. Elapsed time was estimated from peak temperatures, as a result of the passage of the fire front.

Ignition started at the center of the experiment site by means of a small amount of ethanol poured inside a 0.1 m diameter area and ignited with a match. Ignition in the numerical model is a challenge, and it is important to represent it as close as possible to the actual ignition. Measurements of litter height were made in four areas close to the border of the planned burning site. Field experiment results showed that fire did not spread in thirty-seven experiments and spread in thirty-five.

3. OVERVIEW OF THE NUMERICAL METHOD

The numerical approach used to assess Amazon litter flammability is WFDS (Wildland-Urban Fire Dynamics Simulator), developed by the U.S. Forest Service in collaboration with the National Institute of Standards and Technology (NIST). The equations necessary for understanding the model behavior are described in Bufacchi *et al.* (2016).

WFDS uses methods of computational fluid dynamics (CFD) to solve three-dimensional time-dependent equations, which governs fluid flow, turbulent combustion, and heat transfer. The numerical model relies on a large-eddy simulation (LES) approach to provide numerical solution to the governing transport equations for mass, momentum, and energy. The simulations use a structured Cartesian staggered grid, for which spatial discretization is second-order accurate. The continuity equation is solved simultaneously with the Stokes form of the momentum equations. The momentum equations are advanced using a two-stage projection scheme based on the explicit modified Euler method. Species mass equations are advanced using a modified version of a predictor–corrector scheme. The subgrid heterogeneity of species concentrations and temperature is treated in conjunction with the reaction, heat transfer, and radiation intensity models.

The condensed phase model is composed of fixed, uniformly distributed within the bulk volume, thermally thin, optically black, subgrid fuel elements. More than one type of thermally thin element can be represented, but in the numerical simulations in this work only one element type was represented. Temperature can be assumed to be uniform throughout thermally thin fuel elements. As the temperature of the fuel elements increase, moisture content is removed first, followed by pyrolysis. The endothermic process of pyrolysis is responsible for the generation of fuel vapors. The two-stage endothermic decomposition process (water evaporation followed by vegetative fuel volatilization) results in a mass loss of vegetative fuel. The model for moisture evaporation and fuel thermal degradation uses Arrhenius equations. The fuel volatilization model is based on thermogravimetric analysis. Pyrolysis residue oxidation is modeled, so smoldering combustion is accounted for.

Both convective and radiative heat transfer between the gas phase and the vegetation are accounted for, as is the drag of the vegetation on the airflow. The vegetation removes momentum from the gas through a drag force per unit volume. The value of the drag coefficient CD depends on the local Reynolds number.

Fires from vegetative fuels are soot-laden. It is assumed that, as the radiation spectrum of soot is continuous, the gas behaves as a spectrally independent or gray medium. A soot evolution model is not used. In its place, the mass of soot generated locally is assumed as a fraction of the mass of fuel gas consumed by the combustion process.

Turbulent combustion for the gaseous phase is modeled based on the Eddy Dissipation Concept (EDC) model. The effect of thermal expansion enters the computation through an elliptic constraint, derived using the energy equation, on the velocity field. This is because of chemical reaction and mass and heat transfers. The local average temperature is then obtained via the ideal gas equation of state. Dissipation of kinetic energy is achieved through a simple closure for the turbulent stress: the constant coefficient Deardorff model. The turbulent transport of mass and heat is accounted for by use of constant turbulent Schmidt and Prandtl numbers, respectively.

4. RESULTS AND DISCUSSION

4.1 Spread and no-spread fires

Numerical simulations were initially run considering two scenarios: one for fire spread and another for no-spread. Each scenario was built considering the average value for each variable measured in the field experiments. Mean and standard deviation data for the spread and no-spread conditions are presented in Table 1, for each of the input variables to the numerical model. There is a minor difference on the mean values of the litter moisture content between the two setups. As moisture content is an important variable for the spread / no-spread determination, the numerical model results may not differ between the two scenarios if based only on the moisture content. Although litter bulk density and litter height mean values differ by 53% and 125% respectively, their standard deviations are high enough to prevent differentiation between spread and no-spread scenarios. Litter temperature is not a relevant parameter for the numerical model on the range of temperatures presented and will not be discussed afterwards.

