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Understanding Wildfire as a Dynamic System: A new comprehensive book on wildland fire behavior

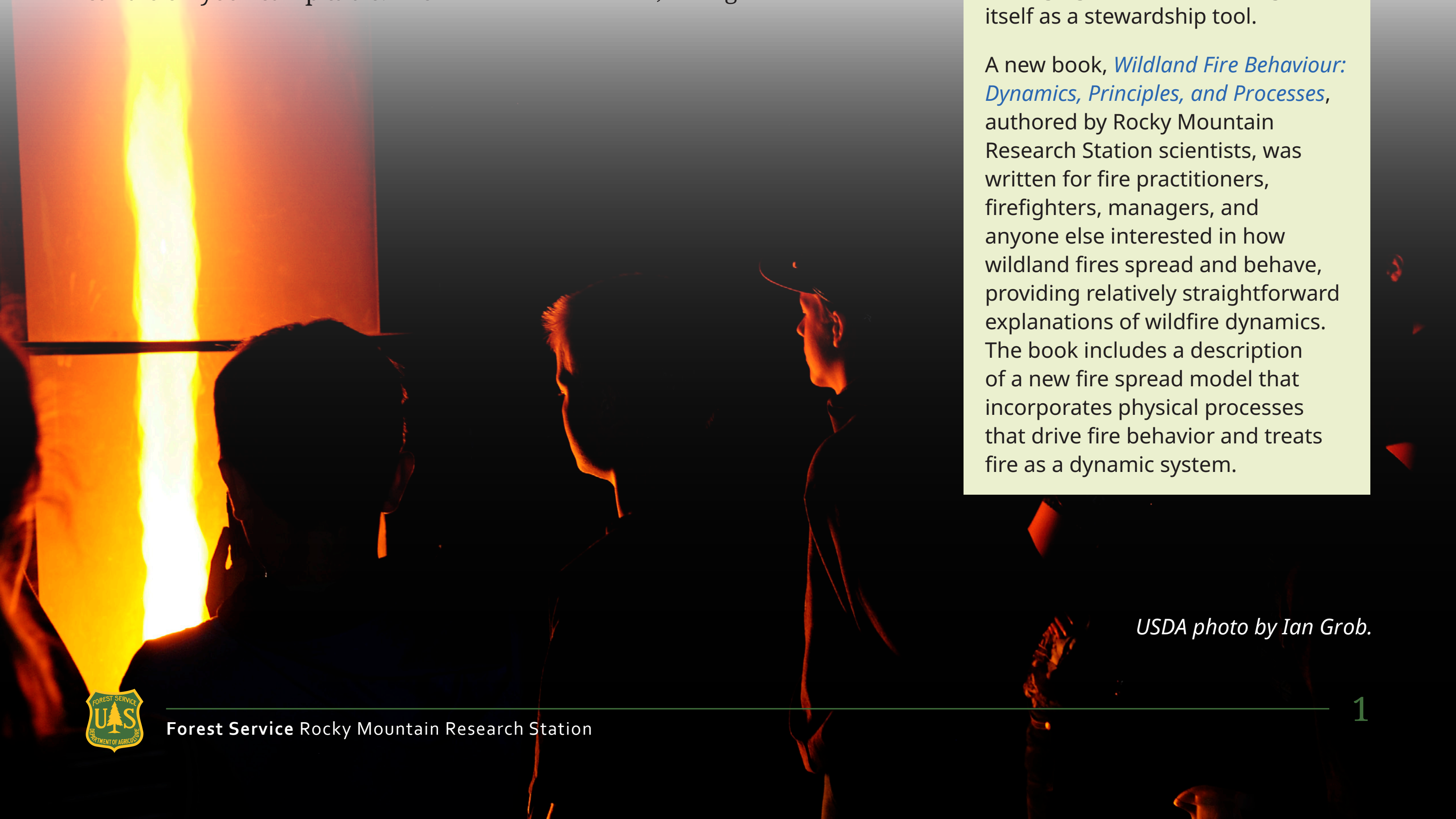
SUMMARY

Understanding wildfire behavior requires knowledge of how physical processes interact with fuels, topography, and weather and can be hard to approach or explain for those without a background in engineering or physical sciences. A greater familiarity with the physics of fire behavior translates to not only a better-prepared fire management workforce but also improved fire behavior prediction models. Both are critical for developing proactive approaches to managing wildfires and using fire itself as a stewardship tool.

