

On the need for a theory of wildland fire spread

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Abstract. We explore the basis of understanding wildland fire behaviour with the intention of stimulating curiosity and promoting fundamental investigations of fire spread problems that persist even in the presence of tremendous modelling advances. Internationally, many fire models have been developed based on a variety of assumptions and expressions for the fundamental heat transfer and combustion processes. The diversity of these assumptions raises the question as to whether the absence of a sound and coherent fire spread theory is partly responsible. We explore the thesis that, without a common understanding of what processes occur and how they occur, model reliability cannot be confirmed. A theory is defined as a collection of logically connected hypotheses that provide a coherent explanation of some aspect of reality. Models implement theory for a particular purpose, including hypotheses of phenomena and practical uses, such as prediction. We emphasise the need for theory and demonstrate the difference between theory and modelling. Increasingly sophisticated fire management requires modelling capabilities well beyond the fundamental basis of current models. These capabilities can only be met with fundamental fire behaviour research. Furthermore, possibilities as well as limitations for modelling may not be known or knowable without first having the theory.

Additional keywords: fire behaviour, fuel ignition, heat transfer, live fuels.

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Introduction

How does fire spread in dry grass, and why does it spread faster when the wind blows?

It should be a simple matter for fire scientists to answer such questions, especially for a uniform bed of dry and dead fine fuels like grass. After all, both fire scientists and practitioners frequently make calculations and model predictions for vastly more complex situations. Fire scientists know, however, that fire behaviour models used for operational predictions are empirical (e.g. Rothermel 1972; Forestry Canada Fire Danger Group 1992) and, thus, are tied closely to gross-scale observations (like fire spread rate) rather than dealing with the underlying processes. In addition to these empirically derived models, other models attempt to represent the physical processes responsible for the observable behaviours (see review by Sullivan 2009). If the physics and chemistry are incorporated correctly, then these ‘physically based’ models should be able to help the scientists answer these questions. However, close inspection indicates that these models don’t share a common formulation of the physical and chemical processes as they influence fire spread (Sullivan 2009). Differences don’t appear to be just about implementation or numerical methods. Examination of these physically based models reveals that the fundamental processes of fuel particle ignition and subsequent fire spread are largely assumed without an experimental basis. We do not explicitly know what processes occur and how they occur at fuel particle ignition scales. A fundamental theory of wildland fire spread is missing. And,

without theory, the sequence and influences of known combustion and heat transfer processes cannot be reliably applied to fire spread. So, in regard to the above questions, none of today’s models seem to provide an explanation.

Why do current operational models that demonstrate such usefulness not explain how fire spreads? Because models don’t have to explain anything in order to be useful – they simply need to organise relevant inputs and yield associated predictions that meet a standard of the intended application. Modern uses of operational wildland fire models are suffused with a great deal of uncertainty, imprecision and scarcity of input measurements. Wind speed and direction, for example, fluctuates constantly at many time and space scales but only a single measurement is typically available for time-spans of hours in very large fires in complex terrain. Scanty and imprecise observations of predicted fire behaviours compound this problem such that the errors can easily overwhelm the ability (or need) to achieve model accuracy. Huge variability is evident in fire spread rate, even from small experimental fires in the simplest and most uniform grass fuel types (e.g. Cheney *et al.* 1998).

Some might argue that a solid wildland fire spread theory is provided by the Navier–Stokes equations through their implementation in numerical models (see Sullivan 2009). As Frisch (1995, p. 1) observes, however, ‘The Navier–Stokes equation probably contains all of turbulence. Yet it would be foolish to try to guess what its consequences are without looking at experimental facts’. Such governing equations (including the Navier–Stokes equations) provide process rules such as

conservation of momentum, mass, energy, etc. These equations do not self-apply, but require simplifying assumptions for closure, interactions and computational resolutions when implemented, all made from personnel judgments. Appropriate judgments rely on guidance from theory. Would the Navier–Stokes equations, for example, predict the existence of crown fire *ab initio* or the roles that radiation and convection play in ignition of pine needles? The dependency of theory upon ‘detailed numerical treatments’ was rejected by Williams (1992), who averred that ‘Theory needn’t be right to be good, theory needn’t be mathematical to be right, and theory needn’t be incomprehensible to be mathematical’.

From a practical standpoint, some may be satisfied that as long as fire behaviour calculations fit the observations, there is little value to having a formal underlying theory. The danger here is three-fold: first, judging model success based only on agreement with observations can lead to an illusion of understanding; second, agreement using *a posteriori* calibration suffers a condition of non-uniqueness (Oreskes *et al.* 1994) and potentially reinforces the first point; and third, models (and the knowledge behind them) will inevitably be tasked with uses beyond their original range of association and thus reliability. These three points suggest profound distinctions between theory and operational models. A theory is confirmed through comparison with the actual phenomenon. Theory provides a general description for how phenomena occur and thus serves as a basis for expanding insights into fundamental processes and can serve as a basis for developing model applications. Numerical models are fundamentally a form of hypothesis and, thus, can never be verified as ‘real;’ it is either accepted or rejected (Oreskes *et al.* 1994). An operational model is validated through its utility for application. An operationally valid model may not correctly describe the processes or phenomena; it need only identify a pattern of behaviour that is useful in some way. The operational model is not necessarily based on fundamental insights as to how phenomena work, does not necessarily extend to other patterns of phenomena, and may not provide a reliable basis for further examinations and insights.

A particularly relevant example of this consideration comes from the development of understanding about the workings of our solar system. In the 2nd Century AD, Claudius Ptolemaeus (Ptolemy) described a geocentric conceptual model of the ‘universe’ where the sun and all the planets orbited the earth (they also had to perform circular epicycles as they made their way around the main orbit). The applied model was a device called the astrolabe that related the Earth to heavenly objects. Despite being dead wrong, the concept was intuitive from the perspective of earth-dwelling humans and worked quite well for the intended purpose – to estimate the positions of the planets and serve as the basis for calendars. It persisted for more than 1300 years until Nicolaus Copernicus proposed in 1543 that a simpler heliocentric system (planets in elliptical orbits around the sun) explained anomalies of Ptolemy’s model. Despite correctly fitting the observations of planetary motion, the more accurate heliocentric model was not inherently obvious – and its acceptance was in conflict with the geocentric dogma promulgated by the religious leadership of Europe. Not much later, in 1587 Tycho Brahe entered the debate by offering his geo-heliocentric model – a complex hybrid whereby the sun

orbited the earth and all planets orbited the sun. A fit to his observations of planetary motion (in fact, the most accurate observations available at that time) required elliptical epicycles for each planet. All three models basically fit the available observations and made predictions that were accurate enough for practical uses. A physically appropriate underlying theory was not of interest and did not exist (nor did a scientific attitude to use such a theory) to check the ‘institutional’ model validity. Ultimately, it took another 30 years and the independent analyses of those such as Kepler and Galileo before the Copernican model was accepted because it alone was able to explain persistent anomalies in the observations (e.g. phases of the planets). A physical theory of gravitation explaining how objects orbited in space did not occur until the late 17th Century (by Isaac Newton) and generally developed into the physics discipline of mechanics.