Table 1. Field experiment measured variables: mean and standard deviation values for spread and no-spread scenarios

	Litter moisture content [-]	Litter bulk density [kg.m^{-3}]	Litter height [cm]	Litter temperature [°C]
Fire no-spread scenario				
Mean	0.28	30.51	1.6	29.4
Standard deviation	0.07	12.88	0.5	1.3
Fire spread scenario				
Mean	0.26	19.93	3.6	28.7
Standard deviation	0.05	11.07	1.9	1.3

The numerical simulations were run with a 12-mm mesh size on a cubic domain 1 m large. As the flame height in the field experiments was around 0.2 to 0.3 m, the domain height of 1 m was found to be enough to represent well all the processes involved. The vegetation represented in the numerical simulation was narrower than the domain length, to avoid interference of the domain boundaries in the results. As the process of discretizing the transport equations generates errors that are proportional to the size of the mesh cell, a sensibility study was carried out. For both scenarios studied, spread and no-spread fires, cell size of 12 mm provides mesh independent results. This is in agreement with other study in the Amazon forest (Bufacchi et al., 2016).

As a result of the discussions on the data presented on Table 1, numerical simulations were not able to precisely reproduce all experimental results. The numerical simulation correctly represents the spread scenario. The mean experimental ROS is 0.151 m.s^{-1}, while the simulated ROS is 0.148 m.s^{-1}. For the no-spread scenario, the numerical simulation predicts a fire spread. Although ROS and the heat release rate (HRR) are low if compared to the spread scenario, numerical result is not in agreement with field experiments.

In an attempt to identify the reasons that directed to a numerical spread in a no-spread scenario, and to assess the spread scenario, numerical simulations were carried out varying litter moisture content, bulk density and height by their standard deviation. Only one variable was changed in each numerical simulation, the others remaining constant. This way, for each scenario, six numerical simulations were run. Results of the parametric variation on ROS is shown on Table 2.

Table 2. ROS for each parametric analysis and percentage variation to ROS mean value for fire spread scenario

	Litter moisture content [-]		Litter bulk density [kg.m^{-3}]		Litter height [cm]	
Variable ± standard deviation	0.21	0.31	8.86	31.00	1.7	5.5
Percentage variation to variable mean value	-19	19	-56	56	-53	53
Fire spread scenario						
ROS (cm.min^{-1})	17.4	12.7	19.5	10.8	9.6	17.5
Percentage variation to ROS mean value	18	-14	32	-27	-35	18

Bulk density has the greatest standard deviation of the three variables, although it is close to litter height variation. It is worth noting that bulk density is equal to litter height times litter load. A variation of ±56% in litter bulk density causes ROS variation from -27% to 32% of its original simulated value.

Litter height variation (±53%) caused ROS to vary from -35% to 18% of its original simulated value. Results show that litter height plays a more important role when its value gets smaller (1.7 cm), as the impact on ROS is greater. Nevertheless, it is necessary 53% variation in litter height to promote a ROS variation of 35%.

Litter moisture content presents the lowest standard deviation of all parameters (19%). As such, variation in ROS because of the variation in moisture content is smaller, from -14% to 18% of original simulated ROS value. The numerical simulated results indicate that ROS percentage variation is approximately the same as moisture content percentage variation.

Its is important to notice that a decrease in litter moisture content and bulk density causes an increase in ROS, while a decrease in litter height causes a decrease in ROS. Impact on ROS because of a unit variation in litter height and bulk density is approximately the same. On the other hand, impact on ROS because of a unit variation in litter moisture content is almost double when compared to litter height and bulk density.

For the no-spread scenario, fire did not spread only when the value of bulk density was one standard deviation below its mean value. For all other variables variation by one standard deviation, the fire spreads. There are some variations around the no-spread mean values that would cause the simulated fire to not spread. The key point is to assess if the problem is on the numerical simulation software or if there is a parameter that was present in the field experiments and was not evaluated, which can make a difference in the numerically simulated results. Data collected in the field were carefully measured, and field experiment planning was thoroughly evaluated. For this reason, field data are considered to be precise enough to not cause any inexact result obtained from the numerical simulation software.

On the other hand, a parameter that was present in the field experiments and was not evaluated is the spatial non-homogeneity of the litter, as seen in Fig. 1.

Fig. 1. Litter non-homogeneity: (a) general view of the forest floor, showing fallen trunks and branches along with areas of uneven litter; (b) no-spread fire, probably because of uneven litter distribution; (c) and (d) detail of litter inside a 0.5 m square frame, showing regions of missing vegetation.

