

Role of buoyant flame dynamics in wildfire spread

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Large wildfires of increasing frequency and severity threaten local populations and natural resources and contribute carbon emissions into the earth-climate system. Although wildfires have been researched and modeled for decades, no verifiable physical theory of spread is available to form the basis for the precise predictions needed to manage fires more effectively and reduce their environmental, economic, ecological, and climate impacts. Here, we report new experiments conducted at multiple scales that appear to reveal how wildfire spread derives from the tight coupling between flame dynamics induced by buoyancy and fine-particle response to convection. Convective cooling of the fine-sized fuel particles in wildland vegetation is observed to efficiently offset heating by thermal radiation until convective heating by contact with flames and hot gasses occurs. The structure and intermittency of flames that ignite fuel particles were found to correlate with instabilities induced by the strong buoyancy of the flame zone itself. Discovery that ignition in wildfires is critically dependent on nonsteady flame convection governed by buoyant and inertial interaction advances both theory and the physical basis for practical modeling.

wildfires | buoyant instability | flame spread | convective heating

Wildland fires are distinguished from industrial and urban fires by the kinds and sizes of the fuels available. Forests, shrublands, and grasslands are characterized by small, discrete particles, such as leaves, pine needles, grasses, bark, twigs, and other wood particles, which are highly dissected compared with pools of liquid fuel spills or the large, continuous, solid surfaces of furniture and buildings. All fires spread by transferring heat from the burning zone to new fuels (1), but the complex chemical nature of natural fuels (2), the fineness of the fuel particles in wildland fires and their separation by air spaces, create fire-spread conditions much different from those in urban fires. In fact, decades of research into ignition processes have not established an accepted theory explaining the ignition and spread of wildfires (3). Without a theory based on fundamental principles, the feedback processes of heat transfer and combustion that govern spread rates and the potential for extinction cannot be reliably modeled. Thus, fire-spread modeling has been based on widely varying physical assumptions (4) and empirical relationships applied to steady-state conditions. Although still useful, these approaches are inadequate for predicting fire spread in a variety of fuel complexes; estimating fire effects on vegetation, soils, and the atmosphere; training firefighters to recognize imminent hazards; and expanding opportunities for vegetation management. As wildfires increasingly impact human communities worldwide, climates continue to change, and more land is developed for human habitation and industry (5, 6), the need for a deeper understanding of wildland fire spread has become more urgent.

The study of physical processes associated with the spread of wildland fires began in the 1940s with the recognition that fuel particles ignite after sufficient amounts of radiative and convective heat are transferred to them from a burning zone (7). Many models have been based on this understanding, but consensus has not been reached on the respective roles of radiation

and convection on fire spread (4). Radiation has been the most intensively studied and has often been assumed to govern spread (3), but recent findings reveal that the heat flux from radiation is insufficient alone to support fire spread. Individual fine particles will not ignite solely from radiation even at the preignition fluxes reported for forest crown fires ($<80 \text{ kW}\cdot\text{m}^{-2}$) (3, 8). The explanation is twofold: First, radiation is heavily attenuated in porous fuel beds, where vegetation blocks some fraction of radiation from the burning zone to unignited fuels until the fire is very near (9). In fire-spread experiments using shallow beds of dry fuels, particle temperatures rose sharply only when the leading edge of the fire was within centimeters of the particles (10, 11). Second, ignition of small particles by radiant fluxes found in wildland fires is “convection controlled” (12), meaning that the thin thermal boundary layer afforded by the short characteristic length scale confers efficient convective cooling by ambient air (13–15). Wildland fuel beds with typically fine-sized fuel particles (16) exhibit high convection heat transfer (3, 17) because heat transfer coefficients for free and forced convection are an inverse function of characteristic surface length, rising dramatically below 1 mm (3, 13). If radiation itself is insufficient to account for fire spread among small wildland fuel particles, convection must provide the explanation.