If the historical experience with modelling our solar system is any guide for modelling wildfires then we ought to be concerned about anomalies observed in fire spread. Anomalies reveal situations where observed behaviours conflict with our models or the way our models lead us to think about the phenomenon. Although fire scientists now obsess with how well spread models fit macroscale observational data (e.g. spread rate), there should be equal concern over whether the models are actually based on a physical understanding of fire spread processes – i.e. on an experimentally confirmed theory of fire spread. In this paper we explore the basis of wildland fire behaviour through the use of known anomalies, written with the intention of arousing or provoking researcher curiosity leading to investigations of fundamental problems that persist even in the presence of tremendous technological advances now used in modelling. We are convinced that true advancement in modelling fire behaviour is not possible without having sufficient understanding for a comprehensive theory that addresses fire spread anomalies and the questions posed above.

A complete treatment of all unknowns in wildland fire spread is not possible but we will characterise anomalies and probe questions related to four areas of fire spread: (1) fuel particle heat exchange, (2) the uncertain role of convection, (3) definition of, and criteria for, ignition and (4) issues associated with burning live fuels. Wildland fire spread occurs among separate fuel particles and is, thus, distinguished from flame spread over solid fuel surfaces (Williams 1977) for which experimentally supported theories have been described (de Ris 1969; Fernandez-Pello 1984). Our approach examines fuel particle ignition as the basic requirement for fire spread (either rate or sustainability of spread). Fire spread is the result of sustained ignition and has long been described as a process of discrete ignitions (Fons 1946), yet almost no effort has been directed to explicitly understand those fundamental processes. Our rationale is that until a proper theory of how ignitions occur in wildland fires is determined, there is little hope that the confusion surrounding fire spread modelling can be sorted out. Furthermore, ignition is experimentally tractable, meaning that there is every possibility that a strong physical theory can be developed for it, and thus the possibility that reliable and testable models of any variety can be supported.

Fuel particle heat exchange leading to ignition

Experimental evidence suggests anomalies to our perception of the way fuel particles are heated to ignition at the edge of an advancing fire:

1. Convective cooling can effectively offset radiant heating of fine particles given the range of heat fluxes in wildland fires.
2. Radiation heating of fine fuel particles alone may be insufficient to yield a combustible mixture of flammable gases.

Although physical processes of radiation and convective heat transfer have been incorporated into wildland fire spread models (Weber 1991; Sullivan 2009), how ignitions occur at fuel particle scales has been assumed without an experimental basis. This may result from a preoccupation with modelling fire spread rate rather than understanding the processes of ignition. Although laboratory and field fire spread experiments have been done, they have not explicitly described ignition processes. This deficiency is critical since fire spread results from sustained ignition. Consequently, a modeller's judgment determines the process assumptions without an experimental basis. For example, radiation is commonly assumed to be the primary mechanism governing fire spread. Most modellers, as Sen and Puri (2008) state in their survey of radiation in wildland fire modelling, have assumed radiation to be the 'controlling heat transfer mechanism that fixes the rate of spread of wildland fires'. Albin (1985) assumed that radiation dominated fuel heating during fire spread and reasoned that under most cases a developed flame zone blocks the ambient wind and prevents flames from extending into adjacent fuel. He then assumed the flame front to be a steady plane interface with radiation as the principal heating mechanism for fire spread. Although he recognised convective cooling of preheated fuels from fire induced inflow and added convection to his model (Albin 1986) he never questioned the sufficiency of radiation heating for ignition and, thus, fire spread. Albin continued to assume radiation to be the principal mechanism for fire spread in his crown fire spread model (Butler *et al.* 2004).

Others, however, have questioned the sufficiency of radiation in heating fuels to ignition (Byram *et al.* 1964; McCarter and Broido 1965; Anderson 1969; Van Wagner 1977; Beer 1990; Pitts 1991; N. J. de Mestre, R. C. Rothermel, R. Wilson and F. Albin, unpubl. data, 1985). Baines (1990) and Weber (1991) examined the research results of de Mestre *et al.* (1989) and found that modelled radiation heat transfer could not reasonably represent fuel particle temperatures in advance of a flame zone. The actual fuel temperature rise primarily leading to ignition occurred within 0.02 m of the flame front and over a much shorter duration than predicted by the model using radiation as the sole heating mechanism (Fig. 1). Baines (1990) found that including convective cooling produced temperatures similar to measured fuel temperatures (smooth solid line in Fig. 1). However, the modelled temperature at flame arrival was 475 K, too low for ignition (Baines 1990). From similar experimental fires, Baines (1990) and Fang and Steward (1969) observed that most heating leading to ignition occurred within 0.025 m of the flame front. Currently, the mechanisms responsible for ignition and thus fire spread have not been explicitly determined at this scale.