Although the no-spread scenario used the average values of the measured parameters, it does not mean that they are homogeneous in the actual scenario, as seen in Fig. 1. Considering that the average value of the bulk density can vary along the numerical domain, as may happen in the field experiments, and that 40% of its original mean value can be randomly located around the ignition point, numerical simulation results show a no-spread fire. In the field, the no-spread fire experiments were characterized by a short fire spread followed by fire self-extinguishment.

As a numerical model is a representation of the actual processes taking place in the field, some modelled processes may not fully represent the actual experiments. To compare the no-spread results of the physical numerical model used, the same scenarios were run in another numerical model – BehavePlus, which is a collection of mathematical models that describe fire behavior, fire effects, and the fire environment. Results showed that BehavePlus also presents a spread fire in the no-spread scenario. Furthermore, when simulating the thirty-seven no-spread experiments, BehavePlus results show a spread fire in all cases it was able to run. BehavePlus can only run cases where litter height is greater than 1.52 cm, but there were scenarios where litter height was 1 cm. According to BehavePlus fire also spreads when bulk density value is 40% of its original value and when bulk density takes its mean value minus one standard deviation, in which cases WFDS results shows a no-spread fire.

To assess the importance of each variable in the spread scenario, parametric variations of litter height, moisture content and bulk density were run in WFDS, spanning the value of plus or minus one standard deviation. Results of the parametric variation are shown in Fig. 2. Trendlines of numerical simulation results for litter height, moisture content, and bulk density present a good agreement, as R squared is higher than 0.9845. All curves are second order polynomials.

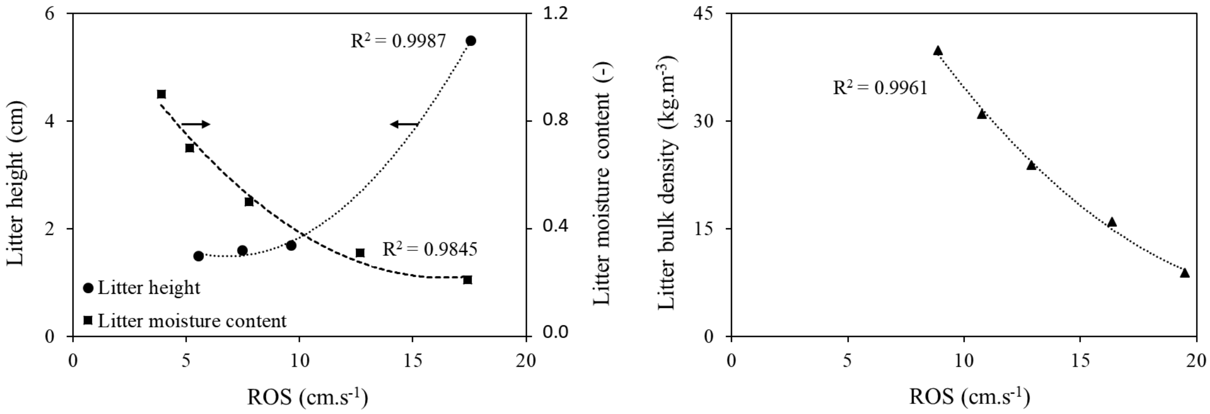

Fig. 2. Parametric variation of litter height, moisture content and bulk density for the fire spread scenario.

Litter height data shows that ROS gets smaller as litter height decreases, and there is a value for litter height that prevents fire from spreading. Numerical simulation for litter height of 1.3 cm showed a no-spread fire. Fire also does not spread when bulk density and moisture content are high.

4.2 Gas phase combustion HRR

HRR is a significant parameter for understanding the combustion process in fires and an important output from the numerical simulations. HRR analysis provides insightful information as shown in Fig. 3, which presents HRR generated by gas phase combustion as a function of time to completely burn the litter in the numerical domain. The fire spread scenario is represented by experiments mean values, along with the variations of each parameter with plus or minus one standard deviation.

The first information that can be retrieved from Fig. 3 is the relative ROS for each run. When HRR goes to zero, all litter has been burned, and the shortest the time, the fastest the spread rate. The lowest litter bulk density has the highest ROS, and the smallest litter height has the lowest ROS, which is in accordance with Table 2.

Another important information from Fig. 3 is that the highest ROS scenario does not have the highest HRR peak value. The highest litter height has the highest HRR peak, followed by the smallest moisture content and the highest bulk density, both with approximately the same HRR peak but in different times. This is shown in Table 3.