A new book, *Wildland Fire Behaviour: Dynamics, Principles, and Processes*, authored by Rocky Mountain Research Station scientists, was written for fire practitioners, firefighters, managers, and anyone else interested in how wildland fires spread and behave, providing relatively straightforward explanations of wildfire dynamics. The book includes a description of a new fire spread model that incorporates physical processes that drive fire behavior and treats fire as a dynamic system.

The campfire has been burning all evening and the coals are hot and glowing red, perfect for roasting marshmallows or receiving a new piece of wood. You reach for a log that has been sitting next to the fire but not touching the coals when you notice the piece of wood has already started smoking. How is it possible that the log is being heated without directly contacting the source of heat? As you ponder this question, you pick up a pine needle and hold it next to the flame of a citronella candle on your camp table. Even though the needle is next to, but not touching the flame, it does not ignite. Yet, when you hold the needle directly above or in the flame, presto, ignition is achieved (and maybe burned fingers).

The processes at work in these two scenarios, radiation in the first, and convection in the second, are among several foundational concepts that explain fire behavior including heat transfer and thermodynamics, fluid mechanics, combustion, and ignition.



USDA photo by Ian Grob.

Understanding the physics of fire is key to understanding how to prevent and extinguish unwanted fires, particularly in the human built environment, and how to use fire to achieve management goals. In wildland settings, the ecological role of fire has been well studied and is often the basis of wildfire training. But understanding how and why wildfire behaves the way it does has not been as foundational.

A long history of fire suppression combined with climate change and population growth into wildland-urban interfaces have all contributed to increasingly complex, and often more frequent and severe wildfires. The organizations tasked with responding to this situation face unprecedented challenges.

"We can't just be reactive anymore," says Mark Finney, a senior fire scientist with the Rocky Mountain Research Station at the Missoula Fire Sciences Laboratory. "We have to formulate strategic objectives and then develop the tactics to achieve them. This means we design landscapes and management regimes not only with the principles of ecology in mind but also with a better understanding of the physical processes responsible for how fire behaves."

A greater familiarity with the physics of fire behavior translates to not only a better-prepared workforce but also improved fire behavior prediction models. Both are critical for developing proactive approaches to managing wildfires and using fire itself as a management tool.

The current Rothermel fire spread model is based on experiments done in controlled conditions. Real-world fire spread is part of a much more dynamic system. USDA photo by Lance Cheung.

To meet this need, Finney along with Sara McAllister, Torben Grumstrup, and Jason Forthofer at Missoula Fire Sciences Laboratory wrote the recently published book *Wildland Fire Behaviour: Dynamics, Principles, and Processes* to explain the dynamics of wildfire behavior and fire spread with physical concepts including thermodynamics, fluid mechanics, and heat transfer as well as combustion and ignition. The book is for fire practitioners, firefighters, managers, and anyone else interested in how wildland fires spread and behave.

Overcoming limitations of the Rothermel model

Approaches to wildfire management today are based largely on a fire spread model created more than 50 years ago. Fire scientist Richard Rothermel developed the first model to quantitatively predict the path of a fire in 1972 at the Missoula Fire Lab. He and his colleagues burned hundreds of experimental fires under different known fuel weather and topography conditions and then measured the spread rate based on those controlled conditions. The Rothermel model remains the most widely used today and many models developed subsequently are based on it, but it has some critical limitations.

"It's kind of a black box model," says Jason Forthofer, a Rocky Mountain Research Station (RMRS) research mechanical engineer at the Fire Lab and coauthor of the book. "We know the inputs that go into the burning experiments—the wind speed, the fuel loading, and other conditions—and then just measure the outputs. But we don't measure the heat transfer that happens, the fluid dynamics, the chemical reaction rates."

In other words, the Rothermel model does not account for the physical processes that cause fire to spread. It is an empirical model based on experimental data derived from controlled conditions, which works well for predicting fire spread under such conditions. But those conditions represent a very small subset of what is encountered in the real world outside of the lab.