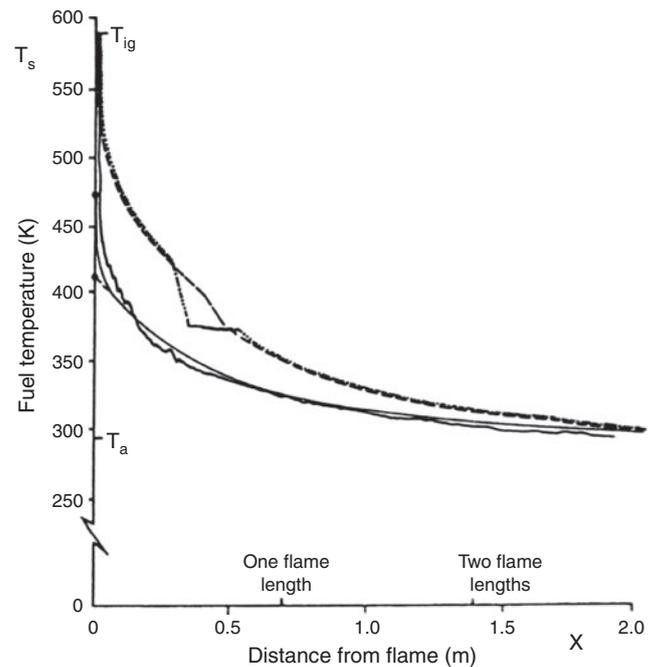


Fig. 1. Graph of fuel particle surface temperature before ignition (excerpted from Baines 1990 with permission) showing measured temperature (rough solid line) compared with radiation models (dotted line: moisture evaporated at 373 K; dashed line: moisture continuously evaporated) (de Mestre *et al.* 1989). Baines (1990) fuel temperature model (smooth solid line) with radiation and convection cooling (constant convection coefficient) predicts the fuel particle temperature of 475 K at flame arrival (Baines 1990). Rothermel and Anderson (1966) also found particles too cool for ignition when the flame arrived.

The experimental fine fuel temperatures of Rothermel and Anderson (1966) were similar to the fuel temperature data of de Mestre *et al.* (1989) (Fig. 1). Importantly, in both experimental cases using dead surface-fuel beds, the fuel particle temperatures were below typical temperatures at ignition. Rothermel and Anderson (1966) measured a fuel temperature of ~450 K when the flame front arrived at or was adjacent to the fuel particle. This fuel surface temperature is 100 K below the production of flammable pyrolysates (Fairbridge *et al.* 1978; Tillman *et al.* 1981, p. 80; Drysdale and Thomsom 1989; Simmons 1995) and 175 K below pyrolysis rates typical for piloted wood ignition (Drysdale 1998, p. 221). These experimental results suggest insufficient heating by radiation before flame contact in fine fuels and are inconsistent with the assumption that radiation is the primary mechanism determining wildland fire spread.

Laboratory results of radiation-heated fuel particles related to particle size also indicate significant differences in fuel particle heat exchange (Martin 1965; Cohen and Finney 2010). From preliminary experiments, Cohen and Finney (2010) found that different-sized fuel particles heat differently when irradiated. Exposed to a 41-kW m⁻² radiant heat flux, 12-mm fuel particles emitted pyrolysates after several seconds (Fig. 2a) with piloted ignition shortly thereafter (Fig. 2b). By comparison, 1-mm particles did not produce observable pyrolysates or significant charring after 2 min when the exposure was terminated (Fig. 2c).

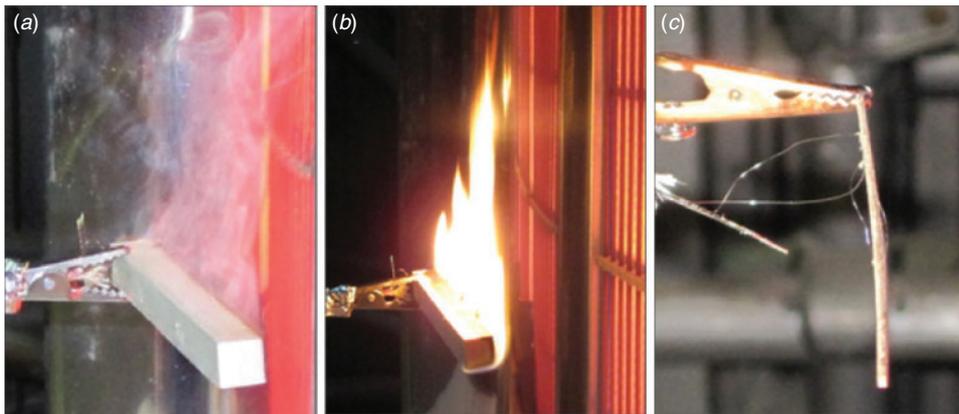


Fig. 2. Photographs of two fuel particles exposed to incident radiation of 41 kW m^{-2} and quiescent air. (a) The 12-mm fuel particle pyrolysing after 15 s of exposure. (b) The same 12-mm fuel particle pilot ignited after 26 s (pilot flame not shown). (c) The 1-mm fuel particle did not ignite or significantly pyrolyse after 2 min.

Although the 12- and 1-mm particle surface temperatures initially increased similarly, they diverged after less than 2 s of exposure at a surface temperature of $\sim 400 \text{ K}$. The 12-mm fuel particle surface temperature continued to monotonically increase. The significant pyrolysis seen in Fig. 2a occurred after 15 s of exposure and corresponds to a measured surface temperature of 590 K (Fig. 3). Piloted ignition occurred at 660 K , as indicated by the abrupt temperature jump 26 s after the initial exposure (Fig. 3). The 1-mm particle temperatures varied between 430 and 470 K after the initial temperature increase (Fig. 3). The 1-mm particle temperatures, the lack of observed pyrolysis and charring, and no ignition are consistent with previous research indicating that this temperature range does not produce significant pyrolysis rates or flammable pyrolysates (Fairbridge *et al.* 1978; Tillman *et al.* 1981, p. 80; Drysdale and Thomsom 1989; Simmons 1995; Drysdale 1998, p. 221).

The apparent perceptual anomaly in fuel particle response to radiation is consistent with heat transfer theory where fuel temperature (transient) is a function of the net radiation and convective heat transfer at particle surfaces in conjunction with the thermal diffusivity of the particle interior. Fuel particle experiments and previous research on heated vertical surfaces (Tibbals *et al.* 1964; Martin 1965; Alvares *et al.* 1970; Incropera and DeWitt 2002, Ch. 9; Kays *et al.* 2005, pp. 370–373) suggest that two different-sized fuel particles of the same material can heat at different rates because their surface (boundary) conditions result in different levels of convective cooling and thus surface temperature. This implies that surface-area-to-volume ratio (SA/V) is not the principal factor; rather, it is the fuel particle vertical surface flow length. For example, the free convection over the 12-mm vertical surface (particle $\text{SA/V} = 333 \text{ m}^{-1}$) results in greater boundary layer development than the 1-mm vertical surface (particle $\text{SA/V} = 4000 \text{ m}^{-1}$). Thus, the greater boundary layer development (Incropera and DeWitt 2002, Ch. 9) of the 12-mm particle is sufficient for its temperature to continue increasing to ignition. This is unrelated to the effect of higher SA/V; indeed, finer fuels result in higher heat release rates and higher spread rates. Higher SA/V increases the particle heat transfer rate (per unit mass) related to a given surface