The area under each curve in Fig. 3 represents the total heat released in the fire spread. The highest heat release occurs when the litter height takes its maximum value (5.5 cm), as seen in Table 3. The highest bulk density (31.00 kg.m^{-3}) has the second largest heat release, corresponding to 90% of the maximum litter height value. The heat release from the lowest moisture content (0.21) scenario comes third and represents 68% of the maximum litter height value. The lowest heat releases are for the smallest litter height (1.7 cm) and smallest bulk density (8.86 kg.m^{-3}), in that order.

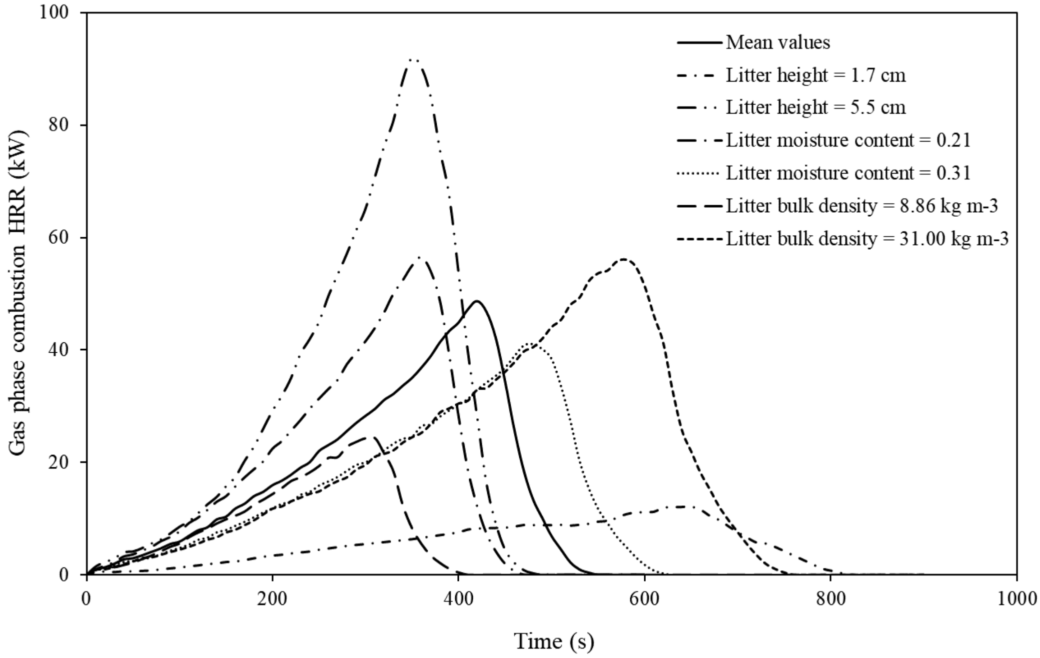

Fig. 3. HRR generated by gas phase combustion as a function of time to completely burn the litter in the numerical domain.

A higher heat release is obtained when there is more fuel to burn, which is the case of higher litter height and bulk density, as shown in Table 3. For the litter moisture content scenarios, where there is no variation in fuel content, energy is partially used to evaporate water from moisture, so that the net heat released is higher for the smallest moisture content scenario.

Table 3. HRR peak and total heat released in gas phase combustion for fire spread scenario

	Litter moisture content [-]		Litter bulk density [kg.m^{-3}]		Litter height [cm]	
Variable ± one standard deviation	0.21	0.31	8.86	31.00	1.7	5.5
Fire spread scenario						
HRR peak – gas phase combustion (kW)	57.1	41.7	25.1	56.6	12.3	93.6
Total heat released (kJ)	130.1	109.2	56.9	172.7	48.3	192.6

4.3 Solid phase smoldering combustion HRR

Another source of heat release refers to the solid phase smoldering combustion. As volatile products from vegetation pyrolysis go to the gas phase, a solid phase composed of char and inorganic matter remains in the forest floor. Char is an organic matter that undergoes smoldering combustion, and char oxidation HRR peak and total heat released for the entire computational domain are presented in Table 4.

