

Stromboli 3 July 2019 Fire: what could have happened?

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Article history: received July 29, 2024; accepted January 23, 2025

Abstract

On 3 July 2019, paroxysmal activity at the Stromboli volcano ignited a fire in the south-western sector of the island. This fire burnt the entire southern and eastern area. Thanks to the intervention of the firefighters, the fire did not spread northward, thus avoiding further damage. What could have happened if there had been no intervention? Would the fire have stopped its spread on its own, or would it have burnt the entire island? We show through numerical simulations what could have happened if the fire had not been put out by firefighters and how numerical modelling can help plan preventive actions to avoid worst-case scenarios.

Keywords: VolcFire; NDVI; NDMI; Fire hazard; Firebreaks

1. Introduction

Volcanic induced fires can be ignited by both lava flows (Kauahikaua, 2007) and fallout of incandescent pyroclastic material (Voight and Davis, 2000) during strong paroxysmal activity. Luckily, in many active volcanoes the vegetation is scarce and scattered (Aplet et al., 1998), thus limiting the fire ignition and/or propagation. However, this is not the case with every volcano: a counterexample is Stromboli, whose slopes are almost entirely covered in vegetation, with the exception of its western area, the Sciara del Fuoco (Fig. 1).

On July 3, 2019 a fire was ignited by incandescent material fallout on the southwest of the island (Bevilacqua et al., 2024) due to a strong paroxysm (Andronico et al., 2021; Giordano and De Astis, 2021). One death was associated to this event (INGV editorial staff, 2019).

The July 3, 2019 fire propagated both to the south putting at risk Ginostra village, and to the south-east. It then spread north along the eastern flank of the island, and it stopped thanks to the firefighters' intervention. Lamentably, multiple fires occurred at Stromboli Island, including the one on August 28, 2019, ignited by a paroxysmal eruption (Turchi et al., 2020) and the one of anthropogenic origin in May 2022, which led to the burning of the northern area of the island (Guardo et al., 2024) and the consequent growth of invasive alien-species vegetation, making the environment even more vulnerable (Turco et al., 2018; Moreira et al., 2011; 2020).

Furthermore, climate change is currently increasing the risk of wildfires (Jones et al., 2020; Masson-Delmotte et al., 2021), urging the study and development of fire prediction spread models (Trucchia et al., 2020). Particularly in volcanic areas, fires belong to the so-called secondary hazards and are related to the vegetation destruction that

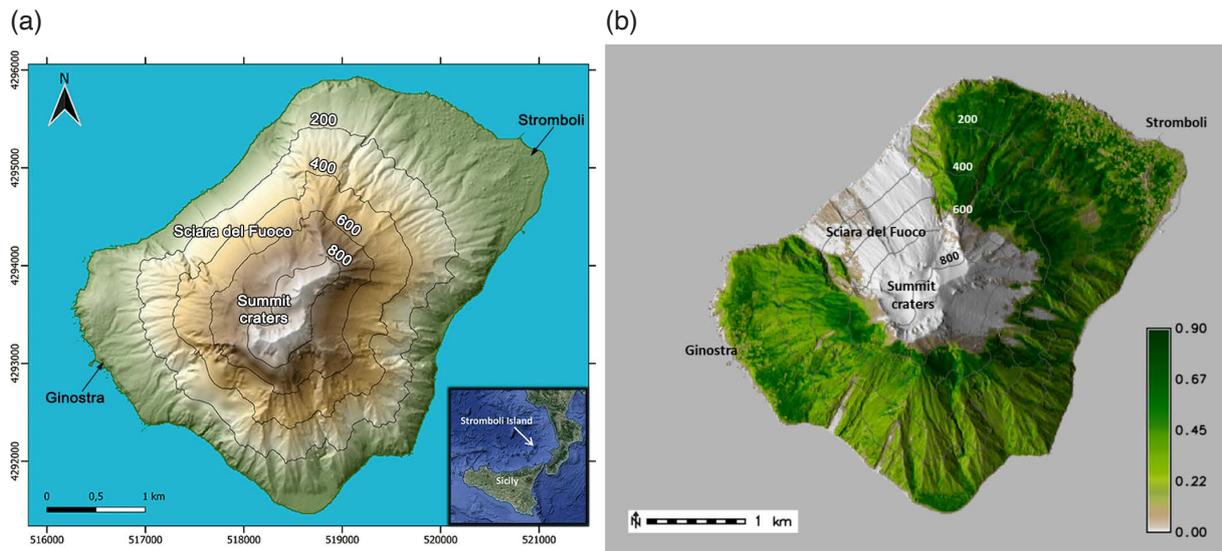


Figure 1. (a) Stromboli island, showing the two main villages of Stromboli (NE) and Ginostra (SW); in the inset, southern Italy with the location of Stromboli Island. (b) The NDVI map derived from the Sentinel-2 image acquired before the fire, showing the distribution of vegetation on the flanks of the volcano on July 2, 2019.

