A New Direction in Firefighting Systems

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Abstract. Recent huge technological development of Unmanned Aerial Vehicles (UAVs) can provide breakthrough means of fighting wildland fires. We propose an innovative forest firefighting system based on the use of a swarm of hundreds of UAVs able to generate a continuous flow of extinguishing liquid on the fire front, simulating the rain effect. Automatic battery replacement and refilling of the extinguishing liquid ensure the continuity of the action. We demonstrate the validity of the approach first computing the critical water flow rate according to the main factors involved in the evolution of a fire, then estimating the number of linear meters of active fire front that can be extinguished depending on the number of drones available and the amount of extinguishing fluid carried. A fire propagation cellular automata model is also employed to study the evolution of the fire. The results suggest that the proposed system can successfully integrate, or in some cases completely replace, current forest firefighting techniques.

Keywords: drone swarm, unmanned aerial vehicle (UAV), cellular automata, firefighting methods, wildfire suppression

Introduction
Forest environments, woods and green areas constitute a natural resource for human life. Unfortunately, they are progressively risking impoverishment and destruction (Jolly \textit{et al.} 2015; Dimitropoulos 2019). Wildfires represent the most serious and prevalent threat to Mediterranean forests (San-Miguel-Ayanz \textit{et al.} 2013); they are a particularly complex phenomenon, influenced by numerous interdependent variables, some of which are constantly evolving in time. In the past decades, the issue of forest firefighting has become increasingly important because of their frequency, incidence and magnitude, and their dangerous consequences involving people, things and natural environment.

Protection in forest fires is generally implemented by means of air/ground interventions, and involves fire brigade, civil protection, police forces, and volunteers. Ground interventions usually include indirect actions, such as targeted deforestation to eliminate potential combustible (vegetation) and the so-called burning out actions aimed at strategically limiting and deviating the spreading of flames (Fernandes and Botelho 2003). There are also direct actions involving the use of hydrants and similar methods to spread extinguishing liquids onto the fire front, e.g. ammonium phosphate mixtures. Air interventions lead to the use of various types of aircraft, such as helicopters or planes equipped with containers to collect water from special reserves and drop it both on the front and on the central part of the fire to counteract its development.

The above-mentioned techniques have several drawbacks. Ground interventions, for example, are generally ineffective because of their limited impact on large fires (Butler 2014); aerial firefighting has a high cost of purchasing, operating and maintaining aircraft and staff training (Stonesifer \textit{et al.} 2016). For this reason, aircraft fleets are significantly fewer than the necessary and cannot meet the demands of firefighting interventions, both in terms of rapidity and geographical coverage of the national territory. Moreover, for safety reasons, in most
countries, aerial firefighting can only be carried out during the day and allows to perform a limited number of drops, given the need after each intervention to refuel at an appropriate nearby place (lake, calm sea, basin, etc.).

During the twentieth century, Unmanned Aerial Vehicles (UAVs), also generically called drones, were exclusively used for military applications, whereas in just a few years of this century, their use in civil applications has increased. Both research institutions and universities, as well as industry, have shown a growing interest in studying this technology. Promising applications include surveillance, precision farming, inspection of potentially dangerous sites, and environmental monitoring.

The use of UAVs has raised in forest fire prevention as well (Floreano and Wood 2015; Witze 2019; Arkin et al. 2019; Lin et al. 2019; Al-Kaff et al. 2020). In the United States, a law enacted in 2019, the “John D. Dingell, Jr. Conservation, Management, and Recreation Act”, pushes federal agencies to expand the use of drones in managing and fighting wildfires (‘DOI Unmanned Aircraft Systems (UAS) Program - 2018 Use Report’ 2019). Civil protection and firefighters equip themselves with drones, to track vegetation and areas at risk and to carry out evaluations and interventions based on images and data transmitted in real time by drones flying over the burning area. The main limitations of this use are the difficulty of going beyond a sporadic monitoring that does not allow a continuity in time (both the phase of data acquisition and processing must be done manually by an operator) and the impossibility of acting promptly to alert at an outbreak of a fire. Generally, the overflight of drones takes place with the fire in progress in case the extent and direction of propagation of the fire need to be estimated. Recent technological advances in UAV field, have increased the possibility to provide real time and high-quality information to end-users. On this issue, in (Seraj et al. 2019), an algorithm for estimating the fire propagation is proposed with the aim of enabling intelligent and long-lasting coordination of UAVs to support firefighters. In (Merino et al. 2012), the authors show how multiple aerial vehicles with on-board infrared or visual camera, can collaborate to automatically obtain information about the evolution of the fire front shape and other parameters.