Table 4. HRR peak and total heat released in solid phase smoldering combustion for fire spread scenario

	Litter moisture content [-]		Litter bulk density [kg.m^{-3}]		Litter height [cm]	
Variable ± one standard deviation	0.21	0.31	8.86	31.00	1.7	5.5
Fire spread scenario						
HRR peak – solid phase smoldering combustion (kW)	1.99	1.44	0.76	2.15	0.18	3.80
Total heat released (kJ)	13.94	14.83	3.45	37.93	2.29	30.34

For the fire spread scenario, time history curves for char oxidation HRR for varying values of litter height, moisture content and bulk density are presented in Fig. 4. The continuous line in each graph refers to the case of mean values of the variables. The discussion for gas phase combustion HRR is also valid for solid phase HRR.

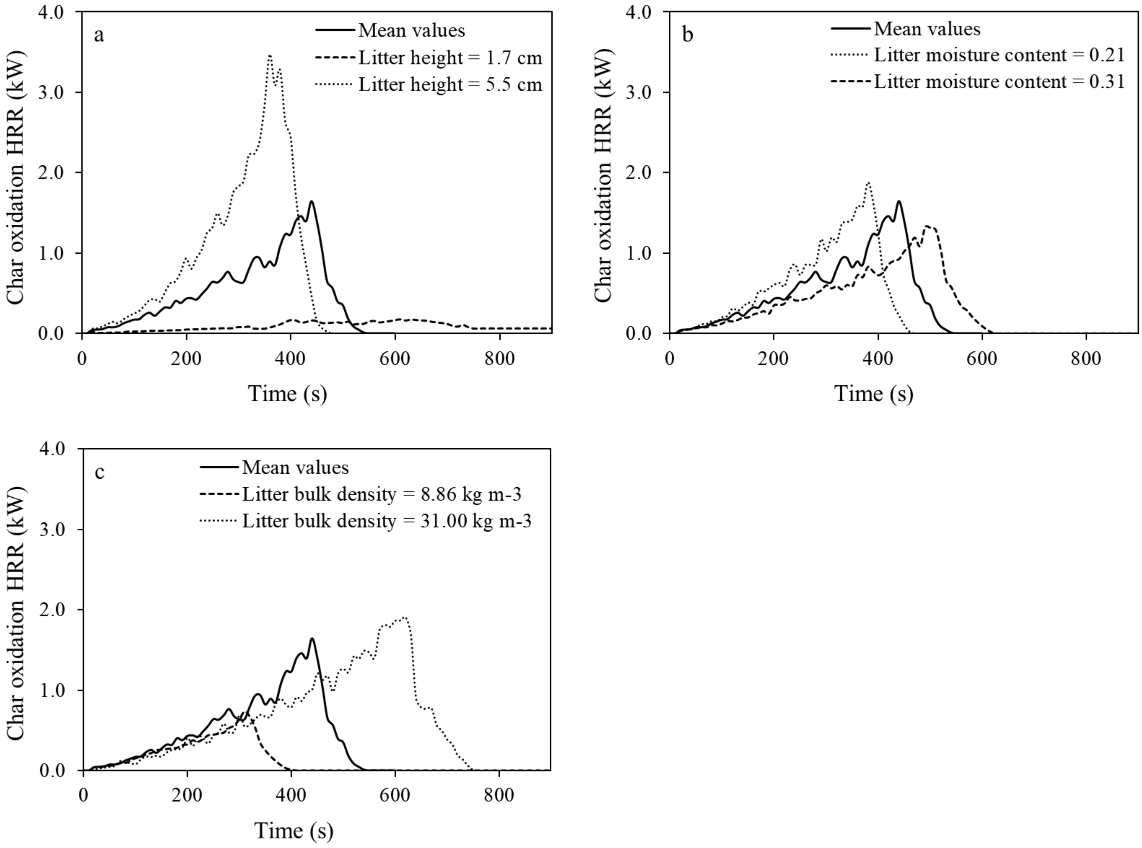

Fig. 4. Char oxidation HRR for the mean parameter values and for each of the parametric cases of the fire spread scenario: (a) litter height, (b) litter moisture content and (c) litter bulk density.

Comparing Tables 3 and 4, it is clear that gas phase combustion has a much higher HRR than char smoldering combustion, as shown in Fig. 5. This happens because the amount of char produced according to the numerical simulation is very low, as shown in Fig. 6.

