**A breakthrough in the understanding of flaming wildfires**

or

**Understanding wildfires starts now**

or

**Mechanisms of wildfire spread are not trivial**

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In this article, I oversee the recent contribution of Finney et al. (1) to our understanding of how wildfires spread by providing its scientific context and also by putting forward the possible impact on the field.

The rise of humanity was intimately bounded to fire. Humans first observed flames when fleeing wildland fires, the natural version of the phenomenon that would then become the most important technological achievement of the human race: the mastery of fire for cooking, lighting, settlement, hunting, and warfare (2).

Wildfires are important to the natural sciences. Since deep time, the top surface of the Earth's crust has been the interface where abundant plant organic matter meets an atmosphere rich in oxygen. This interface is flammable, especially in dry, windy and hot conditions, and leads to wildfire after an ignition event. Not only has fire contributed to shaping most ecosystems on Earth, but it plays essential roles supporting life through the regulation of atmospheric oxygen, the carbon cycle, and the climate (3, 4).

Part to the current anthropogenic age, humans have also modified the fire regimes of many ecosystems, and have contributed for example to its cessation in certain regions (e.g., in the USA National Parks until 1960), or to increasing its frequency and severity through drainage (e.g., peatlands) and possibly through climate change (e.g., arctic fires). Of note, multiple US$ billions are spent annually across the world to fight wildfires for the protection of communities and valuable ecosystems.

Despite its central importance to the planet and to humanity, our understanding of fire remains very limited. For example, we

currently cannot accurately forecast the location of a fire in 30 min time. To quote Hottel (5): “A case can be made for fire being, next to the life processes, the most complex of phenomena to understand”. It comes as no surprise, then, that the discipline of fire science is less mature than other Earth science topics. For example, a quick look at the literature shows that there are three times more scientific studies published per year on volcanoes than on wildfires. Fire science requires more decades of fruitful research to mature and gain full understanding of this natural phenomenon.

The fate of a flaming wildfire starts with its genesis at ignition, by natural means like a lightning strike, or by anthropogenic means like slash-and-burn. Once ignited, part of the heat released by the flames will drive the spread over connected fuel beds of grass, shrubs, and trees. Another mechanism of propagation is by lofting burning embers that land farther away, but flame spread is more important. The dynamics of spread are such that wildfires accelerate with tail winds, dry weather, or up-slopes; and decelerate with head winds, rain or down-slopes.

The most lasting contribution to the science of wildland fires is the pioneering work of Rothermel in 1972 (6). He formulated an empirical model for predicting the spread rate of a wildfire. This formulation is ubiquitous and can be found at the core of most wildfire behaviour simulations. These simulations are currently in use by forestry agencies and firefighting command centres across the world. For example, Rothermel’s model is part of the US Wildland Fire Decision Support System, used in planning of every large and long duration federal wildland fire incident. However, Rothermel’s formulation is empirical: Whilst it can provide rough predictions of the rate of spread by calibration to previous laboratory data, it does not explain how fire spreads. Its empirical nature hinders scientific progress and does not allow for improvements to simulations. Until very recently, there was no valid scientific theory of wildfire spread that could complete Rothermel’s model.

In this context, we see that the recent work of Finney et al. (1) is a scientific breakthrough. Finney et al. have discovered the long-missing piece of the puzzle to understand wildfire dynamics. Their seminal work puts forward for the first time a fundamental, comprehensive and verifiable theory of flaming wildfire spread. Finney’s theory relates the rate of spread to basic fluid mechanics and heat transfer, and it is strongly supported by laboratory data and field observations across a wide range of scales from 10 cm to 15 m.

Fire dynamics dictate that spread can be seen as the succession of ignition events (7). This way, the rate of spread $S$ of a fire is given in Eq. (1) by two terms, the length of fuel bed heated by the

flames (expressed as $\delta$) and the time that a fuel particle takes to ignite (expressed as $t_{ig}$) (8).

$$s = \frac{\delta}{t_{ig}} \qquad (1)$$

We know that $\delta$ mostly depends on flame inclination and the slope of the terrain, whereas $t_{ig}$ depends mostly on fuel properties like particle size, moisture and plant composition.