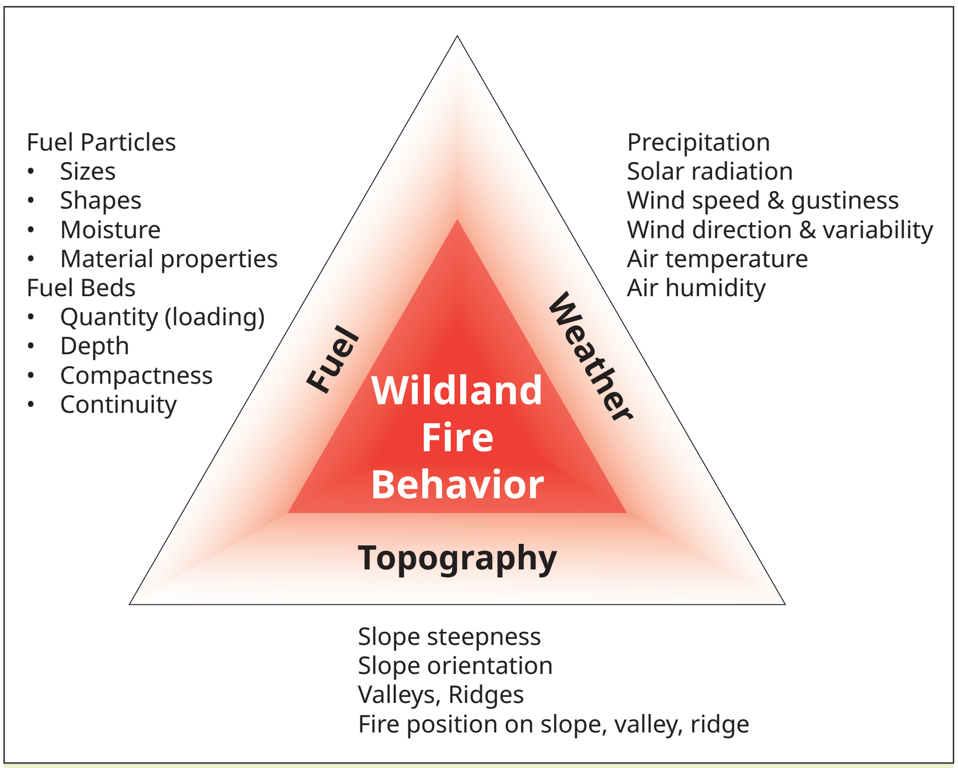
Another limitation is that the model assumes that fire will burn and that when it does, it will spread at a steady rate. But fire doesn't always burn and when it does, the spread is often anything but steady. While interacting with weather and topography, wildfires burn through an assortment of live and dead fuel types and can ebb and flow over time.

"It's a dynamic system," Sara McAllister, coauthor of the book and a research mechanical engineer at the Missoula Fire Sciences Laboratory, says. "Tweak one part of that and the whole thing is going to shift." To understand fire as a dynamic system she says, "We really have to get into the meat and potatoes of the physical processes. We look at fuels, weather, and topography [the fire triangle] with a new lens."

Looking at the traditional fire triangle through the lens of physical processes, McAllister and her colleagues are developing a simple one-dimensional model that they hope will eventually replace the Rothermel spread model. Fire management personnel will benefit from a better understanding of the underlying physics of wildfire behavior not only because it will help them better understand what they see on the ground, but it will also help them better understand how these new physically based models work.

McAllister, who has a passion for lighting things on fire and a Ph.D. in combustion science, contributed to chapters on the physics of ignition and combustion. She explains that wildfire spread involves a cycle of ignitions. Initially, a fuel ignites and then burns and releases heat and energy, which is then transferred to new fuel ahead. For the spread to continue, enough heat must be transferred for new fuel to ignite.

The different modes of combustion, such as flaming and smoldering, is a topic McAllister says is



Scientists are developing a simple one-dimensional model that they hope can replace the Rothermal spread model by looking at the traditional fire triangle through the lens of physical processes (heat transfer, fluid dynamics, chemical reaction rates, etc.). Figure adapted from Figure 2.7 in Wildland Fire Behaviour.

underappreciated in both structure fire and wildfire. For example, in longer duration wildfires that spread over many days, a back-and-forth pattern of flaming and smoldering can be observed over the course of a day. As humidity rises at night, fire often shifts to smoldering and spreading slows down or stops altogether. But the next morning as the sun heats things up, humidity decreases, the air dries out, and the fire transitions back to flaming and spreading.

Accurately predicting this pattern of smoldering and flaming is important for predicting fire spread across a landscape over many days. The new fire spread model is being developed with this capability among others in mind.

"What managers do now is kind of just make a guess," says Forthofer, who is the lead developer of the new model. Forthofer began fighting wildfire 27 years ago and still goes out on fires during fire season, an experience which complements his job as a fire research engineer also with the Rocky Mountain Research Station. To forecast the spread of the fire using the current model, which assumes that fire is always spreading, Forthofer says that managers must somewhat arbitrarily specify a specific period over a 24-hour interval. Otherwise, the model will forecast that the fire spreads farther than it otherwise would.