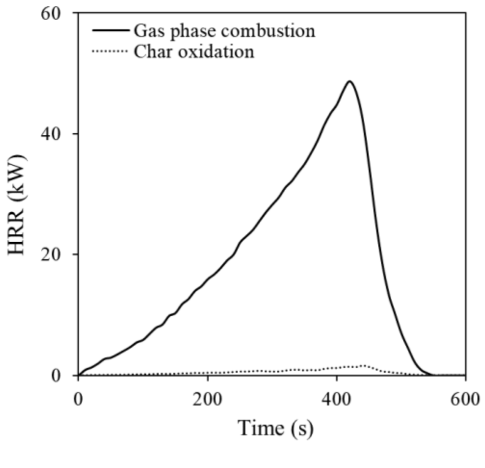

Fig. 5. HRR generated by gas phase combustion and char oxidation as a function of time to completely burn the litter in the numerical domain, for the mean parameter values in the fire spread scenario.

4.4 Mass loss time history

Mass loss time history curves for dry matter, moisture, char and ash of the fire spread scenario is shown in Fig 6. Curves represent the mean fire spread scenario. Char and ash masses are very low, which reflects in a high volatile matter obtained from pyrolysis.

The average dry mass loss time histories for the fire spread scenarios are plotted in Fig. 7. The litter masses are calculated by multiplying the litter bulk density by the litter height and the area of the litter domain in the numerical simulation.

For the cases where litter height and litter bulk density are the smallest, the initial mass is lower. The opposite is valid when litter height and litter bulk density are the highest. Comparing Fig. 7 and Fig. 3, it can be seen that the steepest the mass loss curve in Fig. 7 (the greatest the mass loss rate), the higher the HRR peak value in Fig. 3. The mass loss curve for litter height of 5.5 cm is the steepest curve, and its HRR peak is the greatest. On the other hand, the mass loss curve for litter height of 1.7 cm is the less inclined curve, and its HRR peak is the smallest.

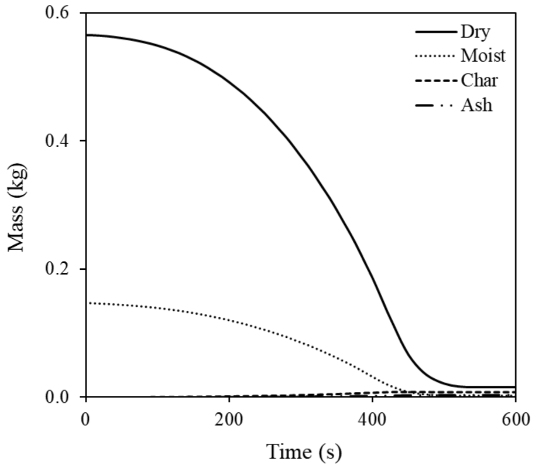

Fig. 6. Mass loss time history curves for dry matter, moisture, char and ash of the fire spread scenario.

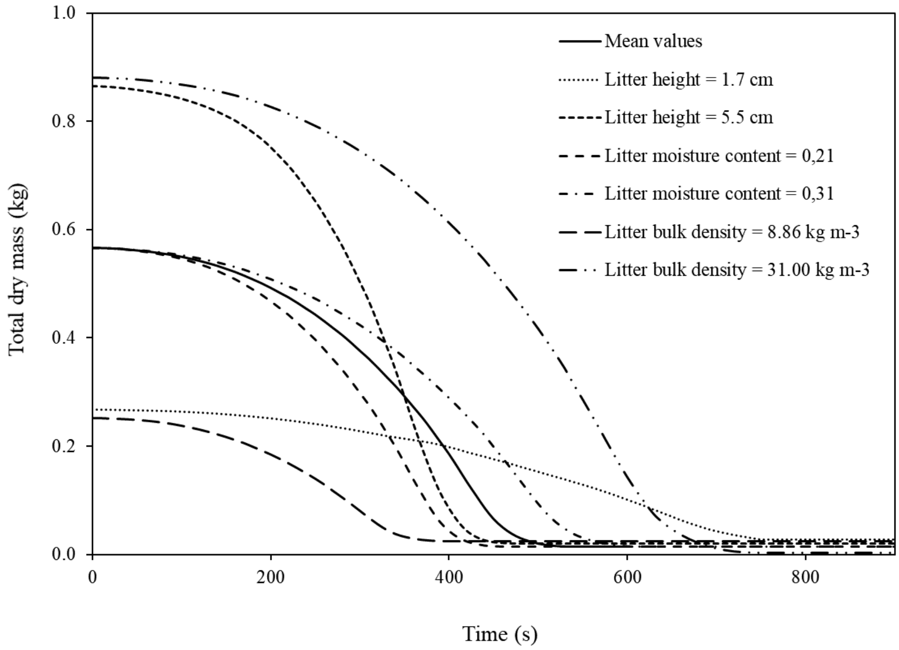

Fig. 7. Mass loss time history curves for each of the parametric cases of the fire spread scenario.