may lead to floods in case of heavy rain (Leonard et al., 2014; Zscheischler et al., 2018; Areu-Rangel et al., 2020, De Ruiter et al., 2020). Given this, the analysis and definition of intervention areas in order to avoid the spread of fires becomes essential. To this aim, the integration of models with Geographic Information System (GIS) technologies can play a crucial role in modeling and predicting fire spread. Indeed, these tools facilitate the analysis and visualization of complex data layers, including topography and/or vegetation indices, enhancing the accuracy of hazard maps; among these, open-source GIS solutions have proven effective in simulating forest fire propagation (see e.g. Mangiameli et al., 2021).

The work we present here discusses the July 3, 2019 fire on Stromboli island from a numerical perspective, comparing the original fire spread with what models can tell us about what could have happened if there had been no intervention from the firefighters. These results are then expanded to illustrate the application of the model to explore possible preventive firebreak solutions.

2. Material and Methods

2.1 Fire propagation model

Recently, we developed a probabilistic cellular automaton model for volcanic-induced fire propagation, VolcFire (Guardo et al., 2024), designed for the construction of fire propagation hazard maps and relying on satellite data for input information such as the topography of the area, the vegetation cover and its moisture.

As part of the validation process, VolcFire has been used to reproduce two past scenarios, the fires that occurred at Stromboli Island in 2019 and 2022. In detail, we considered only the July 3, 2019 fire and not the one of August 28, 2019, due to both the lack of information regarding the ignition point of the latter, and the general overlap of the areas burnt by the two fires. Since its first publication, the model has been improved by incorporating more robust data handling, introducing parallel computing support when modelling multiple scenarios, and optimizing the cellular automaton approach for enhanced performance.

The model takes as input a data file containing ignition coordinates and wind conditions (direction and strength), a 1-meter Digital Terrain Model of the area (at 10-meter resolution for this study) that is also used as basis for the automaton cells, Sentinel-2 satellite imagery from which the vegetation and moisture indices (NDVI and NDMI) are derived, and the number of runs over which the total ignition probability is computed, as detailed in Guardo et al. (2024).

The topography and the NDVI and NDMI indices are combined to mark cells that cannot be ignited, and if the initial ignition point(s) fall in a burnable cell, the model computes the fire propagation until it naturally extinguishes, or a predetermined maximum number of propagation steps is reached.

At every step, the ignition probability from adjacent cells is computed using physical parameters such as slope, wind, moisture. An optimization over the previously presented version of the VolcFire model is to take into account that these values are assumed constant in time, and that the propagation probability can thus be precomputed at the beginning of the simulation. At the expense of some memory, this leads to a 15% speed-up in the model execution.

The original model ran for every cell in the automaton, checked if any neighbors were ignited, and then determine the probability of ignition for the current cell. An optimization that has been introduced since the previous model consists in the use of a marker to identify cells near the fire propagation front, and only check for ignition in those cells: every time a new cell is ignited, it unmarks itself as candidate, and marks all its adjacent cells. This significantly reduces computational time, from ~15 minutes to ~40 seconds per simulation for the 2019 and 2022 Stromboli fires.

Finally, for the purpose of this work, we have also added the possibility to include a firebreak. This is implemented by a geometric specification of cells that cannot burn (regardless of vegetation and moisture indices) either by elevation or in a straight line specified by its endpoints.

VolcFire remains a probabilistic model, computing the cumulative probability of combustion across multiple runs (by default, 100 runs are done for each given scenario) and calculating the number of runs in which each cell has burnt.

2.2 Test case for intervention and firebreak analysis

The case study we take into consideration is the July 3, 2019 fire on Stromboli. We remark that our model cannot take into account firefighter intervention explicitly, but an upper limit on the number of steps can be used to artificially terminate propagation before the natural extinction, and this can be used as a proxy.