"Right now, because we don't have the ability to predict those transitions, we rely on firefighters' knowledge based on what they see on the landscape," says Forthofer. For example, the observation that a multiday fire slows down at a certain time in the evening gets entered externally into the current model. But as conditions from day to day change, the resulting spread forecast may be way off. Observations don't fully account for what Forthofer calls "the ingredients of what causes fire to spread," the physical processes at work like heat transfer or fluid dynamics.

The new model will. Because it will internally compute those ingredients, the hope is that the new model will scale up to conditions that scientists cannot work with in a lab setting. In other words, it will make better predictions at the landscape scale, and this will better prepare managers to make decisions about when and how to work with fire at that scale.

"These improvements to modeling," Finney says, "will have the most potential for benefiting land

Smoldering (left) is flameless combustion that occurs at a lower temperature than flaming combustion. Glowing combustion (right) is an intense smoldering reaction. Not nearly as much is known about smoldering and glowing as is known about flaming combustion, but these are very important processes during wildland fires, especially after the flaming front has passed and even when the fire might be presumed "out." Left: USDA Forest Service photo taken in the Klamath National Forest. Right: glowing combustion, photo courtesy of Jens Buurgaard Nielsen.

management because they will give us more confidence in our ability to manage fires and use fire as a tool proactively."

Advancing beyond Rothermel's model by including physical processes is a critical step toward proactive fire management. Just as important is fortifying fire management personnel with a better understanding of the ingredients and processes of fire spread.

Preparing fire managers for a wildfire paradigm shift

Wildfire management training in the United States today is generally accomplished through a series of short-term interagency courses that build toward a credential in fire management. Finney recognizes the critical role such courses play in training existing wildfire personnel, and he says it is time to update that training to better cover the physics of wildland fire behavior. Forthofer agrees.

"This would translate to better anticipation of fire movements by on-the-ground firefighters leading to more effective management and safer operations," he says. The book they wrote is intended to provide a framework and serve as starting point for both professional and academic training.

Alistair Smith, a professor of wildland fire science at the University of Idaho, says the wildfire science community has been seeking a textbook like *Wildland Fire Behaviour* for decades. Smith began using the book in his courses as soon as it became available.

"Fire behavior is usually covered as only a chapter or two in fire ecology textbooks," Smith says. "Simply no other textbook covers the necessary detail to understand wildland fires, while still being a textbook that can be used in undergraduate and graduate courses."

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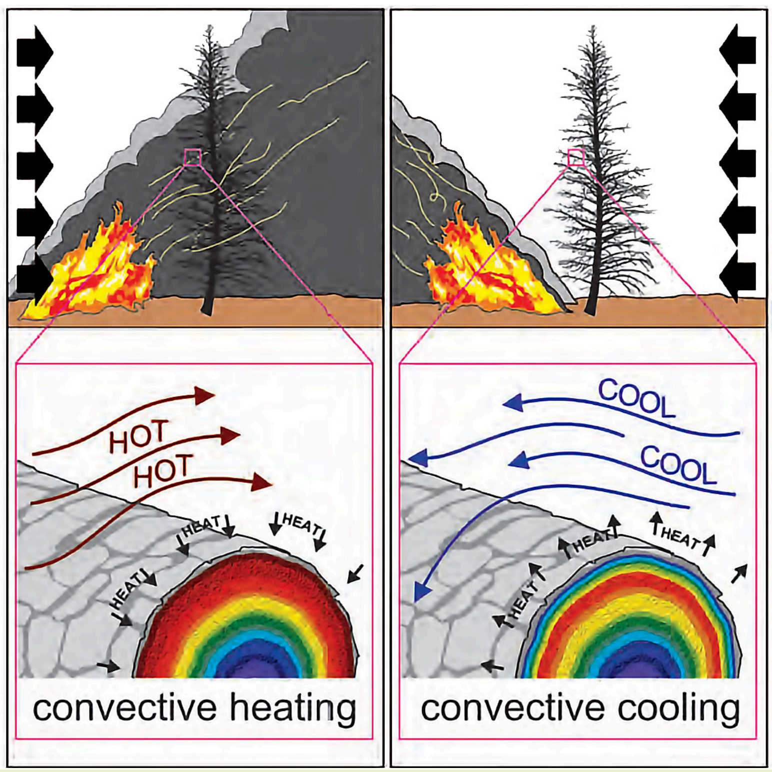
–Mark Finney, Research Forester, USDA FS Rocky Mountain Research Station



Including physical processes like heat transfer in both new predictive models and education for fire management personnel is a crucial step beyond current practices. Conduction, radiation, and convection heat transfer are fundamental to the spread and behavior of all fires, especially wildland fires. Conventional wisdom suggests that the heat of flames approaching any fuel—even the finest particles, such as conifer needles—is transmitted largely by radiation heat transfer. But recent experiments have shown that radiation alone is almost never sufficient to heat fine fuels enough to cause ignition. This is because convection is so effective at cooling such fine particles with low-temperature ambient air. Here a tree branch is being heated, then cooled when the wind shifts, by convection. Illustrations by Brian Elling.