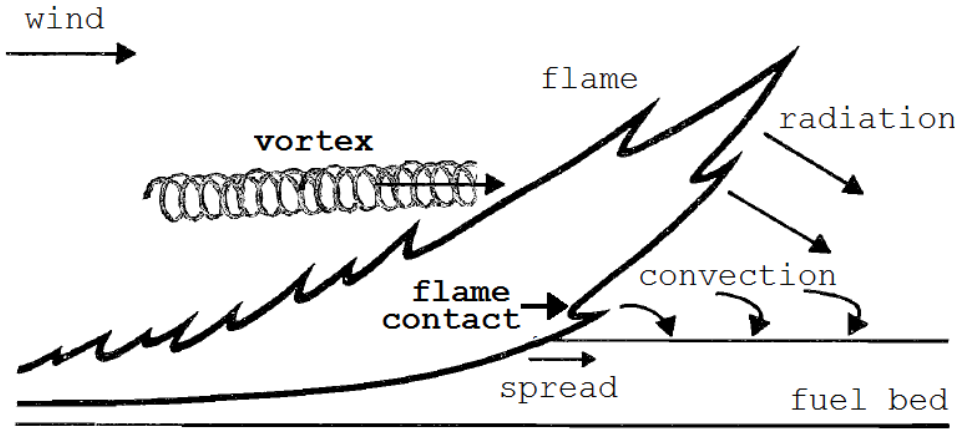



**Figure 1.** Sketch of flame spread of a fire with tail wind over a fuel bed. The paths for heat transfer by radiation, convection and flame contact are noted. According to Finney et al.(1), the vortices are created by buoyant instabilities and lead to ignition of the fuel by flame contact. Figure modified after the original in (6).

The scientific contributions of Finney et al. are cast around the novel identification of the two terms in Eq. (1) that govern wildfires. By careful inspection of visual images of fire across scales, they show that vortex flows and peaks-and-troughs generated by the buoyancy of the flames are responsible for heating the fuel bed length $\delta$. Temperature measurements then show that the intermittency of the peaks-and-troughs causes the flames to instantaneously touch the thin fuel particles, which in turn produces the contact ignition governing $t_{ig}$. Figure 1 shows a sketch including these mechanisms.

Their work feeds into a long-standing debate in the field on whether it is radiation or convection that controls the heat transfer to the fuel bed ahead (see Fig.1). Which is the specific heat transfer mechanism affects predictions made with physically based models (9). Finney et al. settle the debate by identifying with strong evidence that heat transfer is controlled by flame contact, the phenomenon

where both radiation and convection heat transfer are combined, but with the distinctiveness that the timing of flame contact is driven by convective flows.

Finney's theory can have a profound impact in the field. The impact is four-fold regarding i) previous scientific studies, ii) wildfire simulations, iii) new technologies, and iv) multi-disciplinarity. These are explained in the following.

Previous scientific studies on wildfire spread should be revisited to help put Finney's theory into a broader context. Some experimental and computational studies might need to be reinterpreted in the light of the roles of flame intermittency and flame contact. The new state of the art should naturally explain and complete Rothermel's model to give way to a new physically-based Rothermel-Finney's model.

Rothermel-Finney's model would improve simulations of fire behaviour and help them gain in both accuracy and consistency. This in turn would allow the simulations to provide a more reliable layer of information during fire incidents.

The increased accuracy of simulations should eventually allow for high-fidelity forecasting technologies. A technology able to rapidly forecast the movement of a wildfire would lead to a paradigm shift in the response to emergencies, providing the Fire Service with essential information about the ongoing fire (10).