Since VolcFire does not track physical time information, the number of steps necessary to match the firefighter intervention must be calibrated for the case at hand, and it corresponds to an upper limit of 400 steps for the 2019 case study.

The results that we discuss in the next section first concern the removal of the 400-step limit per run, to determine what would have been the natural evolution of the fire in the absence of firefighter intervention. We then discuss the effects of adding firebreaks to the model, with different shapes and positions.

3. Results

3.1 No firefighting intervention

Removing the 400 steps limit that was used in Guardo et al. (2024) as a proxy for the firefighters' intervention, we see that the fire spreads across the entire island (Fig. 2). The average number of steps taken by VolcFire to reach the natural extinction of the fire is 588, nearly 1.5× the limit used in Guardo et al. (2024).

This is a strong indicator that firefighting intervention was crucial to reduce the damage inflicted by the 2019 fire, and naturally leads to the question of possible preventive fire breaking operations that could have been taken in advance to minimize the need for an intervention during the fire. Some possible approaches are explored in the upcoming sections, discussing how the choice of firebreak geometry and extent affect the model results.

3.2 Firebreaks

A firebreak or fireline is an area completely free of flammable material (Wilson, 1988) used to avoid spreading of the fire. As stated in Brou (2022), and reference therein, “the effectiveness of the firebreak is therefore closely related to the length of the flame”, and it is suggested to consider firebreaks twice as wide as the maximum expected flame height. Intuitively, the height of the flames corresponds to the vegetation height (e.g., the crown of the trees), so it is possible to consider that the minimum width of a firebreak should be at least double the height of the vegetation of a given area.

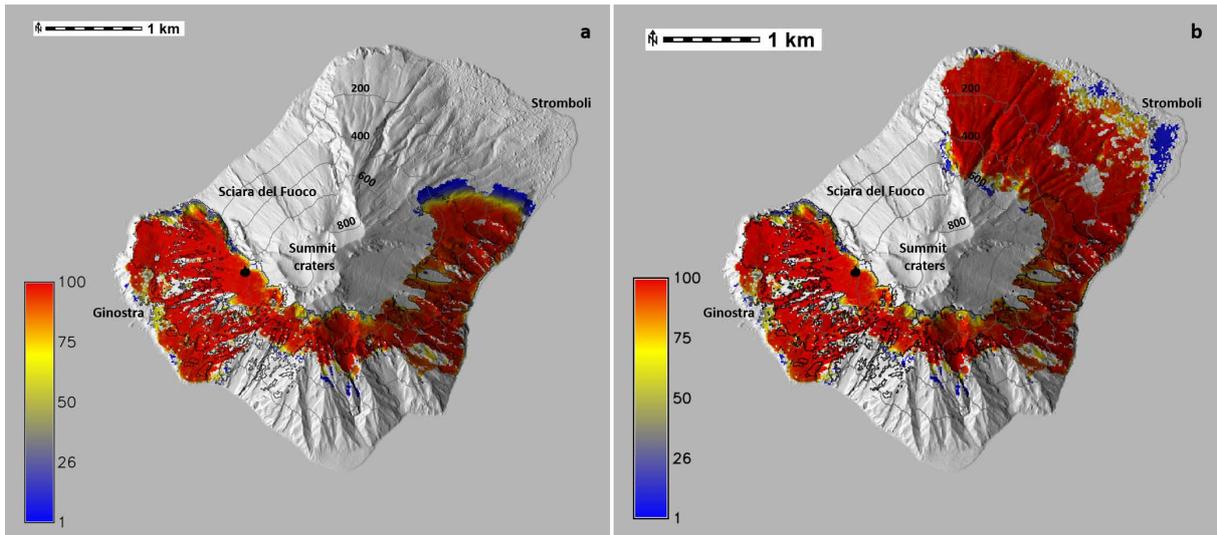


Figure 2. (a) Cumulative probability of combustion given by 100-runs numerical simulations and an artificial stop at 400 steps. (b) Cumulative probability of combustion given by 100-runs numerical simulations. The black flame shows the ignition point.

After both of the 2019 and 2022 Stromboli fire, as mentioned, the vegetation at Stromboli island is mainly constituted by *Arundo donax*, one of the top 100 most invasive alien species (Lowe et al., 2000), with a fast growth (5 cm per day) and a height of about 7 m (Fig. 3).