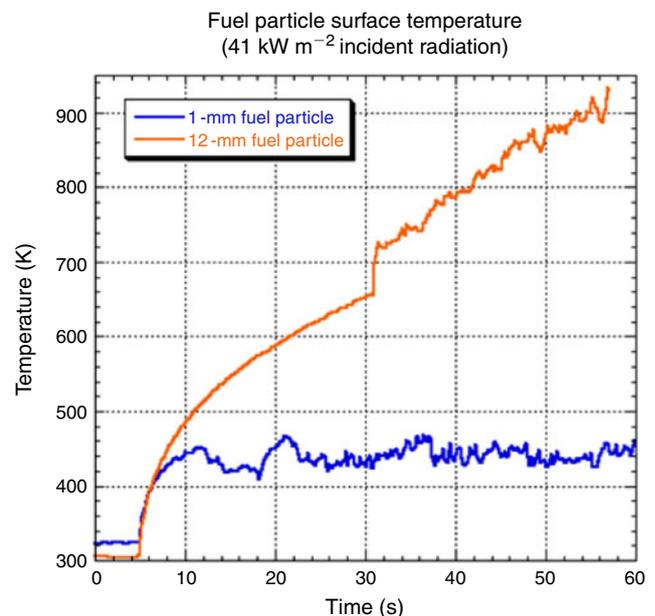


Fig. 3. The 1- and 12-mm particles were separately exposed to an incident radiation heat flux of 41 kW m^{-2} and quiescent air corresponding to Fig. 2. Fuel particle surface temperatures were measured with an imbedded thermocouple in the radiated surface. The 12-mm particle pilot ignited as indicated by the sudden temperature rise 26 s after the initial exposure.

temperature; however, SA/V *per se* does not determine boundary conditions and thus the particle surface temperature. Continuing this logic, a high SA/V particle with a broad surface (leaf) exposure would have higher surface temperatures than the same SA/V particle having an exposed narrow square cross-section (needle). Notably, the experimental 1-mm particle is at the coarse end of fine fuels (Scott and Burgan 2005) and particularly related to some western USA coniferous and shrub foliage known for active crown fire (Rothermel and Anderson 1966; Rothermel and Philpot 1973). On the basis of our computed (heuristic) estimate of a free-convection heat-transfer coefficient

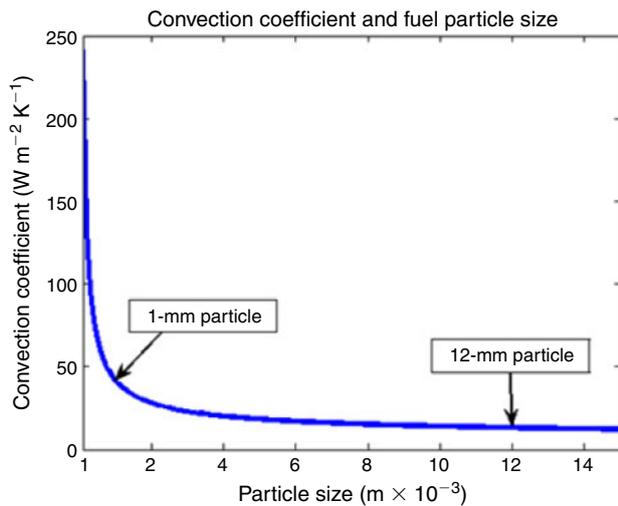


Fig. 4. The computation of potential convective heat transfer as a function of surface flow length (Incropera and DeWitt 2002, eqn 9.27) reveals that the free convection heat transfer coefficient becomes highly sensitive to particle size at less than 1 mm and insensitive to size at 12 mm and larger. For the calculated convection coefficient, incident radiation heat flux and environmental temperatures are assumed constant with a mid-length fuel surface temperature, $T_s = 197^\circ\text{C}$ (470 K).

(Incropera and DeWitt 2002, eqn 9.27) we would expect fuel particles finer than 1-mm (with non-elongated cross-sections) to have greater convection cooling during a flame radiation exposure than demonstrated by our experiments (Fig. 4).

The fuel particle experiments are also consistent with laboratory-scale fuel bed experiments. N. J. de Mestre, R. C. Rothermel, R. Wilson and F. Albin (unpubl. data) showed that fire spread in pine-needle beds was not sensitive to radiation shielding from flames above the fuel bed. McCarter and Broido (1965) found similar effects in crib fires. Laboratory fires in deep fuel beds suggested the necessity of flame contact to adjacent fuels for fire spread (Finney *et al.* 2010); no significant 'smoky' pyrolysate emissions were observed from adjacent fuels within the fuel bed before flame contact and ignition. This indicated that flame contact was not solely a pilot igniter but rather contributed convective heating necessary for ignition and thus fire spread. The apparent lack of significant pyrolysis in fuel adjacent to the flaming region indicates insufficient radiation heating and, thus, fuel temperatures too low for significant thermal decomposition. The results of fuel particle heating experiments (Cohen and Finney 2010) provide a possible physical mechanism consistent with the deep-fuel bed experiments and the fuel temperature–flame front distance data shown in Fig. 1.

In summary, our review of existing research indicates an insufficient experimental basis for determining fuel particle heat exchange during flame front approach and thus an insufficient basis for related fire spread model assumptions. Independent experimental evidence along with heat transfer analysis suggests that radiation heating is insufficient for fine fuel particle ignition and fire spread, at least under some conditions. Our preliminary experiments suggest increased convective heat transfer as fuel particle surfaces decrease (in the flow direction).

This will occur whether heating or cooling. During our experiments free-convection cooling offset the radiation heating. But convective heating during flame contact would rapidly increase fine fuel temperatures. If radiation alone is insufficient for fine fuel ignition, our experiments suggest the possibility of flame contact and convection as a primary mechanism for fire spread. These findings and implications are inconsistent with the assumptions for current 'physically based' fire spread modelling and serve to emphasise the critical need for expanding fire spread theory to the wildland context; that is, understanding what wildland fire spread processes are occurring and how they occur at fuel particle scales.

Convection

Experimental research has not revealed how convection contributes to particle ignition in wildland fires and there is little consistency among modelling approaches for representing convection. The likelihood that particle ignition is produced by fine-scale non-steady behaviour of buoyant diffusion flames inside the fuel bed is at odds with modelling concepts that characterise convection as time-averaged quantities.