Here we focus on the role of convective heating in wildfire spread. Unfortunately, few studies have been conducted on convective heating of fine fuels in wildland fires or the flame dynamics that produce and transport convective heat. If convection is modeled at all, turbulent diffusion is assumed (18). It is known, although, that flames in spreading fires can exhibit periodic behavior (19) and intermittently sweep or burst forward to heat and ignite fuel particles (20–23), but these reports provide little insight into the origins or structure of these flame bursts or consequences for particle ignition. Here we report previously

Significance

Wildfires burn millions of hectares per year on every inhabited continent, but the physical mechanism governing spread is not known. Models of wildfire spread are widely used for prediction, firefighter training, and ecological research but have assumed various formulations of known heat transfer processes (radiation and convection) absent a definitive theory of their organization. New experimental evidence reported here reveals how buoyancy generated by the fire induces vorticity and instabilities in the flame zone that control the convective heating needed to ignite fuel particles and produce spread.

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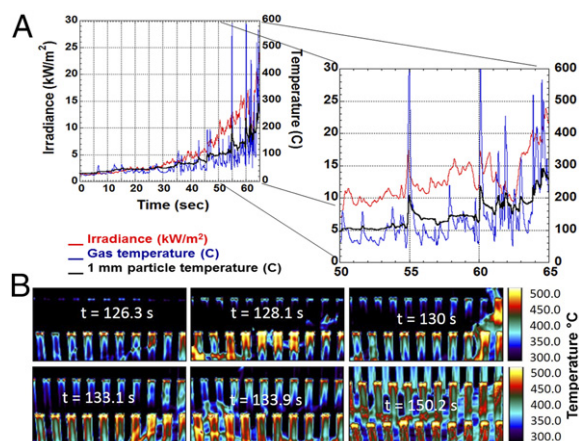


Fig. 5. Time series of irradiance, air temperature, and 1-mm particle surface temperature during flame spread in cardboard fuel bed (A). Fine particles heat and cool rapidly as intermittent flame contacts produce a stair-step temperature rise to ignition. Radiation preheating indicated when particle surface is warmer than air. Thermal infrared image sequence (B) from above and behind the fire show heating patterns on rows of 6-mm-wide cardboard particles as fire approaches. Higher temperature and ignition of corners and edges indicate convection as the principal heating mechanism.

the fire front (indicated by spikes in air temperature), the particle temperature increased and decreased rapidly ($\sim 2,500\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$). The intermittency resulted in a stair-step heating of the fine particles until ignition. Coarser particles showed a similar stair-step heating pattern with significantly lower thermal response rates ($\sim 100\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$) and remained below the nominal ignition temperature of cellulosic materials ($\sim 350\text{ }^{\circ}\text{C}$) until flame contact was continuous (surrounding fuels were ignited). Infrared thermographic images of cardboard particles (6 mm wide) in spreading laboratory fires showed higher temperatures at their corners and edges than on their flat faces (Fig. 5B). This heating pattern is consistent with thinner boundary layers at the short length scales of corners and edges and thus increased convective heating from hot flow over cooler surfaces, confirming an important role of convective heating in the ignition of particles of varying sizes.

The radiation heat fluxes measured during the laboratory-scale fires were generally below $\sim 30\text{ kW}\cdot\text{m}^{-2}$ during preheating with infrequent higher irradiances for durations less than 4 s. Experiments have shown (3, 52) that this level of radiation requires exposure of fuel particles longer than the total 2- to 35-s flame residence times produced in the wind tunnel experiments. Although previous laboratory-scale fire studies (9–11, 53) have failed to resolve the heat transfer mechanisms when flame fronts were within 5 cm and fuel particles heated to ignition, our data clearly link intermittent flame and hot gas contact generated by instabilities to fine particle heating, which is sensitive to the frequency of intermittent thermal boundary conditions (37). This repetitive convective heating thus appears to be the critical heat transfer mechanism causing ignition and spread of these fires.

