Sub Topic: Fire

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A computational study on the fire merging of burning chamise shrubs

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Abstract: The burning of nine, one-meter tall chamise shrubs with a maximum shrub diameter of 0.7 m, placed in a 3×3 horizontal array arrangement was simulated using WFDS (Mell et al. 2009). All shrubs were simultaneously ignited from their bases by individual ignition zones located on the ground beneath the shrubs. Several simulations were performed by varying the shrub separation distance from zero to the maximum shrub diameter. The burning characteristics of the shrubs were examined for the conditions of no wind and a wind speed of 1 m/s. For the no wind condition, the peak mass loss rate of the shrub situated at the center of the array was found to be significantly higher than the rest of the shrubs. This finding indicated the heat feedback enhancement to be dominant and thereby caused the center shrub to burn intensely and exhibit fire merging. On the other hand, in the presence of wind, the shrub positioned in the middle of the array edge in the downstream direction exhibited the highest peak mass loss rate. This behavior was attributed to the tilting of flames in the downstream direction influenced by wind and thereby enhancing the heat feedback from the flames of the upstream shrubs. For a separation distance equal to the maximum shrub diameter, the effect of heat feedback was significantly reduced and the shrubs exhibited a burning behavior akin to that of an isolated, single shrub.
***Keywords:* Wildland fire, Fire merging, Chamise Shrubs, WFDS**

1. Introduction

The recent occurrences of significant fire activity, such as the 2018 Woosley and the Camp fires in the western part of the United States, specifically parts of California, have prompted growing concerns of fire risk in these regions. The shrub lands or the chaparral in the western United States, comprising of plant species such as chamise, sagebrush and manzanita, are often found to be highly flammable and support vigorous fires. The chamise species, as a major component, is found to exist over large contiguous areas. While the presence of resinous foliage and leaf litter enhances the ignitability of these species, intense Santa Ana winds, rugged topography, and the proximity to residential structures pose a grave and challenging wildland fire threat [1].

Interactions among multiple fires commonly occur in terrains composed of contiguous fuel elements, leading to mass fires with high spread rates. In this regard, Padhi et al. [2] and Dahale et al. [3] have performed physics based modeling to study the interaction among multiple adjacent chamise shrub fires. Dahale et al. [3] studied the fire interaction between chamise shrubs, placed in two-shrub and three-shrub arrangements, for various separation distances under still air conditions. They found that for the three shrub arrangement case with zero separation distance, the flames from the individual shrubs interacted strongly, displaying an almost unified flame whereas the two shrub arrangement did not exhibit strong flame merging. Padhi et al. [2] observed interaction of flames form a mass fire for a similar arrangement in the presence of wind. However, owing to the ambient wind condition, the flames were tilted and the upstream shrubs were found to burn vigorously due to an enhanced heat feedback mechanism.

Motivated by the findings of Padhi et al. [2] and Dahale et al. [3], the aim of the current work is to study the interaction of flames in multiple chamise shrubs placed in an array for varying shrub separation distances subjected to wind. Here, the size of array is larger than that of the previous works.

2. Computational Setup

The physics-based computational model, WFDS [4] was utilized to study the burning characteristics of multiple chamise shrubs placed in a 3×3 array. The burning characteristics were studied for shrubs separated by a distance ranging from zero to maximum shrub diameter. All shrubs were simultaneously ignited from their base by individual ignition zones located on the ground beneath the shrubs. The computational domain was 6.4 m$\times$4.8 m$\times$4.8 m along the x, y, and z directions. Simulations were performed with a uniform grid of 320$\times$240$\times$240 along these three directions. A schematic of the shrubs arranged in the computational domain as viewed from the top is illustrated in fig. 1. A dimensionless separation distance [2, 3] was used to characterize the spatial locations of shrubs by which the complex spatial variations of burning rates, under different conditions, were analyzed and physically interpreted. For the no wind cases, the entire computational domain was initialized with zero velocities. Open boundary conditions, wherein gradients normal to boundary are set to zero, were implemented for all except the bottom boundary. A closed boundary condition was used for the bottom, i.e. no inflow or outflow can take place through this boundary. For the wind cases, the vertical left boundary was imposed with a wind speed of 1 m/s along the x direction. The crown fuel comprised of two components, branches and foliage, constituting 53% and 47% of the total mass of the shrub, respectively [2, 3, 5]. The height of the crown fuel was 1 m with a maximum diameter of 0.7 m and 0.65 kg in mass. The bulk densities of foliage and branches were 2.05 kg/m^3 and 1.82 kg/m^3, consistent with the measurements reported by Li [6] and Li et al. [7]. The physical properties of foliage were 500 kg/m^3, 8000 m^{-1}, 28.60% and 3.50% for the fuel particle density, surface to volume ratio, char content and ash content, respectively. The corresponding properties for the branches were 600 kg/m^3, 1800 m^{-1}, 15.40% and 0.50%, respectively. The foliages and the baranches were assumed to have a dry-basis fuel moisture content of 10%. This low fuel moisture content, more typical of dead fuel, was utilized to enhance the possibility of flame interactions.