The above discussion on the sufficiency of radiation for heating fine fuel particles leads directly to questions concerning the contribution and means of convective heat transfer. The term convection is intended to describe heating of a fuel particle by flame impingement (turbulent or laminar flow). The substantial velocity of flame gases exchanged between particles suggests that convective heating is the predominant influence compared with gas phase conduction (de Ris 1969; Williams 1977), soot or gas radiation (Baukal and Gebhart 1996) or even conduction through particles, which have been shown to be responsible for slow flame spread along solid fuel surfaces (Fernandez-Pello 1984). Unfortunately, less wildland fire research has been devoted to direct measurements or investigations of convection than radiation. Some of the early literature was, however, quite concerned with these distinctions. Byram *et al.* (1964) made observations of fuel element ignitions inside wooden cribs associated with random momentary flame contacts well ahead of the burning zone. Similar observations were made by Rothermel and Anderson (1966) and Albin (1967). Byram *et al.* (1964) further investigated convection by recording ignition distances of cotton tufts downwind of a pool fire as a function of windspeed and flame deflection. They generally concluded that 'the nearly continuous envelopment of the surface fuel for some distance ahead of the leading edge of the active burning zone plus random flame contacts at greater distances ignite the surface fuel'. Fang and Steward's (1969) experiments also indicated that 'rapid heating is produced by some complicated mechanism of convection heat transfer between local fires and the fuel particles' within 2.5 cm of the combustion interface, accounting for 60% of the energy required for ignition. Recently, experiments by Dupuy and Marechal (2011) seemed to confirm that slope angle increases fire spread rate because of non-steady convective heating.

Small-scale experiments by Vogel and Williams (1970) and Carrier *et al.* (1991) using matchstick arrays clearly demonstrated a critical, if not exclusive, role of flame contact in determining spread (as did Fang and Steward 1969). Weber (1990) and Beer

(1990) explored the use of modelled laminar flame profiles from these kinds of small fuel elements to produce 'geometric' models of fire spread and behaviour on slopes and with wind. Detailed investigation at even smaller scales of intraparticle spread demonstrated the dependency on buoyant convection from beneath the particle (Weber and de Mestre 1990) and an intriguing correspondence between ranges of spread rates for different particle orientations and compact fuel beds (Weber and de Mestre 1990). At larger scales with laboratory fuel beds up to 1.2 m deep, similar discontinuous fuel geometry resulted in an almost identical dependency of spread and particle ignition on contacts with turbulent flames (Finney *et al.* 2010; Yedinak *et al.* 2010). These studies collectively suggest that buoyant convection could be the principle mechanism of fire spread (Weber 1991). Buoyant convection might explain the cross-scale applicability of Nelson and Adkins' (1988) dimensionless correlation for wind-driven surface fires as well as describing crown fire spread rates (Taylor *et al.* 2004). Baines (1990) argued that turbulent fluctuations that advect flames downward into the fuel bed should be critical to spread in surface and crown fires. Consistent with the notion that intermittent or sporadic convection is responsible for ignition, Clark *et al.* (1999) and Coen *et al.* (2004) reported forward-bursting vortices and periodic coherent flame structures were primarily responsible for the spread of crown fires.

Given the inconclusive experimental research on convection, it is not surprising that convective fuel heating is not addressed consistently, if at all, in modelling fire spread. Models have been formulated with radiation heating alone (Albini 1985) or in a dominant role (Morvan and Dupuy 2001; Simeoni *et al.* 2001). Including convection in such models has required 'strong assumptions' and 'unknown parameters' (Dupuy 2000; Balbi *et al.* 2009) involving idealised flame flow, the gas temperature field or intermittency of the flame edge. Although lacking an experimental basis, some modelling efforts offer insightful conceptual explorations of possible roles for convection. In the 1960s, model concepts by Emmons (1965), Hottel *et al.* (1965) and Albini (1967) introduced mathematical treatments of intermittent convective heating. Hottel *et al.* (1965) offered that penetration distances into the fuel bed by turbulent eddies should follow a Gaussian distribution. Later, Steward (1971) acknowledged the substantial contribution of convection and a role for intraparticle spread and flame contacts as well as convective cooling of fuel particles but did not attempt an explicit description of the convective heating process. A model of a steadily spreading fire by Pagni and Peterson (1973, pp. 1099–1107) included both internal convection for preheating and the Gaussian formulation for turbulent diffusion in the mode of Hottel *et al.* (1965). Behaviour of their model suggested that fire spread was largely a function of convective heating in wind-driven fires. Numerical simulations are now capable of representing large-scale fluid flows and convective heat transfer (Linn 1997; Mell *et al.* 2007) but the models' sub-grid ignition process assumptions largely have no experimental basis. A sound theory of fire spread, including the characteristics of convective heating, would greatly improve the consistency and reliability of these models and afford some hope for independence of spatial grid resolution.

Ignition

Ignition of fuel particles occurs after the solids are heated at a rate high enough to produce a sufficient quantity of pyrolysis gases, that when mixed with air can ignite and burn with a heat release rate greater than the heat loss rate to the surroundings. This description is physically consistent, unlike the assumption of ignition temperature and total heat balance used in wildland fire modelling.

Regardless of whether radiation or convection produces ignition, the question of what defines a state of ignition or sufficient condition for ignition must be answered. To date, ignition criteria of wildland fuels are described only by the crudest approximations, thus limiting the development of a theoretical basis for fire spread. And without a theoretical basis answers to practical questions such as 'when will a fire spread and when will it not?' and 'how fast will a fire spread?' will continue to elude us.