Understanding How Wildfires Spread

Our experiments have suggested a significant, missing physical component of wildfire spread and highlight the challenges facing numerical modeling and future research. Fine-particle ignition in spreading fires appears to be tightly coupled to forward convection from buoyancy-inertia-induced flame bursts at time-scales of 10^{-1} s and length scales of 10^{-2} m. The Strouhal number–Froude number relationship suggests that this forward convective heat transfer becomes more intermittent with greater buoyancy (longer flames), but the heating distance may diminish

with steeper flame trajectory at lower Froude numbers (54). High-fidelity numerical models can potentially represent such processes for research at laboratory scales, but models intended for the large domains of actual wildfires (32, 55) must use coarser resolutions and parameterize the convective heat transfer and ignition processes based on careful comparison with experimental data. This initial work on scaling the intermittency of heating is a first step not only in understanding the physical process, but also in parameterizing heating in a way useful for future modeling efforts. Research will be needed to help understand the sensitivity to vorticity generation and initial conditions of fluid instabilities that grow downstream into the observed flame structures. Our findings will likely require a new examination as to how familiar biophysical factors, such as topography, heterogeneous fuel patterns, moisture of dead and live vegetation, and atmospheric dynamics at larger scales, influence buoyant processes that we observe to govern particle heating and wildfire spread. Both field and laboratory data can help examine these and related questions, particularly the extension and limits of scaling relations over a wider range of wildfires in different weather and fuel conditions. For example, does fire spread in fuel types composed of large particles (logs, logging debris) occur primarily by radiation as suggested by the physics of particle heat exchange? Such research will ultimately lead to discovering how wildland fuel properties (amounts, distributions, etc.) affect fire behavior and thereby improve techniques for characterizing vegetation, assessing spread potential, and mitigating fuel hazards. Although integration of these concepts into practical models will require additional work, our findings have begun to penetrate some of fire's long-held mysteries and outline a theory of wildfire spread.

Materials and Methods

Flame structure and particle ignition were studied using laboratory-scale fires at the wind tunnel facility of the Missoula Fire Sciences Laboratory (MFSL) and the University of Maryland (UMD), and field-scale fires at the MFSL and Fort Swift, Texas. The MFSL has a $3\text{ m} \times 3\text{ m}$ cross-section wind tunnel in which stationary and spreading fires were studied. UMD has a $0.3\text{ m} \times 0.3\text{ m}$ cross-section wind tunnel used to study stationary flame sources from gas burners and fuel-soaked wicks.

Spreading Fire Experiments. Fire spread experiments at the MFSL used uniform fuel beds 1.22–2.45 m in width and 6 m in length made of laser-cut cardboard. This new technique controls for precise physical dimensions of particles (length, surface area) and arrangement (position, separation). A commercial CO_2 laser system was used to cut cardboard fuel elements at regular parallel spacing attached to a common spine, resembling a “comb.” The cardboard, known as brown “chip board,” was 1.27 mm (0.05 inch) thick with $\sim 60\%$ recycled content and a mass density of $600\text{ kg}\cdot\text{m}^{-3}$.