With a low water content and a maximum height of 10 m this kind of vegetation sets up the best condition for fire ignition and spread. For this reason, a firebreak wide at least 14 m to 20 m appears to be necessary to avoid the spread across the island as previously occurred.

The effectiveness of the firebreak was tested considering 3 different orientations: N-S, W-E and a circular/annular firebreak constrained at specific altitude.

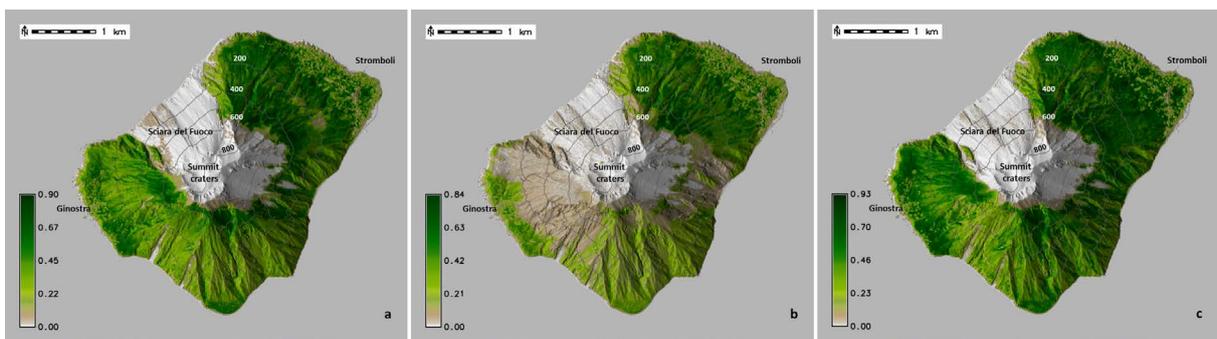


Figure 3. Maps of the NDVI derived from the Sentinel-2 image acquired on 2 July 2019 (a), 7 July 2019 (b), and 11 July 2023 (c).

3.3 Linear firebreaks

3.3.1 N-S firebreak

Setting up a firebreak that covers the entire island from North to South offers the possibility to isolate critical areas such as the eastern flank, which is completely covered in vegetation and located away from the roads, and for which fire extinguishing can therefore only be achieved via air-tankers.

A first firebreak was set passing through the midpoint of the island (Fig. 4a). The fire extinguished after 206 model steps, and the firebreak was sufficient to stop the propagation towards the East side of the volcano, thus

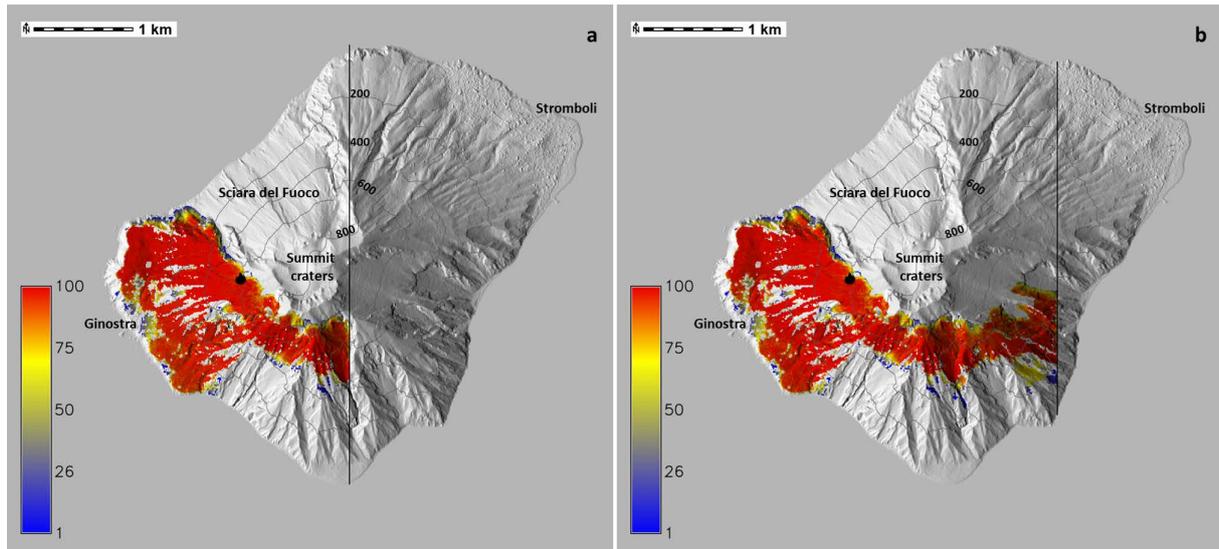


Figure 4. Cumulative probability of combustion given by 100-runs numerical simulations with a linear N-S oriented firebreak located (a) at the middle point of the island and (b) 3 km eastward from the previous one. The black flame shows the ignition point.

saving the township of Stromboli even though Ginostra, located in the South-West part of the island, was still reached by the fire.