Unfortunately, there are still few studies in the literature that suggest the employment of UAVs not only for the prevention and monitoring of forest fires, but even with the aim of extinguishing them (Yuan et al. 2015; Shaffer et al. 2018). For instance, (Innocente and Grasso 2018) and (Soliman et al. 2019) promote the idea of using such technology in fire-fighting applications, especially in areas difficult to reach by humans. The first propose a fleet of self-organized drones, carrying 120 kg of water each, with a coordination mechanism based on a forgetful particle swarm algorithm; the second present a rotary wing UAV equipped with a payload drop mechanism that can carry firefighting spheres and release them against fires. (Aydin et al. 2019) proposes the use of drones carrying extinguishing balls as a supplement to traditional firefighting methods. In (Myeong et al. 2017), a fireproof aerial robot is introduced to avoid the risks affecting electronic equipment directly exposed to flames.

In this work, we propose an innovative method based on the use of a swarm of collaborative UAVs able to transport large quantities of fractionated extinguishing liquid and to release it on fire fronts, simulating the rain effect (see Fig. 1). We first introduce the drone system that manages the swarm of UAVs. Then, we demonstrate
its effectiveness showing that the amount of extinguishing liquid is adequate in suppressing or at least containing a wildland fire. For this purpose, the critical water flow rate, i.e. the rate of water application required to arrest a certain number of linear meters of active fire front, is estimated based on fire parameters such as wind speed, humidity and height of vegetation, etc. Then, assumed that the drone system is positioned at a certain distance from the fire depending on various surrounding conditions, the number of drones necessary to assure such flow of water is computed. Finally, the implementation of a fire cellular automata propagation model allows to predict how the fire front subjected to the action of drones is modified over time.

*Description of the drone swarm management system*

The management system of the drone swarm has to meet a number of requirements in order to be used effectively in firefighting: (i) it has to ensure operational continuity without downtime for a high number of hours (virtually also H24); (ii) it has to be able to automatically replace exhausted batteries and insert it into a charging circuit, given the limited battery duration of the current drones (just over half an hour); (iii) it has to allow for multiple refills of the drones with an appropriate extinguishing liquid placed in containers docked to drones. It mainly consists of a support unit that manages the drone swarm (henceforth called platform) that can be easily moved and positioned close to the fire front.

A system that satisfies these requirements has considerable advantages in fighting forest fires: it can be used both during the day and at night and in low visibility conditions, unlike common aircraft; it does not require the presence of an available water basin in the vicinity; it can be used continuously until the alarm ceases, since the automatic battery change, the continuous charging system and the complete automation of the payload switch (containing the extinguishing liquid), ensures virtually a H24 duration; it can be used in areas not directly accessible by firefighting equipment and in areas with complex orography; it is a precision system because the flight plan, the area concerned, etc. can be planned in an accurate manner; it is a flexible system in which the area of intervention can be modified in real time as the conditions of the fire evolve; it does not put at risk the lives of pilots of aircraft that often have to operate in conditions of considerable danger.

The amount of water transported by a drone is obviously significantly reduced compared to the volume of water of a firefighting aircraft (Legendre et al. 2014). At the same time, however, a large number of drones can guarantee a temporal continuity and uniformity of diffusion that an aircraft is unable to obtain due to the timing of provision. One of the authors of this paper is the inventor of the patent “Methods and apparatus for the employment of drones in firefighting activities” (Ghio 2017) that precisely concerns the creation of a system for drones able to drop small quantities of firefighting liquid on wildland fires.