3. Results and Discussion

The temporal evolution of the total mass of the individual shrubs for dimensional separation distance, $d^* = 0, 0.25, 0.5, 0.75$ and 1.0 are shown in fig. 2. The temporal evolution of the shrub mass for an isolated single shrub case is also shown for comparison. The isolated single shrub was positioned at the center of the domain (location of shrub-5). The shrubs may be categorized into three groupings - center, corner, and center of edge shrubs. It was observed that, for $d^* = 0$, the remaining total mass of the center shrub (shrub-5) after burning was significantly lower than the rest of the shrubs. This indicated that the heat feedback enhancement experienced by the center shrub was dominant and involved intense burning and remarkable dynamic behaviors such as fire merging. On the other hand, the four corner shrubs (shrubs-1,3,7 and 9) had the highest remaining shrub mass since they had the least number of neighboring shrubs and hence received less heat. Finally, the shrubs positioned at each center of edge of the array (shrubs-2,4,6 and 8) experienced higher burn out than the corner shrubs and lower burn out in comparison to the center shrub (shrub-5). A similar trend was observed when the separation distance was varied from 0.25 to 1.0. However, it is noted that the difference in the temporal evolution of mass loss in the individual shrubs became smaller with increasing separation distance, although the relative behavior of the three groups of shrubs persisted. For $d^* = 1$, the heat feedback enhancement was not significant and except the center shrub, the rest of the shrubs did not exhibit a significant difference in the temporal evolution of mass. Hence, the remaining total mass of the rest of the shrubs compared closely with that of the single isolated shrub.

The time history of mass loss rate obtained from computations for each individual shrubs in 3×3 array with increasing separation distance is shown in fig. 3 and compared against each other. The time evolution of mass loss rate for an isolated single shrub case is also shown in fig. 3 (f). Here, it is observed that the maximum mass loss rate for the center shrub is significantly higher than the isolated single shrub and the individual shrubs at all separation distances investigated. For instance, at a separation distance of $d^* = 0$, the maximum mass loss of the center shrub occurs approximately 5 s prior to that of the isolated shrub case with maximum mass loss rate being 21.4% higher. Furthermore, this maximum mass loss rate is higher by 34.2% and 59.4% of the maximum mass loss rate of the corner shrubs and those shrubs positioned at the center of the edge in the array, respectively. It is interesting to note that with increasing separation distance (specifically $d^* = 1$), the temporal evolution of the mass loss rate of all shrubs positioned at the edges is almost identical. To better illustrate this behavior, the maximum mass loss rate as a function of separation distance is shown in fig. 4. Here, it is seen that as separation distance increases to 1, the maximum mass loss rate observed for all individual shrubs positioned at the edges lie within a margin of 8% of one another. The overall trend of the maximum mass loss rate of the edge shrubs increases with increasing separation distance. On the other hand, due to a reduction in the heat feedback, the maximum mass loss rate of the center shrub decreases with increasing separation distance.