In a second scenario, the firebreak was moved 1 km eastward (Fig. 4b), with similar propagation results, highlighting that the morphology of the volcano and the distribution of vegetation provide a natural barrier to the spread of the fire at around 400 m elevation on its eastern flank, and suggesting that the fire propagation towards East is due mainly to vegetation along the coastline. In this second scenario too Ginostra (that is on the same side as the ignition point with respect to the firebreak) is reached by the fire, and Stromboli is protected. A N-S firebreak located between Ginostra and the ignition point would protect Ginostra, but not the Stromboli township, suggesting that a different approach is needed to protect both settlements.

3.3.2 W-E firebreak

A horizontal firebreak oriented East-West, passing through the midpoint of the island, would have prevented the 2019 fire from spreading south to Ginostra (Fig. 5a) and around the island to reach the town of Stromboli.

However, this is specific to the location of the ignition point: if the fire had started 1 km to the South, such a firebreak would have been ineffective (Fig. 5b) in protecting Ginostra. Moving the firebreak 500 m to the South might have protected Ginostra from a fire that started at the 1 km-south ignition point, but not from the actual 2019 ignition point (Fig. 5c).

Of note, both the midpoint and lowered W-E firebreaks would prevent fires starting on the western and southern flanks of the island from propagating to Stromboli town (Figs. 5a,b,c), due to the morphology and vegetation distribution. Moreover, the South-West flank of the volcano appears to be largely unburnable, as highlighted by simulating an ignition point 1.2 km to the South of the 2019 fire ignition point, that fails to reach the lowered W-E firebreak at all (Fig. 5d).

Given the need for specific relative positions between a linear firebreak and fire ignition point to protect Ginostra, a circular firebreak was explored next.

3.4 Circular firebreaks

A circular firebreak is defined by an altitude and tolerance. All cells that are at the given altitude above sea level (a.s.l.) plus or minus the tolerance are set as unburnable before starting the simulation.