A New Model of Wildfire Spread: Positive and negative feedback processes

Rocky Mountain Research Station scientists and engineers at the Missoula Fire Sciences Laboratory are developing a simplified model of fire spread for a wide variety of practical uses, including prediction and education. The model, called LIHTFire (Linear Heat Transfer), is a one-dimensional model that captures the nonlinear behaviors of fire spread and energy release as it accelerates or decelerates over time and, unlike most operational models, allows use of heterogeneous fuel and weather conditions.

The new model, which is described in the book *Wildland Fire Behaviour: Dynamics, Principles, and Processes*, is meant to shed light on how the physical processes of wildfire spread work together to produce the observed fire behaviors. The model results agree well with observations from controlled laboratory experiments, which suggests the model captures the essential processes but will require more work to compare with data from larger scale fires.

Scientists have used the model to evaluate several processes that influence fire behavior, including simple fire spread dynamics, fuel loading, flame front width, effects of wind including nonsteady wind, slope, dead fuel moisture, and fuel continuity.

The model, the book authors write, shows "that fire spread accelerates from ignition to a steady-state, that wider flame fronts spread faster (to a point), that time-varying wind speed produces complex oscillating and lagged behaviours, and that spread/no-spread thresholds are caused by fuel discontinuities interacting with environmental conditions."

The model also identified several positive and negative feedback processes. The table below (from Finney et al. 2021) lists the processes and briefly describes how they function in fire spread.

	Function in fire spread
Positive feedback processes	
Fireline intensity	Higher intensity increases heat transfer by radiation and convection.
Fire front width	Wider fronts can increase convective heat transfer and spread rate.
Slope	Flame attachment to slopes steeper than ~20° increases convective heat transfer, intensity.
Negative feedback processes	
Flame angle/buoyancy	Higher intensity increases buoyant forces, decreasing heat transfer.
Flame zone depth	Deeper flame zones for a given intensity decrease convective heating.
Flame pulsation	Lower frequency pulsation of taller flames may decrease convective heating rate but may also extend further and last longer—the net effect on ignition and spread is unknown.
Frontal curvature	Curved fronts decrease forward convective heating.

The new model is expected to move from a prototype to something anyone can use within the next 5 years.

Susan Prichard is a fire ecologist with the University of Washington who studies fuel reduction treatments including prescribed burning and how wildland fire behavior and its effects are changing under climate change. She agrees that fire behavior curricula are lacking at the university level. Concepts like fluid dynamics or airflow that are critical to understanding how fire spreads are generally missing from fire ecology courses and she has noticed that many fire ecology graduate students don't understand such fundamentals of fire behavior.

She says the book has refined her own knowledge of the physical processes of fire behavior. For example, how different types of fuel particles—leaves, small twigs, litter, logs—burn and are configured on the landscape influences whether conditions are favorable for using prescribed burning.

"There's this feeling in many parts of Western culture that fire is the enemy," Prichard says, "but it is one of our most important stewardship tools. It's critical right now. This book fosters a better understanding and hopefully a better relationship with fire." Because the book describes a complex set of processes in an approachable way, she is considering using it as the primary text in a graduate seminar she is planning.

Ultimately, Finney would like to see universities create a degree or career path for "landscape fire engineering," to see proactive fire management elevated as a profession.

"We do not have the equivalent of wildland fire engineers who design landscapes with fire management in mind and who can inform the public and elected officials on how policy could help advance society's interests in this area," he says. "We're relying on firefighters, first responders, as the authority."