Multiple strategies are possible: either directing the action of drones directly on the flames, or on an adjacent area, so as to increase the humidity of the vegetation and prevent the spread of flames to particularly sensitive areas, for example occupied by inhabited areas or installations at high risk. Moreover, the drone system creates the so-called rain effect, i.e. dropping small quantities of firefighting liquid by drizzling it over the fire (Volkov et al. 2018) or the surrounding vegetation, instead of spreading it in a concentrated manner. This method, both theoretically and experimentally, is acknowledged as being particularly effective in domestic and/or industrial firefighting systems (fire sprinkler systems) (Liu and Kim 1999). Although it is not the purpose of this work to assess this effect by comparing it with the impact produced by aircraft carrying the same amount of water, it is an interesting feature that requires further investigation. At the moment, the cost of the system compared to the current firefighting tools cannot be estimated, as it depends on many factors, primarily the implementation choices and the cost of drones. However, the price of UAVs has been continuously decreasing in recent years thanks to significant technological advancement in the field, with costs expected to decrease further.

The drone system involves the use of a platform that manages drones and changes their battery and payload. Such a platform can be considered as a base station for drones. Drone base stations are gaining popularity mainly for their use in video surveillance and inspections (Williams and Yakimenko 2018). In the field of forest firefighting, there is very little literature concerning the use of drone base stations. Among them we mention the charging base designed in (Al-Kaff et al. 2020) for fire surveillance, equipped with an upper sliding door and a
vertically moving bed for take-off and landing maneuvers. The aim of this work is to prove that a management system of a drone swarm that fulfills the requirements (i)-(iii) is able to generate a sufficient flow of extinguishing liquid to effectively fight a forest fire. Technical implementation of the system or practical management of a drone swarm deployed on a fire front will be studied in future papers, but particular care has been taken in choosing reasonable ranges of parameters concerning the amount of extinguishing liquid carried by each drone (Vergouw et al. 2016), the timing of automatic battery and payload replacement and the number of drones that a platform can handle in an interval of time.

Calculation of critical water flow rate CF

Although retardant liquids exist (Giménez et al. 2004), the main substance used to suppress wildfires is water, thanks to its high availability, low cost and great extinguishing capacity (Grant et al. 2000). In order to test the validity and effectiveness of using a large number of drones to contain and extinguish forest fires, it is essential to estimate the critical water flow rate (CF). CF is a function of the rate of spread (RoS) of the fire, which in turn depends on the main factors involved, such as wind speed, terrain slope, humidity and height of vegetation. Using (Fernandes 2001; Hansen 2012; Penney, Habibi, Cattani, et al. 2019), CF (L m min⁻¹), the critical flow rate required to extinguish 1 m section of active head fire front, is estimated as a function of wind speed U measured at 2 m in km h⁻¹, and moisture content percentage of the elevated dead fuels MD:

\[ \text{RoS} = 0.06 \ a \ U^b \exp (-cM_d) \]  \hspace{1cm} (1)

where \(a\), \(b\), and \(c\) are some parameters obtained experimentally by non-linear regression analysis (see Table 1). Differently from (Fernandes 2001), the rate is multiplied here by 0.06 to be expressed in km h⁻¹. Given RoS, critical water flow rate is computed in (Penney, Habibi, Cattani, et al. 2019) as a function of RoS and active flame depth \(D\) (measured in m):

\[ \text{CF} = 6 \ e \ \text{RoS}^f \]  \hspace{1cm} (2)

where \(\text{CF}\), measured in \(L \text{ m} \text{ min}^{-1}\), is the critical flow rate required to extinguish 1 m section of active head fire front, whereas \(e\) and \(f\) are some parameters depending on \(D\) and summarized in Table 1. In (Penney, Habibi, Cattani, et al. 2019), CF is calculated on 10 linear meters, while here it is on 1 linear meter. Moreover, for the subsequent utilization of the equation (2), it is more convenient to write the rate in \(L\) per minute, instead of \(L\) per second. For these reasons, the original formula was multiplied by 60 (s) and divided by 10 (m). From this derives the multiplicative factor of 6. Replacing RoS of equation (1) in equation (2), the critical flow rate can be estimated as a function of the following factors, i.e. wind speed \(U\), moisture content \(M_d\) and active flame depth \(D\):

| Parameter | Symbol | Value |
|-----------|--------|-------|
| Rate of spread parameters | \(a\) | 3.258 |
| | \(b\) | 0.958 |
| | \(c\) | 0.111 |
| Active flame depth | \(D\) | 2 (m) |
| Parameters depending on \(D\) | \(e\) | 2.72 |
| | \(f\) | 0.42 |
The dependence of $CF$ on $D$ is given by $e$ and $f$. Fig. 2 shows some graphs of $CF$ computed using (3) by varying two of the three factors, maintaining the third one fixed. As expected, $CF$ is directly proportional to wind speed and active flame depth and inversely proportional to moisture content.