The processes of fire spread have long been described as a series of piloted ignitions (Fons 1946). Ignition is commonly viewed, both in the wildland fire and fire-protection engineering communities, as simply heating the fuel to its ignition temperature. Though the ignition temperature assumption is very common and, in fact, empirically derived (see, for example, Babrauskas 2001, pp. 71–88), it is not physically consistent with what is actually occurring. The ignition temperature assumption may be satisfactory for some situations, but a physically consistent approach for describing ignition and predicting fire behaviour thresholds in highly heterogeneous and non-uniform wildland fire conditions is required. The well known problem of using temperature to empirically determine a fuel's ignition arises in part because it is very challenging to reliably measure the surface (or even in-depth) temperature of a solid fuel (Babrauskas 2003). Additionally, an ignition temperature does not exist but rather it varies from fuel to fuel, different environmental conditions, heating method and rate, and even spatial orientations (i.e. horizontal versus vertical) (Fangrat *et al.* 1996; Torero 2008). For example, changing the rate of heating from 15 to 30 kW m⁻² (still much lower than expected in a wildfire) of wood can decrease its ignition temperature by up to 100°C (Li and Drysdale 1992; also see Atreya and Abu-Zaid 1991; and Moghtaderi *et al.* 1997)! (To further illustrate the unreliability of ignition temperature, non-charring polymers can actually demonstrate the opposite trend where the ignition temperature increases with heat flux – see Cordova *et al.* 2001.) As previously discussed, there is a fine balance between heating and cooling in spread through fine fuels and this amount of uncertainty in the ignition criteria can have a significant influence on the outcome of the predictions. Furthermore, most ignition temperature measurements were performed by radiative heating of the samples, not convective heating as would be expected in a wildland fire (Babrauskas 2001, pp. 71–88, 2003), which essentially renders the tabulated values useless! Because the ignition temperature is purely an empirical quantity, there is no way to predict it *a priori*. In order to make accurate predictions, a physical understanding of ignition is required.

The physical definition of ignition derives from understanding the inception of flaming combustion of solid fuel which actually occurs in the gas phase. Described thoroughly by

Torero (2008), as the solid fuel is heated, it thermally decomposes or pyrolyses, and it is these pyrolysis gases (pyrolysates) that actually ignite and burn (for discussions on wood pyrolysis see, for example, Sullivan and Ball 2012 or Roberts 1970). Solid pyrolysis is a temperature-dependent (Arrhenius-type) reaction, so that the hotter the solid gets the faster the pyrolysis reaction occurs. The pyrolysates escape from the solid and mix with the ambient air. In order for sustained ignition to occur, a mix of flammable pyrolysates must be generated at a high enough rate to produce a sufficiently hot flame above the solid surface. If this isn't the case, then the heat losses from the flame, both to the ambient and to the solid itself, will extinguish the flame. Physically, ignition is a coupled solid and gas phase phenomenon and there is a critical pyrolysis rate (Rasbash *et al.* 1986; Drysdale and Thomsom 1989) or heat release rate (Lyon and Quinterre 2007) from the establishing flame for sustained ignition to occur (Torero 2008). Currently, there are only approximations of the 'critical mass flux' and 'critical heat release rate' in the literature for solid wood (e.g. Koohyar Welker *et al.* 1968; Melinek 1969; Atreya and Wichman 1989; Delichatsios 2005; Lyon and Quinterre 2007) and no study has been performed looking at this for leaves, needles and fine branch materials. As with ignition temperature, however, the critical mass flux and heat release rates can vary with environmental conditions, such as heating rate, wind velocity and ambient oxygen concentration (Rich *et al.* 2007). In addition, the effect of moisture content on these critical parameters is completely unknown. Theoretically, these are parameters that can be derived once sufficient material properties and pyrolysis reaction mechanisms are known (Rich *et al.* 2007). Unfortunately, material properties of fine fuels are virtually unknown, even completely dry and room temperature. The variation of density, specific heat and thermal conductivity with temperature and moisture content is a vital piece of the puzzle in understanding ignition.

With few exceptions (Drysdale 1998, pp. 222–227), ignition studies have been performed with a constant radiant heating rate. However, as discussed above, this is not a realistic representation of the heating that fine fuels experience during fire spread. Given that flame contact is a likely heating mechanism for fire spread, a flame's non-steady, fluctuating flow produces intermittent convective heating. The necessary conditions for sustained ignition are required to determine the relationship of non-steady heating produced by intermittent flame contact with the fuel particle thermal response.

The fuel temperature depends on the relationship between the frequency of convective heat pulses and the thermal response time of the fuel particles. The thermal response time of the fuel depends on particle thickness (SA/V), thermal diffusivity (density, specific heat, thermal conductivity and moisture content) and the convection heat transfer coefficient of the flames (Incropera and DeWitt 2002, pp. 240–297). If the frequency of the variations in flame convection is sufficiently larger than the response time of the fuel, the fuel cannot respond fast enough to the changes in heat input. The fuel temperature will then appear to increase as if a constant, average heating rate was used. However, if the frequency of the variation in flame convection is on the order of the fuel time response, the time-dependent fuel temperature will show some correspondence with the temporal variation of the flame convection. Whether

this time-dependent temperature extends throughout the fuel volume (for a thermally thin fuel, lumped capacitance assumption) or primarily occurs at the surface (for a thermally thick fuel, semi-infinite solid assumption) will depend on currently unknown fuel properties such as density, specific heat and thermal conductivity.

Sustained flaming occurs as thermal and pyrolysate conditions cross the ignition threshold. Our previous discussion of fuel particle heat exchange not only relates to convection cooling but heating as well and indicates a non-linear dependency of convection heat exchange related to particle size. Additionally, our combined preliminary findings (Cohen and Finney 2010; Finney *et al.* 2010; Yedinak *et al.* 2010) indicate that fire spread processes occur with non-linear dependencies at fuel particle scales. Sustained ignition thus corresponds to a critical set of conditions rather than an average or central tendency of conditions. This suggests that simple averages of fuel and flame characteristics and ignition conditions cannot be reliably applied at bulk fuel bed scales. Simplifying assumptions necessary for applied fire spread models can only be applied after first understanding the ignition processes at the particle scale.

Live fuels are distinct from dead fuel

Fire spreading in live vegetation presents another set of anomalies that presently defy modelling and theoretical explanation:

1. Experimental evidence shows that live fuels can sustain spreading fire with many times the moisture content of dead fuel beds incapable of supporting fire spread.
2. Water content of live fuels cannot be defined the same as for dead fuels (dry weight basis); unlike dead fuels, the live dry weight is composed of seasonally varying non-structural carbohydrates, fats and other compounds.
3. Although dead fuels diffusively lose water during preheating, live fuels appear to retain most water during preheating until structural failure releases the plant's water solution.

Moisture content

Intrinsic fuel characteristics, such as fuel moisture content, are commonly assumed to influence live fuel fire behaviour (Countryman 1974; Richards 1940). This assumption was framed by early fire spread research in dead fuels that suggested fuel moisture plays a dominant role in determining the rate of spread and heat release of a fire (Fons 1946; Hawley 1926; Rothermel 1972). Consequently, because of the strong apparent dependence of fire behaviour on dead fuel moisture, researchers simply assumed that live fuels behave like very moist dead fuels. Dead fuels rarely support flaming combustion with moisture contents above 35% (Hawley 1926); however, fire can spread through exclusively live foliage even though the moisture content is 2–3 times higher (>100%) (Weise *et al.* 2005). These relationships are further complicated when both live and dead fuels occur in the same fuel volume (Catchpole and Catchpole 1991). This suggests different fuel structures and ignition conditions for live fuel fire spread compared with dead fuel beds. And importantly, this paradox emphasises our near complete lack of understanding for live fuel fire behaviour and thus the need for fundamental research.