In the same way that we rely on trained engineers to design structures to withstand fires and prevent catastrophes, Finney contends that learning to better

MANAGEMENT IMPLICATIONS

- Wildland Fire Behaviour updates and modernizes fire behavior concepts to prepare managers and decision makers for fire in the future. Foundational training in the physics of wildland fire behavior will help prepare fire management personnel to develop and implement strategies to work with fire as a stewardship tool, a goal of the Forest Service's Wildfire Crisis Strategy.
- Understanding the science of wildfire behavior can help managers predict when and how to take advantage of wildfires to achieve landscape-scale ecological benefits and implement sustainable long-term management strategies. It also provides perspective on the limitations and assumptions of modeling systems that current wildfire training is based on.
- The physical processes of combustion, heat transfer, and ignition in wildland fuel fires often operate very differently from other kinds of fires—those in buildings or industry—largely due to differences in fuels that vegetation presents.
- Contrary to conventional wisdom, experiments have shown that radiation alone is almost never sufficient to heat fine fuels enough to cause ignition. This is because convection is so effective at cooling such fine particles with low-temperature ambient air.
- Understanding how fires spread and behave in response to fuel properties is necessary for developing proper methods for measuring and describing fuels.
- Understanding fine-scale processes is critical for developing physically realistic models that scale up to large fire behaviors.

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–Susan Prichard, Fire Ecologist, University of Washington live with fire and to use it to some advantage, requires specific expertise and the same kind of professionalization that is at the core disciplines like engineering.

“Fire suppression is not a winning strategy in managing the wildland fire problem in most of our western forests,” Finney says. “The ‘fire paradox’ means that the harder we fight, the worse the fires become. Suppression only succeeds in removing mild and moderate fires, leaving only those under extreme conditions to burn the accumulated fuel. The only way to win is to welcome fire as an ally and use fire as a tool— and for that, we need a higher level of expertise and understanding of fire behavior.”

A critical pathway forward is through improved understanding of the physics that drive wildfire behavior.

KEY RESEARCH FINDINGS

- Scientists with the Rocky Mountain Research Station’s Fire Lab in Missoula, Montana, have summarized what is known and unknown about wildland fire behavior in a new book: *Wildland Fire Behaviour: Dynamics, Principles, and Processes*.
- Written in an approachable format, the book explains how physical processes including combustion, heat transfer, and ignition produce spreading wildfires.
- To overcome the limitations of existing fire spread models, scientists at the Missoula Fire Lab are developing a new model that incorporates physical processes that drive fire behavior and treats fire as a dynamic system.
- The new model shows that fire spread accelerates from ignition to a steady state, that wider flame fronts spread faster (to a point), that wind speed that varies with time produces complex oscillating and lagged behaviors, and that discontinuity of fuels interacting with environmental conditions causes thresholds for fire to spread or not spread. The model also allows scientists to identify several positive and negative feedback processes and how they function in fire spread

FURTHER READING

Finney, M.A.; McAllister, S.S.; Grumstrup, T.P.; Forthofer, J.M. 2021. *Wildland Fire Behaviour: Dynamics, Principles, and Processes*. CSIRO.

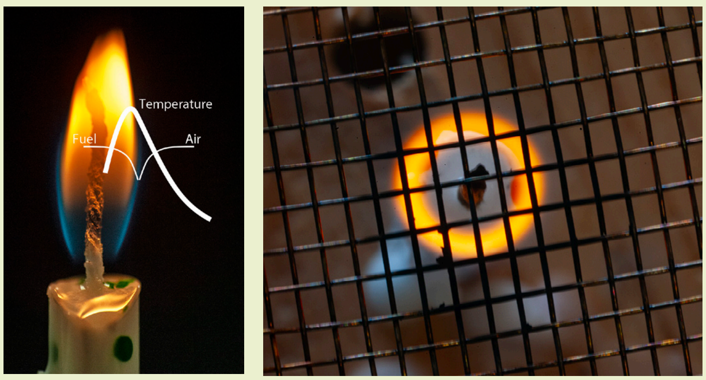
USDA Forest Service. 2022. Confronting the wildfire crisis: A strategy for protecting communities and improving resilience in America’s forests. FS-1187a. 47 p.

Calkin, D.; Crotteau, J.; Finney, M.; Larkin, S.; Johnston, M.; Hoagland, S.; Johnson, D.; McCaffrey, S.; Squires, J.; Urbanski, S. 2022. Getting more fire on the ground: Landscape-scale prescribed burning supported by science. Science You Can Use Bulletin, Issue 57. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 13 p.