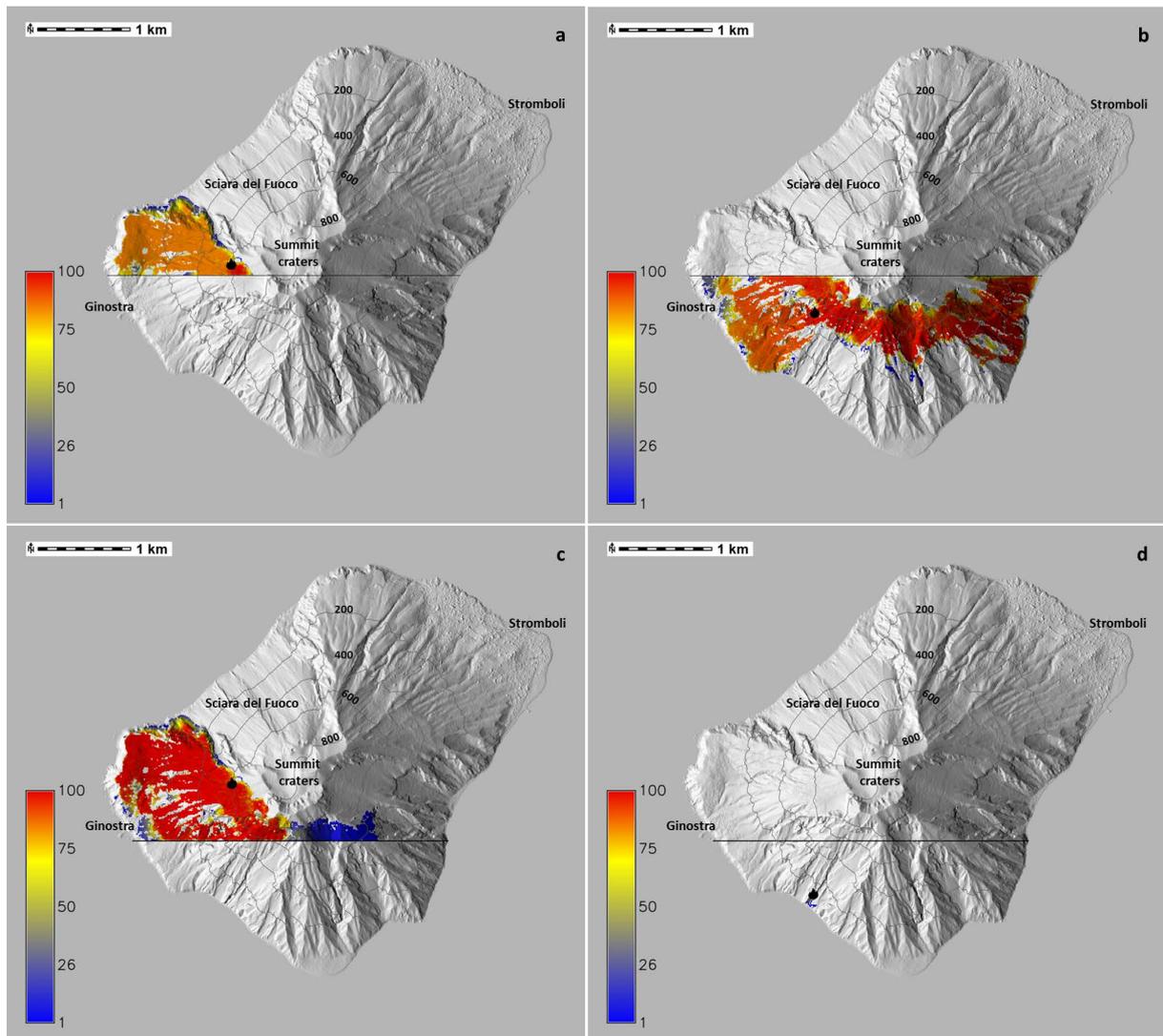


Figure 5. Cumulative probability of combustion given by 100-runs numerical simulations with a linear W-E oriented firebreak located (a) at the middle point of the island; (b) at the middle point with the ignition point 1 km southward; (c) 500 m South of the middle point; (d) 500 m South of the middle point with the ignition point 1.2 km southward. The black flame shows the ignition point.

The first test case we explored creates the firebreak at an altitude of 500 ± 7 m a.s.l., and sets as unburnable only the cells that match the criteria, thus effectively creating an approximately circular firebreak with an average width of approximately 20 m. (Fig. 6a)

In this case, the fire propagates for an average of 240 iterations before reaching the firebreak, which is a small percentage of cases (<2%) manages to escape the ring and propagates both westwards and eastwards (and hence northwards), reaching both Ginostra and Stromboli town.

This probability, while low, is nonzero, and is due to geometric issues due to altitude differences higher than 7 m between neighbouring cells, particularly along the diagonals. This can be solved by adding to the firebreaks also all the cells that are immediate neighbours of the original firebreak. With this setup (Fig. 6b), the fire fails to escape the ring and naturally extinguishes after 216 steps on average.

This result highlights how efficient a circular firebreak would be in leading the fire to self-extinguish at high altitude, being surrounded by unburnable areas characterized by either Sciara or high moisture vegetation content (NDMI).