**Fig. 2.** Critical water flow $CF$ computed as a function of the main parameters of the fire. (a, b) $CF$ with wind speed and moisture content varying, respectively, and $D$ fixed at 2 m. (c) $CF$ as a function of wind speed with $D$ varying in the different curves and $M_d$ fixed to 18%. (d) $CF$ as a function of moisture content while $D$ varying in the different curves and wind fixed at 20 km h$^{-1}$.

**Impact of drones on the evolution of the active fire front**

Based on the critical water flow rate computed in the previous section, it is possible to estimate the number of linear meters of active fire front that can be extinguished as these factors vary. The platform is assumed to be positioned at a certain distance from the fire depending on various boundary conditions, such as wind direction, terrain orography, presence of roads. A certain time interval is also required to automatically switch the battery and the payload (the extinguishing liquid) carried by each drone; this timespan can vary from a minimum of a few seconds to a maximum of one minute. A very short, almost instantaneous, time is also required for the liquid...
to be released on the fire by each drone. Since in this work we do not describe how these technical features would be effectively implemented, we consider them in a single variable: the time interval $\Delta t$ (min) in which a drone arrives on the platform, is charged with a new payload, takes off, reaches the active fire front, releases the liquid and lands back on the platform. A $\Delta t$ equal to 6 minutes is assumed to remain fairly cautious, but even lower values are possible if the platform is positioned against the wind next to the active fire front, as in the case of firefighters’ vehicles.

The liquid carried by each drone is identified by $L_d$ (L). It is reasonable to assume this value to be between 15 and 50 L. In fact, the coordinated system proposed concerns the use of a large number of small-sized drones carrying a limited amount of liquid, in contrast to self-guided vehicles similar to current firefighting aircraft with a capacity of thousands of liters. Moreover, each platform is capable of handling a number $n_d$ of drones, ensuring battery replacement and liquid refilling for each drone. Reasonable values of $n_d$ are between 80 and 120. Once these variables are introduced, it is easy to estimate the water flow that a platform assure in the time unit. Each drone is able to deliver $n_h$ discharges of extinguishing liquid per hour corresponding to

$$n_h = \frac{60 \text{ (min)}}{\Delta t \text{ (min)}}$$  \hspace{1cm} (4)

Therefore, a platform, managing $n_d$ drones, is designed to deliver $n_h^{\text{tot}}$ discharges of extinguishing liquid per hour

$$n_h^{\text{tot}} = n_h n_d$$  \hspace{1cm} (5)

and to spread $L_h^{\text{tot}}$ of liquid equals to

$$L_h^{\text{tot}} = L_d n_h^{\text{tot}} \text{ (L h}^{-1})$$  \hspace{1cm} (6)

Dividing this value for 60 (minutes), it is possible to estimate the drones flow rate ($DF$), i.e. the amount of liquid that one platform spreads each minute

$$DF = \frac{L_h^{\text{tot}}}{60} \text{ (L min}^{-1})$$  \hspace{1cm} (7)

Replacing in (7) the expression of the variables stated in (4) - (6), we obtain the flow rate that the platform handling $n_d$ drones spreads per minute:

$$DF = \frac{L_d n_d}{\Delta t} \text{ (L min}^{-1})$$  \hspace{1cm} (8)

For instance, a platform with $n_d = 120$ drones, each carrying $L_d = 20$ liters of fire extinguishing liquid and completing a round trip in $\Delta t = 6$ min, ensures a flow of

$$DF = \frac{20 \cdot 120}{6} = 400 \text{ (L min}^{-1})$$  \hspace{1cm} (9)