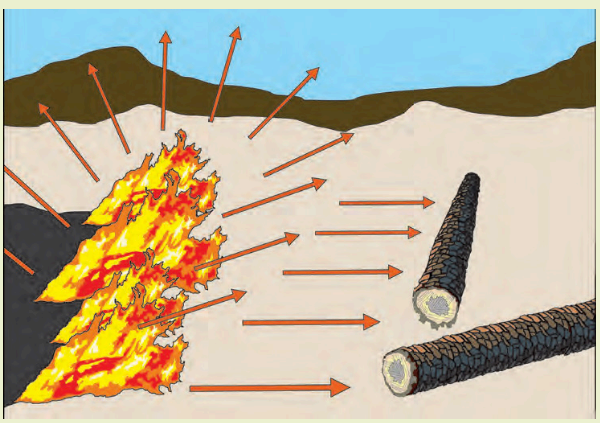
Key Principles of Fire Behavior

The more we understand wildfire behavior, the better we'll be able to envision ways to use fire as a tool. Being comfortable with proactive uses of fire depends upon more advanced fire behavior knowledge. Here are some key principles described in the new book, *Wildland Fire Behaviour: Dynamics, Principles, and Processes*.

- **Fire behavior is dynamic.** Fire behavior at any given time depends on preceding fire behavior, not just the immediate combinations of fuels, topography, and weather factors.
- **Fire behavior is a function of interacting physical processes.** The three main processes are combustion and energy release, heat transfer, and ignition of fuel materials. Some of the heat released by burning fuels is transferred to adjacent fuel materials and ignites them. The rates at which fires spread are determined by the balance of these processes as they interact with the fire behavior itself over time. Some examples of the dynamics of each of these processes are shown below:



Combustion *occurs only as a thin sheet where the fuel and air meet, so candle flames are hollow. The temperature near the wick of a candle rises due to heat from combustion and continues to rise as it reaches the flame, which is the hottest part. Photographs by Ian Grob.*

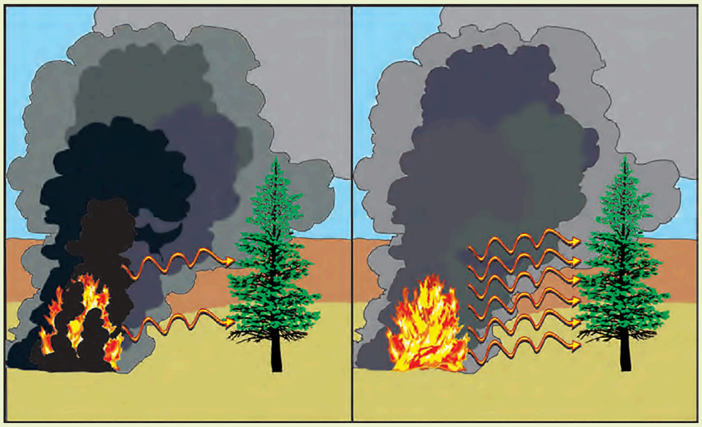


There are three modes of ***heat transfer****: conduction, radiation and convection. Radiation heat transfer occurs when heat moves from one surface to another as electromagnetic energy. Fuel shape, orientation, and distance from an advancing flame front influences how much thermal radiation might be absorbed. Even though the flames are emitting thermal radiation in all directions, only a fraction of it is absorbed by the logs. Illustration by Brian Elling.*

Ignition *of a wood rod as recorded by high-speed infrared videography. The 0.64 cm diameter rod is heated with air at 600°C. Ignition first takes place in the gas–air mixture above the solid fuel and then burns back towards the fuel particle itself. Total elapsed time in this series of photographs is 3.5 ms.*

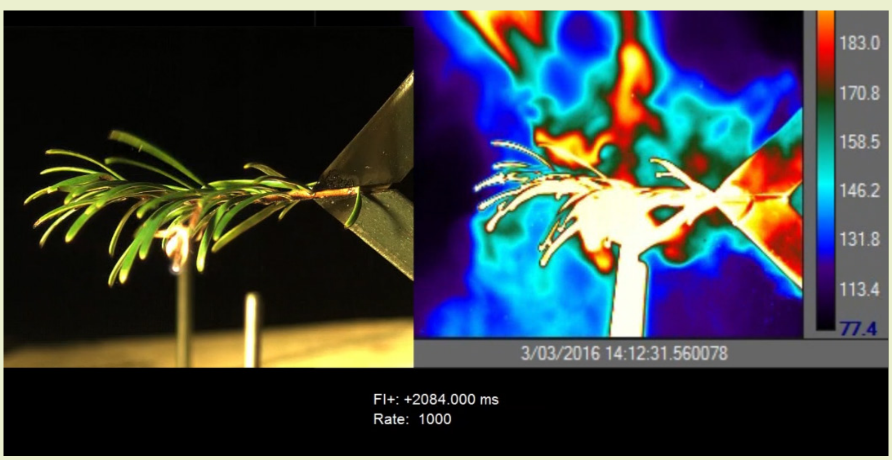
Key Principles of Fire Behavior (continued)

- **Most existing fire prediction models don't address behaviors seen every day in real wildfires.** This is because most wildfire prediction models assume fire spreads as a thin line of flaming combustion, but wildfire behaviors are much more diverse. Fires that burn over large areas, for example, can produce fire behaviors that depend on the characteristics of the whole fire, not just a section of the fire independently.