An observation concerning the effect of shrub separation distance on fire evolution can be made by examining the time variation of the heat release rate per shrub, shown in fig. 5 for various separation distances. Since the overall heat release rate is significantly larger for the case with nine shrubs, it makes sense to divide the overall heat release rate by the number of shrubs when quantifying the effect of multiple shrubs in contrast to an isolated shrub. Time variation of the heat release rate for isolated single shrub case is also shown for comparison. From fig. 5, it can be seen that the maximum heat release rate per shrub increases with increasing separation distance. It can also be observed that the maximum heat release rate is the highest for the single shrub case. Thus, although some individual shrubs burn vigorously as noted in discussions associated with fig. 3, the overall effect of a cluster of shrubs burning together is a reduction in burning rate on a per shrub basis in comparison to the burning of an isolated shrub under similar conditions.

Simulations were also performed to study the burning behavior of the shrubs in the presence of wind with a speed of 1 m/s along the x direction. In fig. 6, the total mass evolution of the individual shrubs is shown for two separation distances. Here, unlike the no wind cases, it is observed that the shrub positioned at the center of the edge of the array in the downstream direction (shrub-6), burns most vigorously. It also had the least remaining total mass with a corresponding maximum mass loss rate fig. 7. This behavior was observed because the ambient wind affected the flames by tilting it in the downstream direction and enhancing the heat feedback from the upstream shrubs. Finally, from fig. 8 it is evident that clustering observation noted in connection with the situation under no wind holds in this case for a wind speed of 1 m/s. This observation requires more detailed analysis.

4. Summary and Conclusions

The fire merging behavior caused by multiple burning 1 m tall chamise shrubs placed in a 3×3 array arrangement was studied in this work. Computations were performed for varying separation distances and for conditions of no wind and wind speed of 1 m/s. For both the wind cases, the fire merging/mass fire was most significant for zero shrub separation distance. With an increase in shrub separation distance, the individual shrubs burned akin to that of an isolated, single burning shrub. In absence of wind, the shrub positioned at the center of the array exhibited a significant peak mass loss rate due to the heat feedback enhancement from all of the neighboring shrubs. For the simulations with a wind speed of 1 m/s, the flames were significantly tilted and the shrub positioned in the center of the array in the downstream direction was observed to burn vigorously. This indicated the enhancement of heat feedback from the flames of the upstream shrubs in the presence of wind.