Once calculated the continuous flow that a platform can guarantee and the flow rate necessary to extinguish one linear meter of active front, it is possible to estimate the number $m_f$ of linear meters that can be extinguished:

$$m_f = \frac{DF}{CF} \text{ (m)}$$  \hspace{1cm} (10)

or equivalently

$$m_f = \frac{L_d n_d}{\Delta t \ CF} \text{ (m)}$$  \hspace{1cm} (11)
Replacing (3) in (11), we obtain the expression of \( m_F \) as a function of the fire parameters:

\[
m_F = \frac{L_d \, n_d}{\Delta t \, 6 \, e^{0.06 \, a \, U^b \, \exp \left(-cM_d\right)} \, \Delta t} \, (m)
\]  
(12)

Using (12), the number of linear meters of active fire front that can be extinguished as the fire parameters vary, was computed. Since the calculation of linear meters does not take into account the time required to ensure the flow of extinguishing liquid, drones are assumed to continue to provide such flow throughout the duration of the fire. Fig. 3 shows the linear meters of fire that can be arrested by using the proposed firefighting method. For example, approximately 35 linear meters of active front can be extinguished with 120 drones each carrying 20 L or with 80 drones carrying 30 L (Figs 3a, 3b).

These results show that a platform managing up to 120 drones is a valid alternative to current firefighting systems in the case of moderate fires. In a large wildland fire, the system can control a part of the front, e.g. to prevent advance in critical areas. The effectiveness can be further improved by the simultaneous use of multiple platforms that can attack the fire front from multiple sides. Moreover, the effect of the platform can be directed to the fire front or to areas that have not yet caught fire thereby creating a firebreak without risk for firefighters who are not forced to approach the fire.

**Estimate of the drones required to extinguish a specified number of linear meters of active fire front**

Considering the total or partial extent of the fire front whose propagation is to be prevented, it is possible to determine the number of drones required. It is assumed to have drones carrying \( L_d \) liters of extinguishing liquid and to locate the platform so that the time interval required for a drone to reach the fire, release the liquid onto it and return to the platform is \( \Delta t \) (min). Depending on the fire parameters, wind, moisture content, etc., the requested water flow rate changes and consequently the required number of drones. The drone flow rate \( D_F \) required to extinguish \( m_r \) of active fire front is

\[
D_F = m_r \, CF \, (L \, min^{-1})
\]  
(13)

since \( CF \) is the flow rate for 1 linear meter. Therefore, replacing (13) in (8), we obtain the number \( n_d \) of drones required:

\[
n_r = \frac{CF \, \Delta t \, m_r}{L_d}
\]  
(14)

or equivalently, replacing the expression of \( CF \) from equation (3):

\[
n_r = \frac{6 \, e^{0.06 \, a \, U^b \, \exp \left(-cM_d\right)} \, \Delta t \, m_r}{L_d}
\]  
(15)

For instance, in a fire with a moisture content of 18% and a wind speed of 15 km h\(^{-1}\), to extinguish 30 meters of active front with drones carrying 20 liters and completing a loop in \( \Delta t = 6 \) min, the number of drones required is

\[
n_r = \frac{6 \, e^{0.06 \, a \, 15^b \, \exp \left(-c \cdot 18\right)} \, \Delta t \, m_r}{20} \approx 95
\]  
(16)
Fig. 3. Linear meters of fire $m_f$ that can be arrested by using the proposed firefighting method. In all figures the active flame $D$ is fixed to 2 m. (a) $m_f$ as a function of the number of drones with the extinguishing liquid carried by drones varying in the curves. (b) $m_f$ as a function of the extinguishing liquid carried by drones with the number of drones varying in the curves. In (a, b) the wind speed and the moisture content are fixed to $20 \text{ km h}^{-1}$ and 18%, respectively. (c) $m_f$ as a function of the wind speed with the number of drones varying in the curves. The moisture content is 18% and the liquid carried by drones is 20 L. (d) $m_f$ as a function of the rate of spread with the number of drones varying in the curves. The liquid carried by drones is 20 L. (e) $m_f$ as a function of the rate of spread with liquid carried by drones varying in the curves. The number of drones is 120. (f) $m_f$ as a function of the wind speed with the number of available platforms varying in the curves. Each platform manages 120 drones each of them carrying 20 L. The moisture content is 18%.
Cellular Automata model for studying the effect of the platform on fire evolution