Unconsumed soot, which is the result of incomplete combustion, escapes through flames. Soot of a candle may appear as tiny wisp of black smoke. In the flames of wildland fire, much more soot is seen largely due to the highly turbulent nature of the flames. Soot can create such thick black smoke that it can block thermal radiation from flames to the surroundings. Illustration by Brian Elling.

- **Wildfire fuels vary immensely but are notable for having fine-sized fuel particles.** The physical processes of combustion, heat transfer, and ignition in wildland fuel fires often operate very differently from other kinds of fires—those in buildings or industry—largely due to differences in fuels. Vegetation fuel materials are usually made of individual fine particles that may be combinations of living or dead, rotten, or sound, a wide variety of sizes and arrangements, and with highly variable but mostly unknown material properties (density, conductivity, etc.).



Fire behavior in live fuels differs from dead fuels due to chemical composition and water storage. Side-by-side images of live fuel as it is heated taken simultaneously by visual and infrared cameras show dramatic jetting of hot gases (red arrows). When heated rapidly in a spreading flame front, live vegetation does not release water vapor and pyrolysis products in the same gentle way that dead vegetation does. Instead, the process can be quite violent, with jets of moisture and possibly flammable carbohydrates issuing out from ruptures in the surface at high velocities.

- **Ways to describe wildland fuels are currently inadequate.** This is partly because the knowledge of which fuel properties are crucial to fire behavior requires a better understanding of how fire is sensitive to specific fuel properties. In other words, if we don't understand how fires spread and behave in response to fuel properties, then we can't come up with proper methods for measuring and describing fuels.
- **Scale matters.** One of the major challenges to advancing wildfire modeling is the range in scales between the finest scale physical processes that produce the behavior (sub-millimeter and sub-second) and the large scales of interest in behaviors (usually miles and hours). Only through better understanding of the fine processes will we be able to figure out how to capture these efficiently for developing physically realistic models that scale up to the large fire behaviors.

RESEARCHER PROFILES

The following individuals were instrumental in the creation of this Bulletin.

MARK FINNEY is a research forester with RMRS at the Missoula Fire Sciences Laboratory in Montana. Mark's research interests include fundamental processes in fire spread and applications of fire behavior models for fire management decision support and actuarial risk assessment.

SARA MCALLISTER is a research mechanical engineer with RMRS at the Missoula Fire Sciences Laboratory in Montana. Her research interests include understanding fundamental combustion and heat transfer processes related to the spread of wildfires.

TORBEN GRUMSTRUP was a research mechanical engineer at the Missoula Fire Sciences Laboratory and currently works for Los Alamos National Laboratory.

JASON FORTHOFER is a mechanical engineer at the Missoula Fire Sciences Laboratory. His research involves numerical, field, and laboratory studies of heat transfer and fluid flow relating to wildland fires. He is currently working to develop a new fire spread model. His fire qualifications include division supervisor and fire behavior analyst trainee.

SUSAN PRICHARD is a fire ecologist and has worked as a research scientist for the past 20 years at the University of Washington School of Environmental and Forest Sciences. Her main interests are in the effects of fire and other disturbances on forest dynamics, climate change on forest ecosystems, and fuel treatment options to mitigate fire severity and smoke impacts in fire-prone forests. She lives full-time in the Methow Valley near Winthrop, Washington.

ALISTAIR SMITH is a professor of wildland fire science at the University of Idaho. His research focuses on investigating the mechanisms of fire induced tree mortality and assessing the physiological mechanisms and the morphological traits in the trees that survive fire.

WRITER'S PROFILE

SYLVIA KANTOR is a science writer for the Rocky Mountain Research Station in Fort Collins, Colorado, as well as the Pacific Northwest Research Station in Portland, Oregon. She has a master's degree in forestry from the University of Washington and lives in Seattle, Washington. Her portfolio is available at www.sylviakantor.com.

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