Acknowledgements

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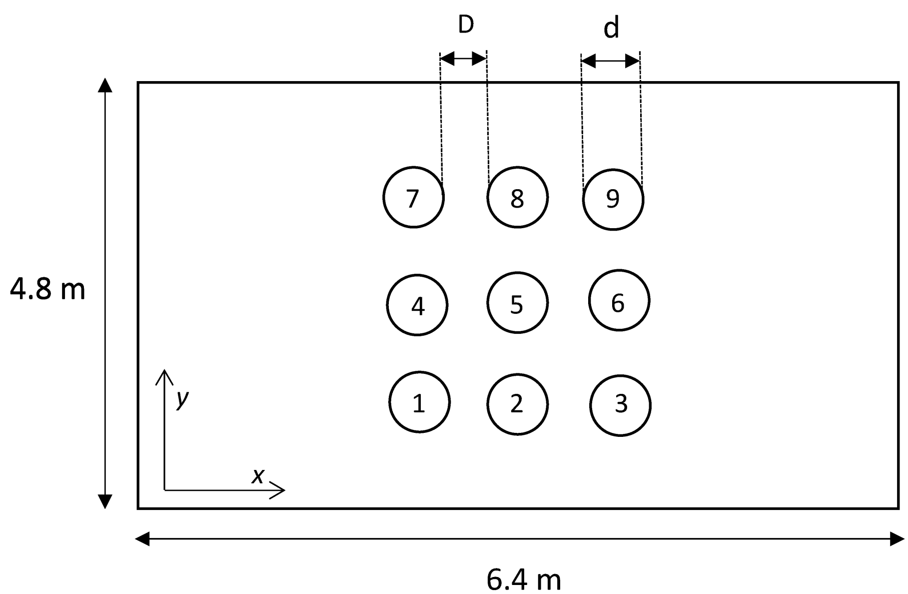
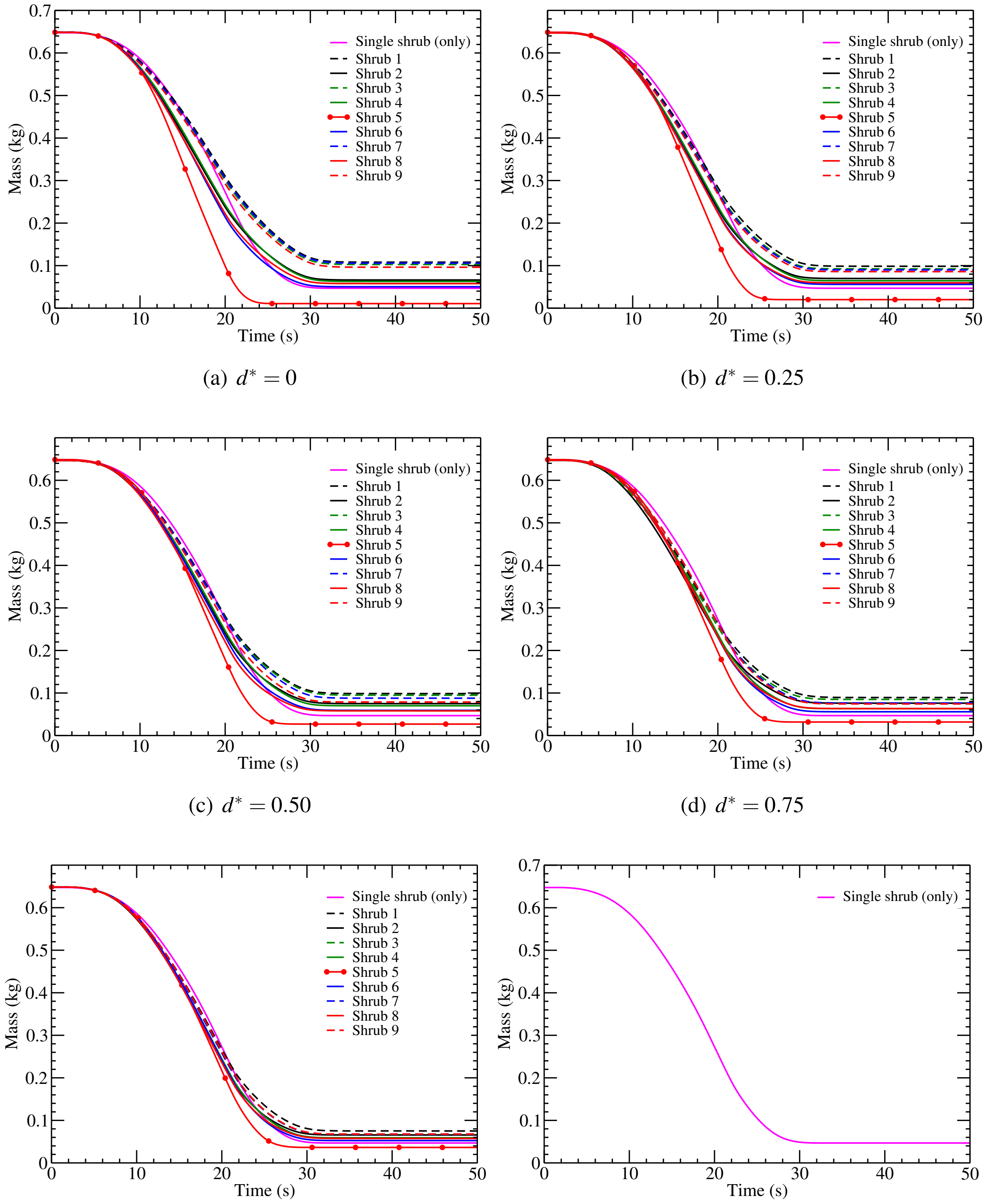


Figure 1: Schematic of the 9 shrubs placed in a (3×3 array) in the computational domain, 6.4 m in x, and 4.8 m in y direction. The shrubs are numbered 1-9, starting from the lower left and sequentially moving to the right and up. Note, dimensionless separation distance, $d^* = D/d$.