In the previous sections, we estimated the number of linear meters of active front arrested using one or more platforms handling a given number of drones carrying extinguishing liquid. Starting from this value, in this section we use a fire propagation model for studying the evolution of a fire as a result of the containment action of the platforms. Forest fires are a particularly complex phenomenon, influenced by numerous interdependent variables, some of which are constantly evolving in time. Risk assessment, propagation and effect models are the three categories in which fire models are grouped by (Preisler and Ager 2013). The objective of forest fire simulation is therefore to improve prevention and control operations: assessment of the attack surface, prediction of the evolution of the fire front, preventive mobilization of rescue teams, and containment of the front-line and fire extinction. In our case, in order to prove the effectiveness of using a coordinated system of drones, among all models of fire evolution, we choose a cellular automata model to simulate and calculate the modification of the front by the contribution of the extinguishing liquid provided by drones.

Cellular automata (CA) are mathematical idealizations of physical systems, represented by connected and organized elements that interact with each other and constitute a single entity with the external world. The definition of the physical environment determines the universe upon which the CA is modelled, physical quantities take on a finite set of discrete values (Wolfram 1983), depicted in grids (2 or 3 dimensional lattices) that evolve at discrete time intervals, according to stochastic rules. Every single cell has a finite state characterized by one or more variables and the respective numerical values. Cell states vary according to a local transition function applied to all cells in the lattice, updated synchronously and simultaneously. Specifically, the state of a cell \((i, j)\), at a given time \(t\), depends only on a transition function and on the state of the cell itself and of neighboring ones at the previous discrete time step.

CA have proven their strength in predicting macroscopic and complex dynamics using simple rules that define the physics of a phenomenon on a microscopic grid scale. For this reason, CA models emerge as a useful choice for modelling the complex behavior of wildfire spread (Karafyllidis and Thanailakis 1997). In several researches, CA have been applied to simulate fire spread for the purpose of assisting firefighters in identifying fire suppression tactics and in planning policies for fire risk management (Ferragut et al. 2008; Cistriani et al. 2009; Dumond 2009). They can also be easily integrated with digital data from Geographic Information Systems or other sources including local meteorological data (Yassemi et al. 2008; Gaudreau et al. 2016; Russo et al. 2016). CA can be identified by the geometry of the regular cell arrangement, i.e. square or hexagonal cells in two-dimensional case (Trunfio 2004; Hernández Encinas et al. 2007), and the number of neighboring cells taken into account: 4 neighbors in the case of the Von Neumann neighborhood, 8 neighbors in the Moore neighborhood (Albinet et al. 1986). In (Trunfio et al. 2011), the authors present a novel algorithm for wildfire simulation through CA, which is able to effectively mitigate the problem of distorted fire shapes, allowing spread directions that are not constrained to the few angles imposed by the lattice of cells and the neighborhood size.

In the present paper, the CA model introduced in (Alexandridis et al. 2008, 2011) is utilized to simulate the evolution and the consequent confinement of a wildfire thanks to the action of one or more platforms of drones. It consists in a square-meshed grid represented as a two-dimensional matrix, easily simulating a forest area. Each cell is generally defined by a finite number of evolving states. Four states characterize the system:

- **State** = 0. The cell cannot catch fire (empty cell). This state could describe cells corresponding to parts of the territory in which there is no vegetation that can burn.

- **State** = 1. The cell contains live fuel, not yet burned (tree cell).

- **State** = 2. The cell contains material that is burning (burning cell).

- **State** = 3. The cell contains completely burned fuel (burned cell).