These fuel beds were burned in the MFSL wind tunnel. The wind profiles are laminar except along the bottom surface where an upstream trip fence produces a turbulent boundary layer $\sim 0.25\text{ m}$ thick at the start of the fuel bed. Wind speeds were varied from 0.22 to $2.3\text{ m}\cdot\text{s}^{-1}$ with relative humidity of $\sim 25\%$. The combs were supported and arranged on a foundation of cement-board strips $0.635 \times 5.08\text{ cm}$ each, separated by a steel spacer $0.158 \times 2.54\text{ cm}$ that exposed only the vertical tines. Tine lengths of 2.54, 10.1, 20.3, and 35.6 cm were used in the burns. The longitudinal spacing of the combs could be adjusted every 0.64 cm, allowing control of exact fuel bed properties including packing ratios (0.00133–0.088) and loading (0.079–2.682 $\text{kg}\cdot\text{m}^{-2}$). Range of flame length in experimental burns varied from 0.1 to 2.5 m and spread rate varied from 0.57 to $7.72\text{ m}\cdot\text{min}^{-1}$ (Table S1). To limit lateral air entrainment causing flame front curvature, the sides of the beds were lined with paper treated with the flame retardant $(\text{NH}_4)_2\text{HPO}_4$ to limit independent flaming combustion but allow the paper to burn in conjunction with the advancing fire front (21). The consumption of the paper sideliners at the trailing edge of the burning zone avoids channeling of air inflow to the rear of the fire, which has been shown to affect fire spread on slopes (19).

Temperature fluctuations at the upper surface of the fuel bed were measured with a linear rake of 64 thermocouples (Type K, bead thickness 0.025 mm) oriented in the stream-wise direction. The first 32 thermocouples

were spaced 1.5 cm apart, and the second 32 thermocouples were spaced 3.0 cm apart. The thermocouple beads were positioned vertically at the top of the fuel and laterally 0.7 m inside the fuel bed, as measured from the lateral edge. Data were recorded at 500 Hz with a National Instruments Inc. data acquisition system. Digital video cameras recording at 60 frames per second were positioned at upwind, downwind, overhead, lateral, and oblique angles to capture flame structure and dynamics. High-speed movies taken at 300 frames per second were used to record flame impingement on fuel particles at the leading edge of some of the burns. Movie segments were processed using flow-tracking analysis software (60) to visualize flame parcel movement related to vorticity and bursting (Fig. 3E and Movie S2).

Gas Burner Experiments. Stationary forced-flow experiments were performed at the MFSL and UMD. At the MFSL, a propane burner used sintered metal as the porous burner surface measuring 0.3 by 0.25 m. A volumetric flow meter controlled the flow rate of propane gas to achieve energy release rates of 7.5, 10.9, and 15.1 kW. Ceramic insulation board surrounding the burner made a continuous flat surface that limited side-air entrainment. The apparatus was tested at free-stream velocities of 0.22, 0.44, 0.67, 0.89, 1.11, and 1.34 m s⁻¹. Side view video was captured with a Phantom brand high-speed camera at 120 frames per second.

At UMD, a laminar wind blower was designed and built for uniform forced-flow combustion experiments. The wind blower pressurized a 0.75-m³ plenum box with a centrifugal fan, producing a fully developed laminar boundary layer exhausted at the duct outlet 1.35 m downstream. The velocity profile of the boundary layer was measured along the center line of the blower above the burner surface using a hot-wire anemometer and confirmed precise forced-flow control between 0.6 and 4.8 m s⁻¹ with turbulence intensities less than 3% at maximum velocities. High-speed videography captured digital images of side and top views of the flame. The side-view camera was a Phantom, recording 120 frames per second at 1,920 × 1,080 pixel resolution. The top-view camera (Casio EFX-1, recording 120 frames per second at 640 × 480 resolution) was positioned directly above the rear burner edge and aimed forward to observe the flame leading edge at approximately a 45° angle.

Field Experiments. A wooden crib of rough-sawn 2.5-cm square ponderosa pine lath was burned to generate large-scale flame dynamics from a stationary source (Fig. 1F). The laths were arranged with square spacing (0.124 × 0.124 m) stapled at the ends with the intent of achieving non-ventilation limited burning. Cribbs were 1.2 m wide and 0.61 m tall and constructed in 2.4-m-long sections that were assembled in the field to create an overall length of 15.8 m (Fig. 1F). The crib was arranged in a normal orientation to the prevailing wind direction and burned on January 30, 2014, in an outdoor field 250 m square with average wind speed of 3.1 m s⁻¹ measured by four cup-anemometers positioned at 6.1 m height. Flames extended from the bed ~6 m and deflected downwind. Four thermocouple rakes, each with a linear series of 16 fine-wire 0.025-mm thermocouples spaced 0.2 m apart and 1 m above ground, were located in a normal orientation to the crib in the downwind direction to record temperature fluctuations with a Campbell Scientific CR1000 data logger at 33.33 Hz. Flame structure was documented with digital movie cameras surrounding the crib recording at 60 frames per second. Vertical scale was referenced visually from poles with 0.25-m graduations.