Fuel moisture content is expressed as the ratio of water in the foliage to its dry weight. It has been shown to vary diurnally (Philpot 1965) and seasonally across a range of plant functional types (Philpot and Mutch 1971; Pook and Gill 1993; Pellizzaro *et al.* 2007) and many studies have correlated live moisture content to the ignition and spread characteristics of fires (Xanthopoulos and Wakimoto 1993; Dimitrakopoulos and Papaioannou 2001; Weise *et al.* 2005; Sun *et al.* 2006; Pellizzaro *et al.* 2007; Pickett *et al.* 2010). It is frequently measured seasonally and compared with fire activity in order to assess fire seasons or determine critical fire behaviour thresholds (Chuvienco *et al.* 2009; Dennison and Moritz 2009).

Diurnal and seasonal changes in live moisture content are usually interpreted as the fuels 'drying out' during the approach of a fire season even though foliar moisture content is poorly related to soil moisture (Pook and Gill 1993). However, changes in live fuel moisture content are much more difficult to interpret than changes in dead fuel moisture content because both their fresh weight and dry weight can change seasonally. Live fuel fresh weight is altered through changes in soil water uptake and loss by transpiration (Nelson 2001) whereas dry weight is modified by accumulating and depleting carbon stores and the translocation of various compounds throughout the plant (Larcher 1995). All of these factors can modify the apparent foliar moisture content and can confound the seasonal interpretation of fuel moisture changes (Kozłowski and Clausen 1965; Little 1970). Phenomena such as the 'spring dip' observed in Jack Pine forests (Forestry Canada Fire Danger Group 1992) are explained as a drying of the vegetation during spring but some workers have suggested that the dip in foliar moisture content is due to changes in crude fats and carbohydrates that alter their dry weight (Little 1970). Additionally, it is unclear how these relationships vary between species or across plant functional types. The causal uncertainty of seasonal changes in live fuel moisture content abound in the literature and little is known about how the changes in leaf moisture and chemical composition alter ignition and heat release rate.

Leaf chemistry

Live fuels contain fat-based phytochemicals such as waxes, essential oils, terpenoids and other trace compounds, commonly referred to as 'ether extractives' (Philpot and Mutch 1971). These compounds are of particular interest because they have the highest heat content of any compound in forest fuels (Núñez-Regueira *et al.* 2005). However, their contribution to ignition and combustion has been the source of much speculation but little experimental investigation. Philpot (1969) found that the heat content of forest fuels was related to their ether extractive contents and Ormeño *et al.* (2009) found them to be an important factor in the spread rate and flame heights of fires in dead leaf litter. Conversely, others have found that ether extractives were of little use in determining flammability of forest fuels (Bunting *et al.* 1983; Alessio *et al.* 2008). Extraction methods rarely differentiate between the types of phytochemicals being tested and this lack of differentiation may be one of the reasons for conflicting results from these studies. Owens *et al.* (1998) found that certain types of monoterpenes can increase flammability of juniper foliage whereas other monoterpenes decrease flammability but both occur concurrently in the live plant tissue. The effect of ether

extractives on ignition during fire spread remains speculative, with fundamental research required to elucidate their contribution to fire behaviour.

Although ether extractives are frequently the discussion topic regarding live fuel fire behaviour, live fuels are not simply composed of moisture and fats. Rather, plants are composed of several categories of compounds that can be broken down into four main groups: carbohydrates, fats, protein and inorganics (ash). Structural carbohydrates give foliage support and rigidity and are generally composed of cellulose, hemicellulose and lignin. Non-structural carbohydrates store energy in the forms of sugars and starch and are generally composed of mono-, oligo- and polysaccharides. Fats serve as additional energy reserves, waxes to prevent leaf water loss and terpenoids for defence against herbivory (Kozłowski and Pallardy 1979). Proteins are primarily composed of the enzymes and substrates used in photosynthesis. Inorganic or ash content makes up the total mineral content of the foliage. Although all of these categories are essential for plant functioning, they vary throughout the season. For example, once a leaf is fully developed, the total amount of structural carbohydrates changes very little whereas the amount of non-structural carbohydrates varies significantly throughout the season as a function of photosynthetic rate and allocation to other plant parts (Larcher 1995). Non-structural carbohydrates can make up over 40% of the foliar dry weight. Because the dry weight does not distinguish the type of carbohydrates and other compounds, the live fuel moisture content does not reflect the seasonal changes in foliar composition (Kozłowski and Clausen 1965; Little 1970). Virtually nothing is known about the effects of seasonal changes in carbohydrates on the ignition and combustion of living foliage, even though they can make up over 40% of the foliar dry weight.

Live fuels and fire behaviour predictions

Heat transfer theory and experimental data both indicate that ignition takes longer for live foliar fuels with high moisture contents than dead fine fuels at nominal moisture contents. Empirical studies have been performed that correlated ignition time with moisture content (e.g. Xanthopoulos and Wakimoto 1993; Dimitrakopoulos and Papaioannou 2001), but these studies are applicable only to the materials tested and the testing method. Currently, no reliable methods exist to predict or describe live fuel ignition. Thus, a fundamental, physical understanding of live fuel ignition processes is needed. Live foliar moisture affects ignition in both the solid and gas phase, resulting in increased ignition time (Babrauskas 2003). Water changes the thermal properties of the solid fuel (density, thermal conductivity and specific heat), and its evaporation is strongly endothermic. Water vapour dilutes flammable pyrolysates and absorbs energy. Preliminary studies (Cohen and Finney 2010; Finney *et al.* 2010; Pickett *et al.* 2010; Yedinak *et al.* 2010) suggest that fire spread through live canopy fuels does so with significant water remaining within and adjacent to burning foliage. Water vaporisation occurs simultaneously with pyrolysis and, thus, affects the gas phase by diluting flammable pyrolysates, absorbing energy and possibly altering combustion reactions, resulting in ignition delay (King 1973; Janssens 1991; Babrauskas 2006).