- **State** = 4. The cell has a continuous flow of water that provides fire extinction (see CF) thanks to the drones. Each cell is subject to local rules that guide the evolution of the spread of the fire. At each discrete time step \(t\) of the simulation, the following rules are applied to elements \((i, j)\) of the state matrix (and therefore to all cells):

  - **Rule 1** states that an empty cell \((i, j, t)\) maintains the same state without burning at next time step.
• Rule 2 states that if a cell contains vegetation fuel and there was at least one neighboring cell burning at the previous time step such that \((i \pm 1, j \pm 1, t - 1) = 2\), it can catch fire with a probability \(P_{\text{burn}}\) greater than a certain threshold. As the wind speed increases, we also consider next-nearest cells as in (Bodrožić et al. 2006) and in (Freire and DaCamara 2019). In particular, we add two layers of cells for wind at 25 \(km h^{-1}\) and three for wind at 35 \(km h^{-1}\).

• Rule 3 determines that a cell that is burning at the present moment will be completely burned at the next one. In subsequent times, it will no longer be able to spread the fire.

• Rule 4 implies that a previously burned cell remains burned. Due to the square grid based on Moore neighborhood, fire can spread to the eight adjacent cells, i.e. horizontally, perpendicularly and diagonally.

In the following, all the probabilities are computed as in (Alexandridis et al. 2008, 2011). The rule 2 implies that when a cell ignites at the current time, the next instant the fire may spread to nearby cells containing unburned fuel with a \(P_{\text{burn}}\) probability:

\[
\text{\(P_{\text{burn}} = p_0(1 + p_{\text{veg}})(1 + p_{\text{den}}) p_w p_s p_m\)}
\]

It is a function of several variables that affect fire propagation, such as fuel properties, wind conditions and topography. The probability \(p_0\) measures the chance for a cell in the neighborhood of a burning one to catch fire, supposing flat terrain and no wind conditions. The other probability factors are related to the vegetation typology, to the density and humidity of fuel in each single cell, to the wind blowing over the total area, and to the landscape altitude. Vegetation is considered as a combustible material composed of a set of solid particles distributed in the environment; a density, a typology and a percentage of humidity characterize it. Three density categories are present in the model, sparse, normal, and dense, and each of them corresponds to a \(P_{\text{den}}\) value. Two types of fuel were chosen, grassland and shrubland, corresponding to the typical vegetative plants of the Mediterranean environment.

The effect due to the moisture content of vegetation is calculated adopting the formulation given in (Fernandes 2001). It links the rate of spread to the moisture content \(M_d\) and to the two coefficients, \(b\) and \(c\) (see Table 1), determined by regressive analysis from experimental data. In experimental studies, this last factor is determined by weighing samples of vegetation before and after drying them, which means that the formula depends on the type of vegetation. The wind-effect probability \(p_w\) takes into account both wind speed and direction and is calculated using the following empirical relation

\[
\text{\(P_w = \exp(c_1V) \exp(Vc_2(c_1 \cos \theta - 1))\)}
\]

where \(\theta\) is the angle between the spreading direction of the fire and the direction of the wind, \(c_1\) and \(c_2\) are constant values. The probability related to the effect of ground elevation is a function of a parameter derived from experimental data and of the slope angle \(\theta_s\):

\[
\text{\(P_e = \exp(a_s \theta_s)\)}
\]

where \(\theta_s\) is calculated using

\[
\text{\(\theta_s = \tan^{-1} \left( \frac{E_1 - E_2}{D} \right)\)}
\]

The value of \(D\) is taken equal to \(L\) or \(\sqrt{2}L\) depending on whether the cell being considered is adjacent or diagonally located to the burning cell.

The model described above has been applied to simulate the forest fire spread in order to enable for the intervention of drones to entirely or just partially suppress the fire. The environment is completely simulated, and it is not based on a real case study. The territory consists of a small-scale surface area of about 40000 square meters, essentially flat, characterized by vegetation types similar to those of the Mediterranean scrub. It is displayed as a grid of 2-meter long side cells created in the form of a matrix in MATLAB® environment. Different matrices are used to characterize the parameters involved in fire: wind velocity and direction, vegetation density,
moisture content, and type (grass and shrubs). All the parameters employed in the CA model are included in Table 2. Random matrices for the vegetation density and typology covering the entire cell grid are generated.