At the end of the domain, when vegetation burning is complete, the amount of dry matter left is minimal, ranging from 0.003 kg to 0.028 kg, as seen in Fig. 6 and 7. Char formation in the domain is detailed in Fig. 8, which shows a growth in char mass as pyrolysis proceed.

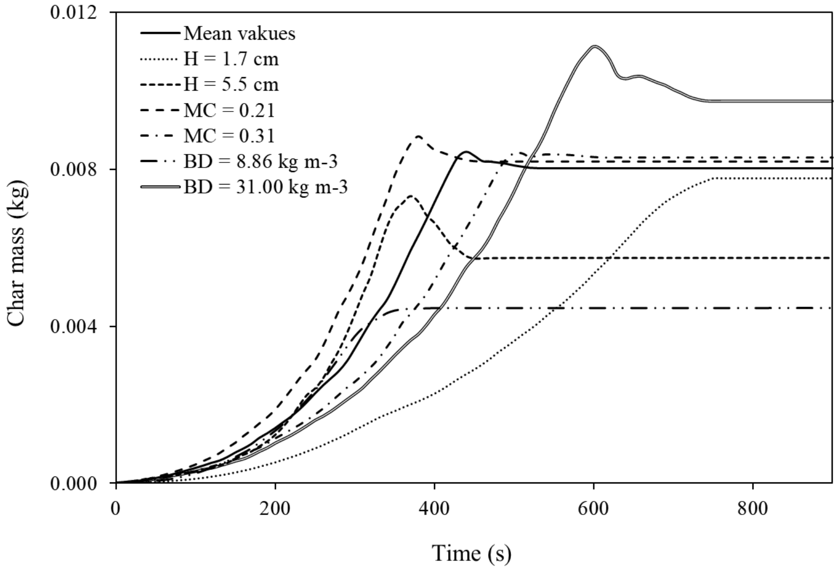

Fig. 8. Char mass formation time history curves for each of the parametric cases of the fire spread scenario.

4.5 Radiation and convection heat transfer

Both radiative and convective heat transfer between the gas phase and the vegetation is accounted for in WFDS. Radiation and convection HRR time history curves for the fire spread scenario are shown in Fig. 9.

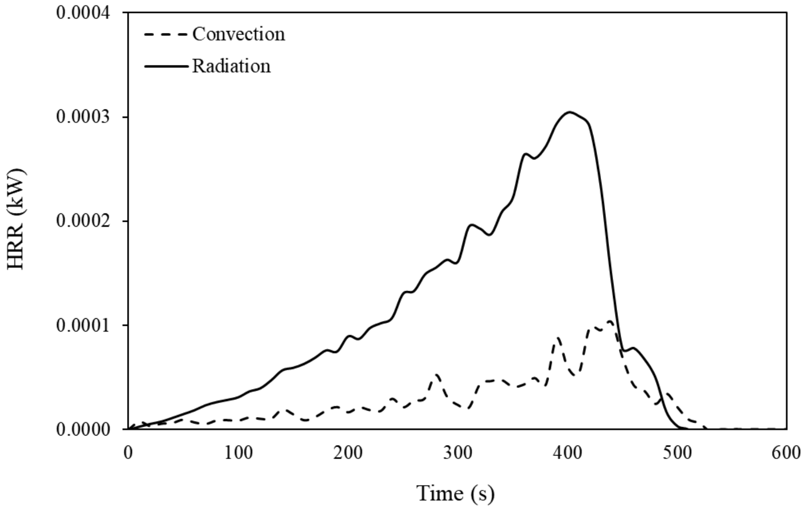

Fig. 9. Radiation and convection HRR between the gas phase and the vegetation, for the mean parameter values of the fire spread scenario.

In this work, radiation is a more important process than convection. The reason is the absence of wind inside the Amazon forest near the ground, as observed by field measurements. Radiation HRR peak occurs at 400 s, close to the litter domain boundaries. Convection HRR peak value occurs at the same time as the char oxidation HRR.

Radiation in the gaseous phase corresponds to 37% of total HRR, being much higher than radiation HRR in the solid phase.

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