Furthermore, the non-structural carbohydrates and other compounds in solution change the water colligative properties and potentially leave the foliage with the water solution. The presence of a solute such as sugar can raise the boiling point to nearly 135°C (Özdemir and Pehlivan 2008). Pickett *et al.* (2010) conducted foliage ignition experiments (convection heating) resulting in measured interior leaf temperatures of 130°C. In addition to elevated boiling points, the cell structure likely impedes solution release. As intercellular liquid water is heated and expands, structural failure occurs and cellular contents are released into the flame as either liquids or gases. This suggests elevated temperatures of cell solutions that require more energy before leaving the cell as well as an eruptive escape of water and solutes. This, in turn, suggests very different ignition and combustion processes for live foliage fuels than of dead fuels. Current literature reflects neither a definitive understanding of live fuel ignition and combustion nor a consensus as to what ignition and combustion processes are important.

Ultimately, live fuel moisture, chemistry and even cellular structure affect the bulk physio-chemical properties that must be considered when developing a complete theory of fire spread that acknowledges the major differences between live and dead fuels.

Considerations and implications for fire modelling

In this article we have identified anomalies in the perceptions of several physical characteristics of wildland fire spread for the purpose of illustrating the weaknesses in the foundations of fire behaviour research and modelling. As long as such anomalies remain unexplained, progress and confidence in fire modelling will be held back. It is obvious that these topics alone are not sufficient for a complete theory of fire spread, but it is also clear that no theory would be complete without them. At the same time that research pursues these elements of theory, it is helpful to consider how these individual physical components contribute to a concept of how fire spreads – and thus, what opportunities and constraints exist for modelling.

The discrete particles that form wildland fuel beds have given rise to descriptions of spread as a succession of ignitions (Fons 1946). The flame zone is the energy source for heating adjacent fuels to ignition. When the heated fuels sustain ignition, they become part of the flame zone – the heat source. Thus a dynamical link exists between the state of the flame zone and fuel heating to ignition. Sustained ignition produces fire spread and it is influenced by the dynamic link in two complementary ways: (1) the time required for fuel ignition and (2) the heat transfer from the flame zone to adjacent fuel. If the heating time to ignition increases (decreases), the spread rate decreases (increases) and, importantly, the flame zone depth decreases (increases). Spread thresholds occur when the flame zone condition sufficiently changes the heat transfer at the flame front such that fire initiates or ceases. Crossing the threshold to active spread will occur when increasing flame zone size produces increasing heat transfer to adjacent fuels, resulting in a reduction of fuel ignition time that further increases flame zone size above the heat transfer minimum for spread. The threshold can be expressed in terms of the fuel mass time to ignition equal to the fuel mass consumption rate.

Fire spread thresholds can occur in dead fuel beds as well as live shrub and tree canopies although there are fundamental differences. Dead litter fuel beds are commonly dense enough that with low enough moisture content the resulting flames from even one fuel particle can ignite adjacent particles (Wilson 1982). A single burning particle can initiate burning, resulting in fire spread. Experience indicates that this would be unlikely in live canopy fuels. Compared with surface litter fuels, the live foliage that commonly sustains fire spread has lower densities and fuel voids within and between canopies (Countryman and Philpot 1970; Brown 1981; Keane *et al.* 2005). Individual or even small clusters of live foliage particles typically do not sustain combustion resulting in fire spread. This suggests that, for any given conditions, a minimum flame zone size, and thus minimum spread rate, is necessary for continued ignitions and sustained propagation.

Understanding fundamental heat transfer and combustion processes is necessary but not sufficient for reliably predicting active fire spread in dead fuel complexes or live canopies. Our ability to predict the behaviour of a phenomenon requires that we: (1) sufficiently understand its processes, (2) that we can adequately measure the conditions that influence those processes and (3) that the phenomenon's behaviour is uniquely the result of the measured conditions. However, our discussion above identified active crown fires in particular as a dynamical system and non-linear near threshold conditions. That is, the flame zone condition (heat source) determines the fire spread (ignition), and the resulting fire spread determines the flame zone condition and so on. When the fuel and flame conditions are well above the spread threshold, the ever-changing conditions during actual fire spread results in changing spread rates. These modulating spread rates largely describe our experiences with dead litter fuel beds. However, when conditions are near the spread threshold, as may be common for active crown fires, varying fuel, weather, topography and flame zone conditions can rapidly produce the onset of active crowning or its cessation. With a different flame zone (heat source) condition, the same fuel, weather and topography conditions can produce a different fire behaviour result. This fire behaviour description indicates that active crown fire near threshold conditions lacks predictability in two possible ways (Schneider and Griffies 1999):

1. The crown fire response occurs at a scale smaller than can be measured for model inputs, particularly near the spread threshold (measurements of the fuel, weather and topography).
2. The initial fuel, weather and topography without the flame zone conditions do not uniquely determine the resulting crown fire behaviour, i.e. more than one distinct outcome is possible for the initial conditions (model inputs).

A theory including active crown fire must consider more than heat transfer and combustion processes; it must also include the behaviour of the dynamical system. Even with a detailed understanding of heat transfer and combustion processes a reliable model for crown fire prediction may not be possible for the two reasons above. Hypothetically, if we were to have complete understanding and created a 'perfect model' of active crown fire spread, our inability to provide sufficient inputs and adequately account for the internal variability of the dynamical system could result in unreliable predictions (Schneider and

Griffies 1999). Thus, a fire spread theory that includes active crown fire will be required to include dynamical considerations. Such a theory is necessary for model applications to assure reliable fire spread process descriptions and, importantly, to associate appropriate data and model accuracy and precision with predictability requirements.

Conclusions

Fire spread research has historically been motivated by needs of fire suppression operations. Because of the desire for practical tools, fire modelling or model engineering was seen as the foundational science. The rapid rates of technological advances in computing have greatly helped in modelling and proliferation of models. These models, however, offer little in the way of solutions to questions of how fire actually behaves. Research into how fire spreads has not received the boost from technology because this research primarily involves asking questions, not finding solutions and providing products. In fact, basic fire research has been largely neglected in the rush to advance technological solutions. We have offered some examples as to why, without a firm understanding or theory of fire spread, model engineering will be limited to addressing only known problems in narrow ranges of conditions. Although models may succeed in this, the underlying validity of the models will not be known and may even be misleading by comparisons only with observations. Ideally, models must be anchored by the principles of an accepted theory, thereby opening the door for models to be more generally applied than indicated by current needs.

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