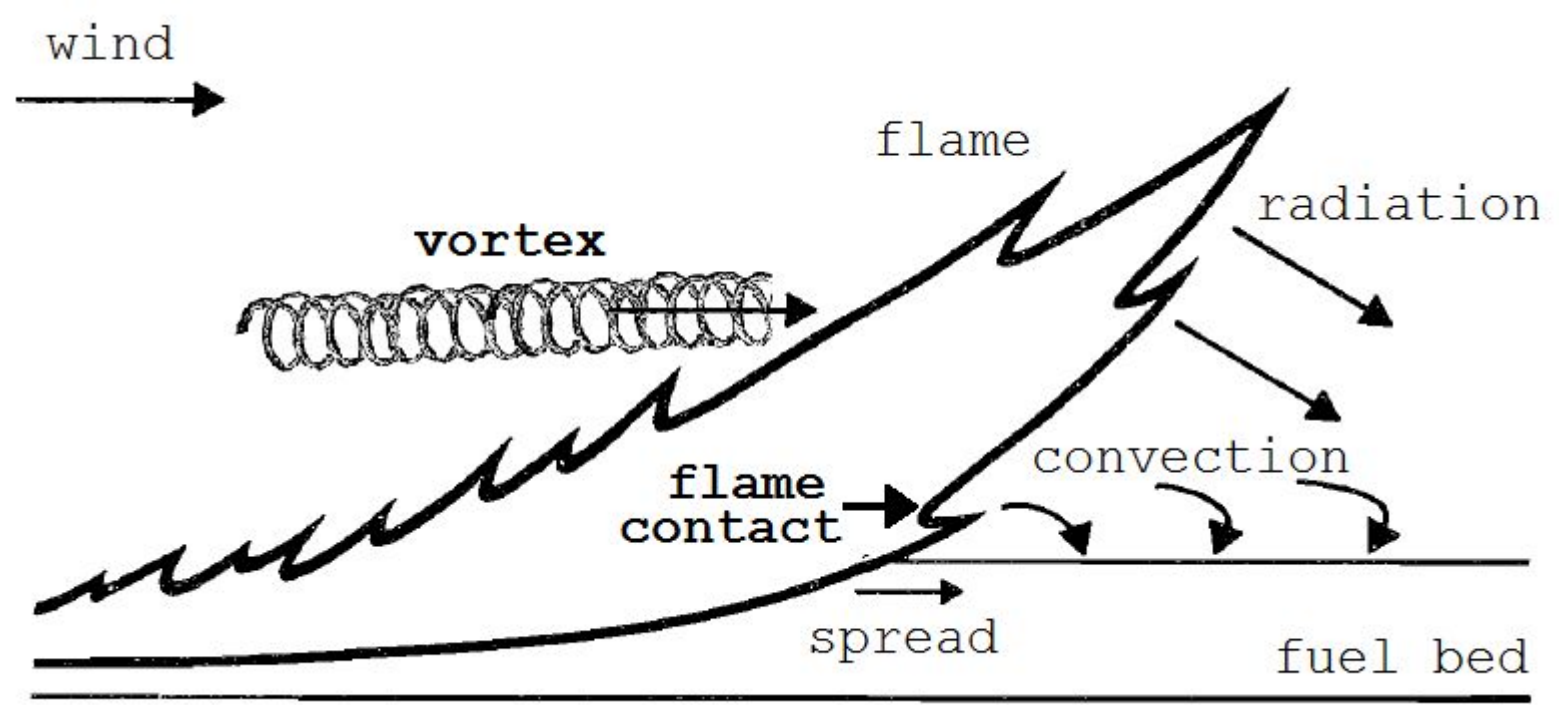
The topic of wildfires is currently fragmented among the fields of biology, ecology, meteorology, chemistry, and combustion. These fields have a lot to offer one another, but better communication and cooperation are essential to move it forward. It is hoped that by strengthening the importance of fundamental knowledge and by settling long-standing debates, Finney et al. will serve as the basis for developing new multidisciplinary collaborations in the study of wildfires.

Finally, I foresee that after reading their work, many readers might start seeing the peaks-and-troughs reported by Finney et al. in every wildfire, as I already do now. As the English poet John Milton once said, "so easy it seem'd, once found, which yet unfound most would have thought impossible".

**References**

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wind
flame
radiation
vortex
convection
flame
contact
spread
fuel bed