(a) $d^* = 0$

(b) $d^* = 0.25$

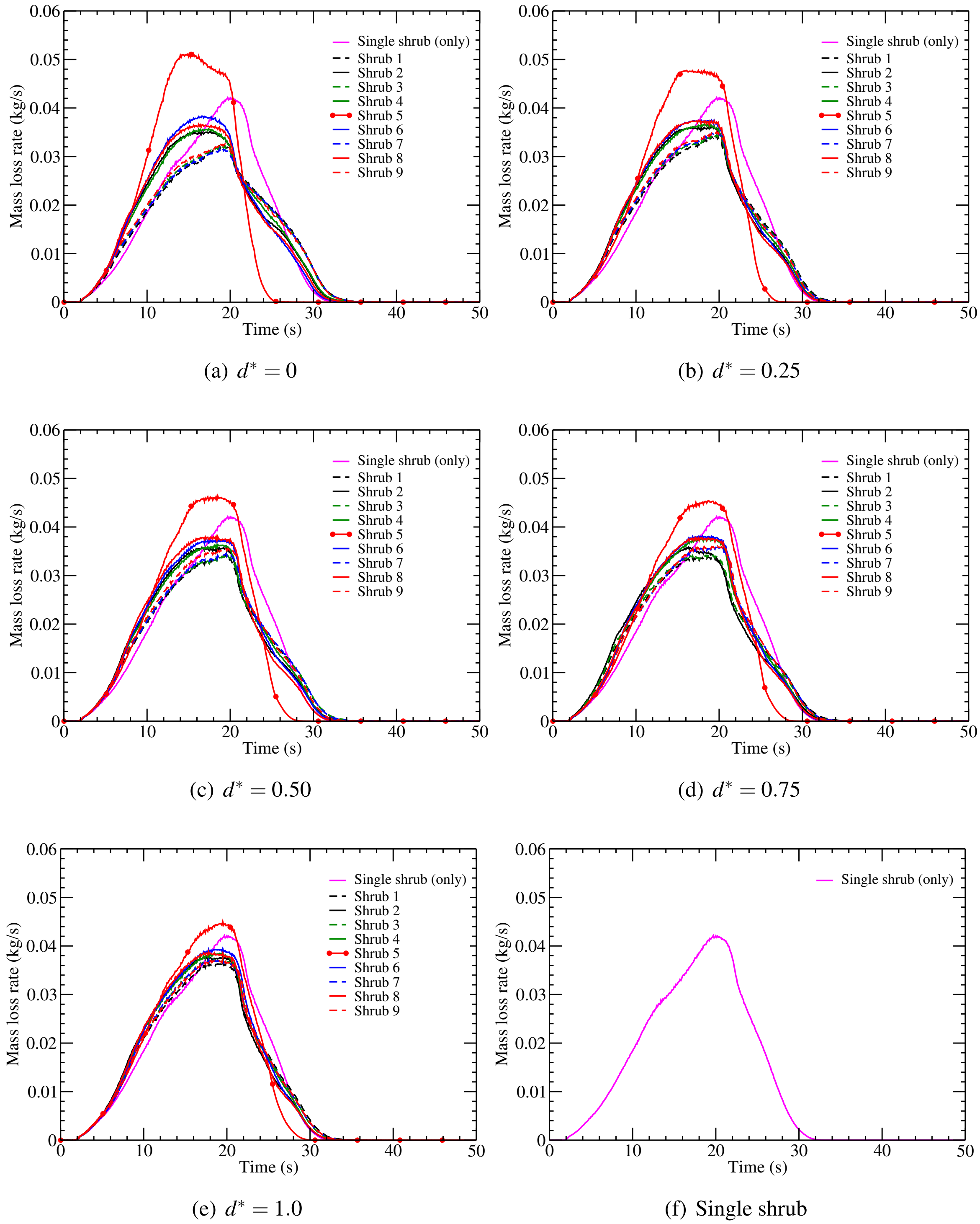
(c) $d^* = 0.50$

(d) $d^* = 0.75$

(e) $d^* = 1.0$

(f) Single shrub

Figure 2: Temporal evolution of mass of the individual shrubs (3×3 array) with increasing separation distance ($d^* = 0$ to $d^* = 1.0$) and the reference single shrub, for zero wind speed.