To carry out the simulations, a platform managing 120 drones each carrying 20 liters of extinguishing liquid was selected. The number $m_f$ of linear meters of active fire front that can be extinguished by using the platform is computed by (12). Given both this value and the cell size, the number of cells $n_c$ where drones can spread the liquid is calculated in two different ways: if the front develops diagonally, $n_c$ is obtained by dividing $m_f$ with the length of the cell side $l = 2$ multiplied by a factor equal to $\sqrt{2}$, i.e. applying the formula to calculate the diagonal of a square $\sqrt{2} l$; otherwise $m_f$ is divided only by $l$.

After deciding the position of the platform (on the south side of the domain in the simulation), we faced the flames with a direct attack on both the head and the flank of the fire, as described in (Penney, Habibi, and Cattani 2019). The state of $n_c$ contiguous cells of the fire front closer to the platform is set equal to 4, i.e. in these cells there is a continuous flow of water that extinguishes the fire. With the intervention of drones, the total area of the fire varies in different ways depending on fire parameters. Specifically, both types of vegetation adopted in the model lead to the outbreak of a fire with low, but rapidly spreading flames. Furthermore, the higher the wind speed, the faster the front spreads, and the more water is needed to extinguish it, all other factors being equal.

Fig. 4 shows the effects of the platform’s impact on the evolution of a wildland fire. Simulations indicate that although a platform is not able to completely extinguish the fire in these conditions, it is nevertheless effective in containing its advance. The use of two platforms allows the complete extinction.

### Conclusions

We have rigorously estimated the impact of the use of one or more platforms managing a variable number of drones able to spread water or other extinguishing liquid on a wildland fire. On the basis of the critical water flow computed as a function of the main factors involved in the evolution of a fire, we have computed the number of linear meters of active fire front that can be extinguished as these factors vary. We have also tested a fire propagation model to study the evolution of the fire as a result of the containment effect of the platforms. By means of the results of the analyses and graphs carried out in both approaches, the use of a platform for the management of a large number of drones has proven to be a valid method for fighting forest fires. As the extinguishing liquid is fractioned into multiple parts, unlike when using aircrafts, future work will investigate a control strategy to decide the part of the fire front where it is preferable to address the action of the drones, also using different fire simulation models (Alessandri et al. 2020). Moreover, the system creates the rain effect, i.e. dropping small quantities of firefighting liquid or drizzling it over the fire, instead of spreading it in a concentrated manner. Therefore, it would be interesting to study the rain effect induced by drones in comparison to the impact produced by aircraft carrying the same amount of water.

### Table 2 | Values for CA model

| Values for the probability $p_{veg}$ and parameter $p_m$ | Grass | Shrub |
|---------------------------------------------------------|-------|-------|
| $p_{veg}$                                               | 0.4   | 0.4   |
| $M_d$                                                   | 0.18  | 0.24  |

| Values for the probability $p_{den}$                  | Category | Density | $p_{den}$ |
|-------------------------------------------------------|-----------|---------|-----------|
| Sparse                                                |           | -0.4    |           |
| Normal                                                |           | 0       |           |
| Dense                                                 |           | 0.3     |           |

| Operational parameters for CA simulations               | Parameter | Symbol | Value |
|--------------------------------------------------------|-----------|--------|-------|
| Spread probability under no wind and flat terrain      | $p_0$     | 0.6    |       |
| Wind parameter 1                                       | $c_1$     | 0.045  |       |
| Wind parameter 2                                       | $c_2$     | 0.131  |       |
| Moisture parameter                                     | $b$       | 0.111  |       |

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Fig. 4. Effects of the proposed firefighting method on the evolution of a wildland fire obtained by CA. (a) Variation of the area of a fire in time without any extinguishing intervention (continuous lines) and with the intervention of the firefighting method (dashed line). Drones start to arrive 9 minutes after the fire ignition. The three curves show the evolution of the fire with the same moisture content (18% for grassland, and 24% for shrubland) but with different wind speeds. (b) Variation of the area of the fire in time with wind speed fixed at 25 km h⁻¹, compared with the spread without any intervention (black line). Drones start the intervention at times \( t_a = 6, 9, 12, 15 \) min. (c, d) Fire evolution fronts (in grey) without any extinction and with the intervention of drones at \( t_a = 9 \) min, respectively. Drones are positioned along the blue line (corresponding to \( n_c = 20 \) cells). Red cells show the front of the expanding fire.

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