Five grass plots (5 ha each) were burned at Camp Swift, Texas, on January 15, 2014. Average wind speeds during ~3 min of burning on each plot were calculated as 1.8 m s⁻¹ for the first three plots and 4.5 m s⁻¹ for the final two plots using anemometer recordings (3-s intervals) located at the plot corners. Dry fully cured grass was ~1 m tall and produced flames ~3 m high. Before ignition, two thermocouple rakes were positioned 1 m above the ground surface (top of the grass) and oriented perpendicularly to the prevailing wind. Plots were ignited along the upwind edge with a drip torch to generate a linear heading fire (spreading with the wind) into the instrumentation site. Each rake supported 32 Type K 0.025-mm fine-wire thermocouples spaced at 0.2 m with temperature recorded by a Campbell Scientific CR1000 data logger at 33.33 Hz. Movie cameras recording at 60 frames per second were located at fixed positions around the plots from multiple angles to capture flame structure and dimensions.

Analysis. Movies for laboratory and field burns were studied to obtain visual estimates of flame length and spacing between flame peaks. Flame length was visually estimated relative to measured reference points in the laboratory and field. For laboratory burns, visual estimates were corroborated against flame length transformed from fireline intensity (44) (kW m⁻¹) ($y = 1.0954x - 0.5218$, $R^2 = 86\%$), which is the product of measured spread rate, fuel loading (kg m⁻²)

consumed in flaming, and heat content of gaseous combustion (56) (14 MJ kg⁻¹). Most cardboard fuel mass was consumed in the flaming phase, and the preburn loading was used for these calculations. Spacing between peaks from spreading fires was calculated by counting the flame peaks in movie frames and dividing by the known width of experimental fuel beds and the reference distances in Texas grass burns.

Temperature fluctuations in MFSL spreading fires were clearly visible in the temperature time-series data recorded by the thermocouple arrays (Fig. 4), as were bursts of the flame beyond the mean flame front in stationary burners. The variable of primary interest for the spreading laboratory fires was the flame burst frequency before ignition because these signals reflect conditions influencing particle heating. Preignition was defined from the first crossing of the 350 °C temperature to where a spline smoothing of the temperature data reached its peak (Fig. 4B). The 350 °C temperature represents a useful but approximate surface temperature at pilot ignition of wood fuel (57) although sustained flaming ignition actually depends upon a critical mass flux (3). The average temperature frequency for the preignition period was obtained using the level crossing of temperature spikes above 350 °C that equates to the VITA method applied to determine frequency of turbulent bursts in boundary layer flows (40). Fourier analysis is difficult to apply because of nonperiodic “spiky” temperature fluctuations (not sinusoidal). The same VITA method was applied to temperature data taken from the Fort Swift grass burns. Analysis of the crib burn omitted the spline fit because it was a stationary flame source.

Nonsteadiness of downstream flame locations was studied in stationary gas burner experiments using side-view high-speed movies and an array of thermocouples ahead of the burner. Image frames were converted to binary (flame, no-flame), and the frequency of the flame pulsations was determined using the VITA method (40) at a range of locations starting at the burner edge and increasing in 1-cm increments. The flame position in time was compared with each of these locations and the number of occurrences was tallied. The frequency at each location was determined as the number of crossings in the total number of frames multiplied by the frame rate of the movie. The maximum VITA frequency among all downstream locations was used for scaling comparison with spreading fire data.