(a) $d^* = 0$

(b) $d^* = 0.25$

(c) $d^* = 0.50$

(d) $d^* = 0.75$

(e) $d^* = 1.0$

(f) Single shrub

Figure 3: Temporal evolution of the mass loss rate of the individual shrubs (3×3 array) with increasing separation distance ($d^* = 0$ to $d^* = 1.0$) and the reference single shrub, for zero wind speed.

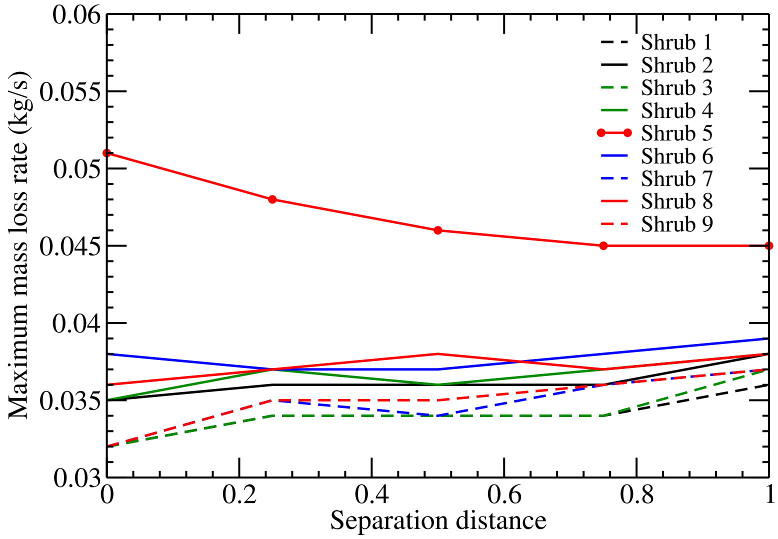


Figure 4: Comparison of the maximum mass loss rate for the 9 shrubs with increasing separation distance, for zero wind speed.

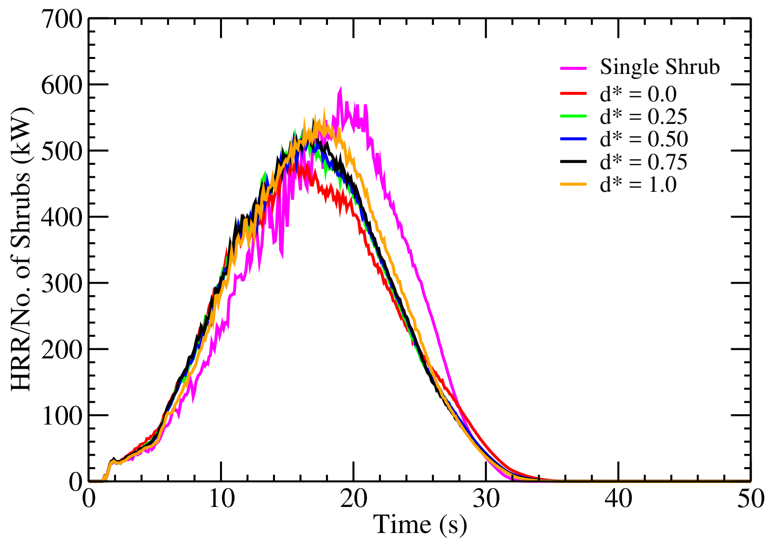
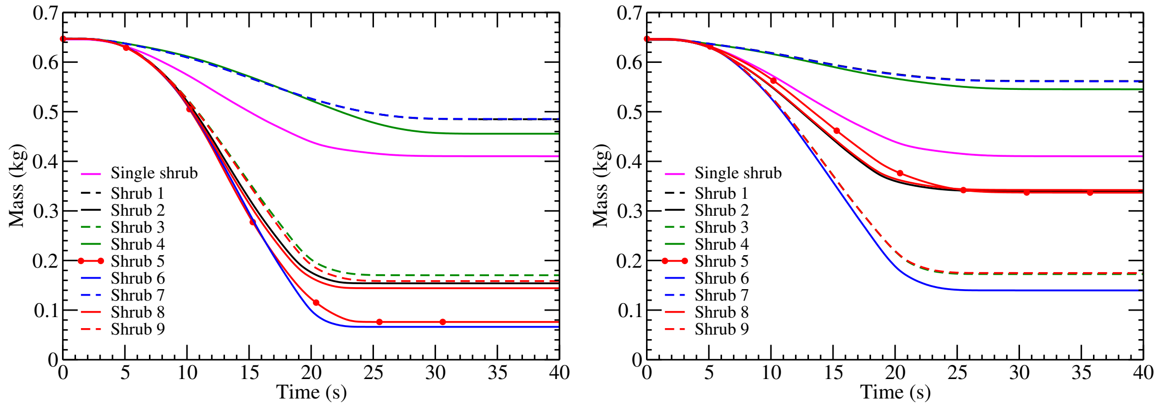
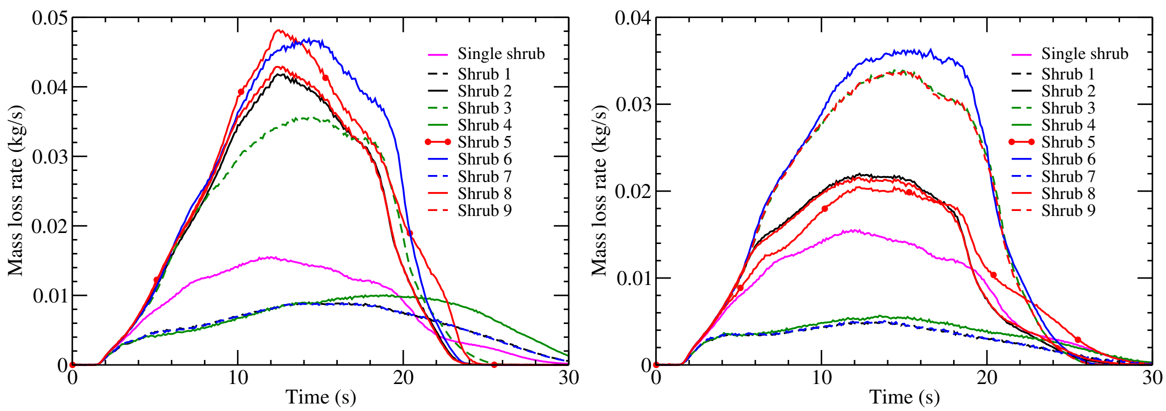


