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Best practices for measuring

Fuel, Fire weather, and Fire behavior

A handbook for prescribed fire science with an overview of prescribed fire operations

Materials to support the Hand-on Fire Science Workshop

Summary

- On 3 April 2013, the Pasture 3B prescribed fire on the Grand River National Grasslands in Perkins County, SD escaped and spread across Federal and private land. After emergency managers misread the name, the incident became known as the Pautre Fire.
- Several landowners have filed suit against the US Forest Service, which manages the National Grasslands and conducted the Pasture 3B prescribed fire. In this report, I consider several claims for damages due to lost forage resources, as well as claims for damages due to other losses including fencing and treed shelterbelts. In considering these claims, I rely on an extensive body of peer-reviewed scientific literature on rangeland fire effects from the US Great Plains.
- This report summarizes my opinions on the reasonableness of plaintiffs' claims:
  - ➥ I found no support for damages caused to forage or grazing. Rangelands of the Northern Great Plains are resilient to fire. The scientific literature, including data collected from the Pautre Fire, indicates that (a) fire effects on native prairie productivity returns to—or exceeds—that of pre-fire or unburned rangeland by the season after fire, and (b) it is unnecessary to defer grazing in the season immediately after fire. Plaintiffs have provided no evidence to substantiate their claims that rangeland on their ranches demonstrated a different response than observed in these studies.
  - ➥ Metal fencing materials are resistant to grassland fire. Loss of integrity of these components is mostly attributable to age, not fire. Thus, in the event damages are awarded for the repair of fencelines and replacement of wooden posts, the award should discount from the full value an amount proportional to the age of the fence.
  - ➥ Many trees used in shelterbelts are short-lived. Damages awarded for shelterbelts should be discounted in proportion to the remaining life of trees were there no fire.
  - ➥ Finally, although the intent of the pasture-to-prairie reconstruction quotation is not clear, the plan far exceeds recommended management practices for weed-invaded rangeland. Weed abundance following fire is mostly attributable to failure to control weed populations prior to being burned. Thus, I found no support for awarding damages related to post-fire weed problems.

Workshop introduction

Wildland fire science literacy is the capacity for wildland fire professionals to understand and communicate three aspects of wildland fire: (1) the fundamentals of fuels and fire behaviour, (2) the concept of fire as an ecological regime, and (3) multiple human dimensions of wildland fire and the socio-ecological elements of fire regimes (McGranahan and Wonkka, 2018, Fig. 1).

Known knowns

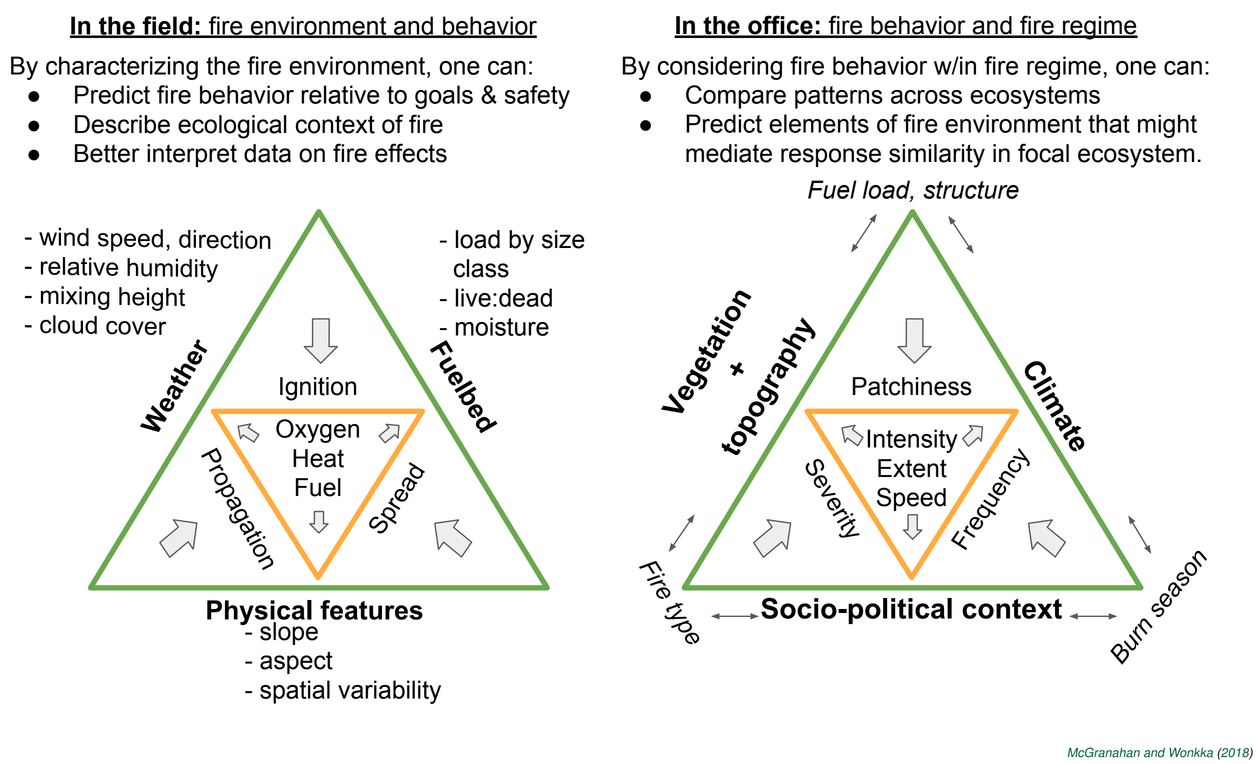


Figure 1: Two arenas of wildland fire science—the field and the office. This figure helps fire professionals from each arena identify characteristics of the fire environment or fire regime that dominate their colleagues' perspective.