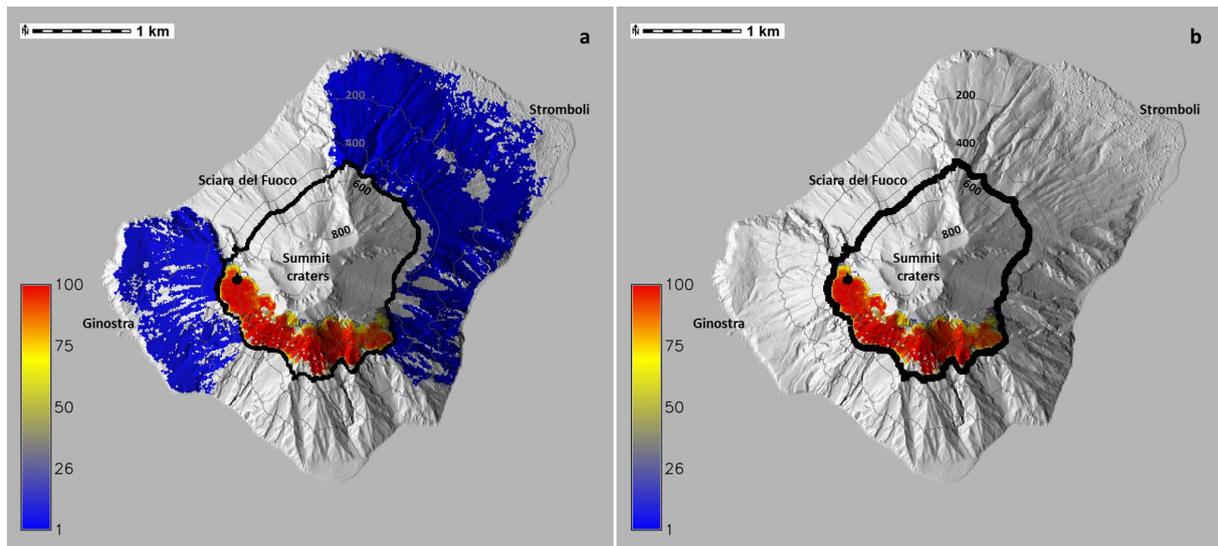


Figure 6. Cumulative probability of combustion with a circular firebreak 30 m wide. Neighborhood radius equal to 1 (a) and 2 (b).

4. Discussion and Conclusions

The numerical simulations performed with the updated VolcFire model illustrate the possible progression of the fire on 3 July 2019 on Stromboli Island under different scenarios. These simulations highlight the importance of firefighters' intervention in mitigating fire damage, since without intervention the simulation suggests that the fire would likely have burnt the entire island, emphasizing the necessity for effective fire suppression measures and the need to explore preventive measures. This becomes of growing importance with the native Stromboli vegetation having been largely replaced by *Arundo donax*, which are highly flammable and can reach heights of up to 7 meters. Moreover, in the main towns, roads are approximately 2 meters wide or less, and the vegetation forms bridges from one side to the other of the road, making roads ineffective at containing fires, and thus increasing the risk of fire propagation even in urbanized areas.

As an application of our numerical model to the development of preventive strategies for volcanic fire risk mitigation, we have explored some possible firebreak placements and how they would have affected the 3 July 2019 fire.

Linear firebreaks in the North-South and West-East directions were shown to be able to protect the town of Stromboli without a need for additional firefighter intervention, but not the village of Ginostra, except for specific positioning of the firebreak compared to the ignition point.

A more effective protection was achieved with an annular firebreak set at an altitude of around 500 m a.s.l., provided that the irregularities in the topography are properly taken into account to produce full enclosure, as this would have protected both Ginostra and Stromboli.

These findings highlight the importance of maintaining strategic firebreak placement in fire-prone areas, to limit fire spread and enhance the effectiveness of firefighting efforts, and that numerical models can be an important tool to help determine the optimal shape and position of the firebreak. In highly vegetated areas around volcanoes (Fig. 3), specialized models become particularly valuable tools for stakeholders in planning interventions ahead of high-risk seasons like the summer (with higher risk of fires due to climate and higher population density due to tourism), and during periods of more intense paroxysmal activity.

Future applications of the VolcFire model will focus on incorporating seasonal environmental changes and probabilistic material fallout map in order to develop hazard maps for fires of volcanic origin, which would provide supplemental information to help direct the design of such firebreaks, possibly leveraging existing infrastructure such as hiking paths and dry stone walls.

Data availability statement. Sentinel-2 Images were downloaded from <https://browser.dataspace.copernicus.eu/>. The figures were generated using the software GRASS GIS.

Acknowledgements. This research has been conducted within the INGV-DPC Agreement All. B, 2022-2024 – “Sistema Unico Stromboli”, Task 4.2: Risk analysis from fires of volcanic origin in Stromboli. This work was partially supported by the INGV project Pianeta Dinamico (CUP D53J19000170001) funded by MIUR (“Fondo finalizzato al rilancio degli investimenti delle amministrazioni centrali dello Stato e allo sviluppo del Paese,” legge 145/2018), Tema VT SAFARI (PI Gaetana Ganci), and “HARVEST-Integrating tHermal cAmeRa data and SPH modeling to quantify Volcanic dEposits at STromboli” (Bando di Ricerca Libera 2021 of INGV, PI Giuseppe Bilotta).

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