Scaling Laws and Scaling Analysis. We examined the application of scaling laws developed for stationary pool and crib fires (58) and for spreading fires (59) to the scaling of our flame intermittency measurements. Of the six different pi numbers in these laws, the Froude number (Fr) = (the inertia force of air)/(the buoyancy force acting on the heated gas and flame) relates to fluid motion, and the other five are related to the condensed and gas-phase heat balances. The dynamic aspect of flame in relation to the spread of wildfires may be addressed as a possible seventh pi number, π_7 = (dynamic force)/(the inertia force of horizontal flow). The denominator of π_7 is the same as the numerator of Fr , meaning that three different forces are assumed to control flame dynamics (the buoyancy force acting on the heated gas and flame, the inertia force of horizontal flow, and the dynamic force due to turbulent instability or buoyancy-driven instability or possibly coupling of both).

As the first step of investigating the appropriateness of π_7 for wildfire spread, we assumed that π_7 is the Strouhal number (St) and evaluated the Strouhal number (fL U⁻¹) and Froude number [U^2 (g L)⁻¹] (St - Fr) correlation common to the study of pulsating pool fires (41, 43, 58). A high St - Fr correlation strengthens the interpretation of dynamic scaling in wildfire spread for the range of our scale model and outdoor experiments. Thus, $St = fL$ U⁻¹ and $Fr = U^2$ (g L)⁻¹ were obtained for flame intermittency measurements where f is the VITA frequency measured, U is the free-stream wind velocity, and g is acceleration due to gravity. Flame length was chosen as the characteristic length scale L and represents the magnitude of the buoyant force related to energy release rate in spreading fires (44) (kW m⁻¹) and non-spreading fires (45) (kW m⁻²) and is practically useful as a visual indicator of wildfire intensity. Burner diameter has most often been used as the length scale for St - Fr scaling of pool fires (43), but the horizontal flame zone depth of our spreading and stationary fires did not yield significant correlation.

Particle Heating in Laboratory Fires. We measured fuel particle temperatures and adjacent convective temperatures and irradiances (Fig. 4) during fire-spread experiments in the MFSL wind tunnel facility. Fuel particles of two sizes (1- and 12-mm square cross-sections) were made of yellow poplar, placed end-to-end at the center and laterally across the top of experimental fuel beds and instrumented with a pair of fine thermocouples (0.051-mm diameter). One thermocouple was embedded in the center of the upwind particle surface and the other was located 5 mm away from the surface to measure air or flame temperatures. Rates of particle heating and cooling (°C s⁻¹) associated with intermittent flame pulses were calculated from thermocouple measurements

during the final 2 s before ignition. A water-cooled radiometer was placed at the level of the instrumented fuel particles and equidistant (65 mm) from each front-face embedded thermocouple. The 1-mm fuel particle is at the coarse limit of wildland fine fuels in the 1-h time-lag category based on characteristic surface area to volume ratios used in the United States (16).

Infrared thermography was used to capture the transient temperature history of 6.0-mm wide cardboard fuel particles approached by an advancing flame front (Fig. 5B). The FLIR SC4000 infrared camera has a spatial resolution of 320×256 pixels and a spectral range of 3–5 μm . A broadband flame filter with a spectral range of 3.7–4.2 μm allowed imaging of fuel-particle surface temperatures through the flame zone. The IR camera was fixed ~93 cm behind the spreading flame zone, looking down at the fuel bed with

a view angle of 30.6° from the horizontal. The camera was housed in an air-purged aluminum container 33.02 cm in diameter containing ice packs to limit heating of the camera during burns. The amount of noise and saturation captured in each movie image was reduced using a superframing algorithm that repeatedly takes a succession of four images (subframes) at progressively shorter exposure times. The subframes from each cycle are merged into a single superframe to record thermal features across the temperature range.

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