Figure 5: Time evolution of the heat release rate per shrub for cases with varying separation distances and for the reference single shrub case, at zero wind speed.



(a) $d^* = 0$ (b) $d^* = 0.25$

Figure 6: Temporal evolution of the total mass loss of the individual shrubs (3×3 array) with increasing separation distance ($d^* = 0$ and $d^* = 0.25$) and the reference single shrub subjected to wind speed of 1 m/s along the x direction.



(a) $d^* = 0$ (b) $d^* = 0.25$

Figure 7: Temporal evolution of the mass loss rate of the individual shrubs (3×3 array) with increasing separation distance ($d^* = 0$ and $d^* = 0.25$) and the reference single shrub subjected to wind speed of 1 m/s along the x direction.

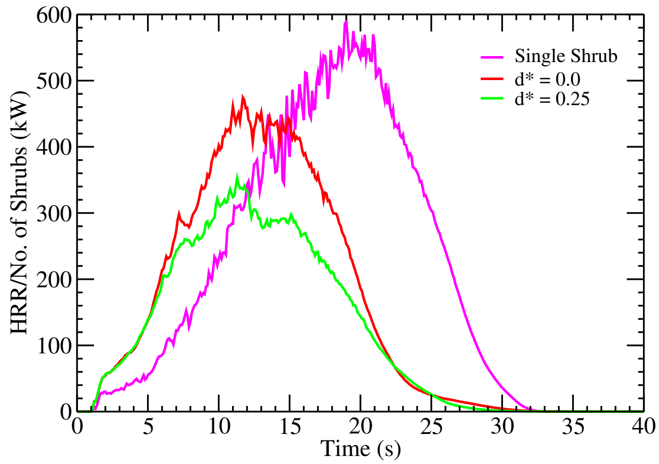


Figure 8: Time evolution of the heat release rate per shrub for cases with varying separation distances and for the reference single shrub case subjected to wind speed of 1 m/s along the *x* direction.