Known unknowns

Unknown unknowns

Contents

Part I

Prescribed fire science

Fire science basics

In a given year, about 3% of Earth's terrestrial surface burns (Archibald et al., 2018). All this fire affects air quality, alters vegetation, and drives processes such as climate and nutrient cycles (Sullivan and Ball, 2012). A basic understanding of how fire burns is important for anyone involved in wildland fire science and management. The first part of this chapter introduces the processes of combustion, heat transfer, and fire spread. The second part introduces some basics of how scientists measure and describe wildland fire.

Fire in space and time

When conducting any type of fire science, one must be aware of multiple spatial and temporal scales at once. It is important to consider individual fires within the broader context of biogeography and climate, as well as consider the location of individual sample points within the landscape context of the individual fire. Thoughtful placement and timing—spatial and temporal considerations, respectively—of samples helps data from one fire fit into knowledge of many fires.

The story of fire in a landscape unfolds at three spatio-temporal scales (Fig. 2). Each scale is relevant to the fire scientist. The finest and fastest scale is that of individual flames and the movement of the *flaming front*, the series of ignitions that propagate fire through the fuelbed, and across the landscape.

In prescribed fire, most personnel and planning focus on the middle triangle—the factors that affect how a fire behaves within the defined burn unit within the operational time period (often less than 1 day). How wind, topography, and fuel affect fire behavior is discussed in detail in the fire behavior chapter.

Good fire management bases broad objectives within a model *fire regime*, which is discussed in more detail later in this chapter. Within a given climate and vegetation type (e.g., grassland, savanna, or forest), managers often have fairly specific goals they desire to achieve, and various elements of prescribed fire can be manipulated to serve those goals. For example, both the season in which a burn occurs and the

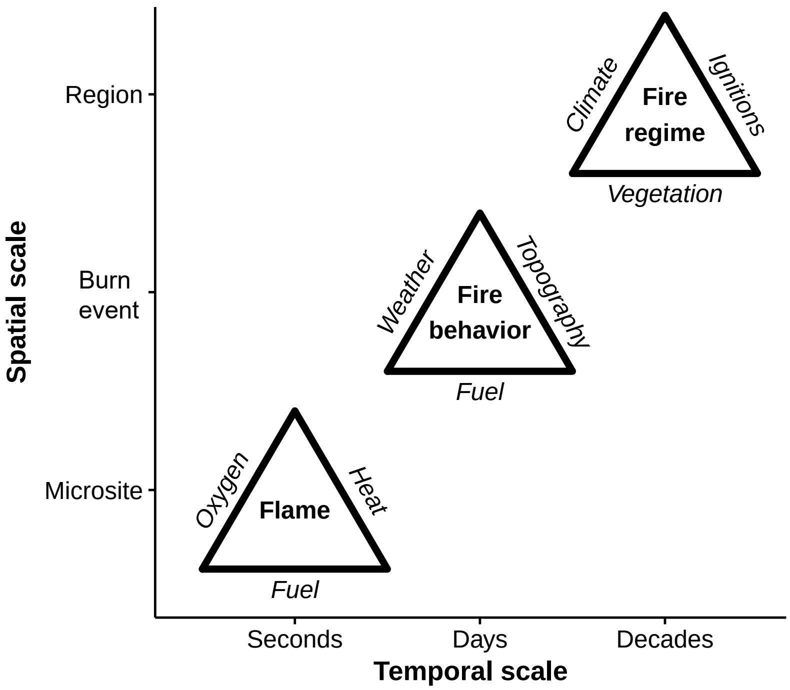


Figure 2: Three scales of wildland fire. Modified from Parisien and Moritz (2009).

ignition pattern used to set it can affect the intensity of the prescribed fire. But burns in different seasons can target plants at different stages in their life cycles, as well, so clearly these two elements of the fire regime have important interactions in determining the ultimate effects of a single fire, and especially over time, if fires are repeated. Collecting quality data from the fire environment before and during a fire can provide a lot of information to fire managers about what their burns are doing, and how to better plan future operations to increase their chances to achieve their goals.

What is fire?

All fire results from the combination of the three fundamental components of the Flame Triangle: Fuel, heat, and oxygen (Fig. 2). In the wildland fire environment, fuel consists of plant material. The ambient air provides oxygen. Wind can increase oxygen input, while physical barriers can block air flow. Heat must come from an ignition such as lightning or an incendiary device, or from an already-burning fire nearby.

Combustion

Combustion is a chemical reaction in which the rapid oxidation of plant material produces energy as heat:

$$(C_6H_{10}O_5)_n + O_2 + \text{energy}\underset{temperature}{\ kindling\ } \rightarrow CO_2 + H_2O + \text{energy}_{heat} \quad (1)$$

The left-hand side of Eq. 1 is simply the three components of the flame triangle in Fig. 2:

- $C_6H_{10}O_5$ is the chemical formula for cellulose, which represents plant material as fuel.
- Oxygen O_2 comes from the air.
- *Kindling temperature* is what fuel must be heated to before it ignites and combustion proceeds as a self-sustaining reaction (500°C).

Note that in this format, combustion is the reverse of *photosynthesis*, the processes that assembled the plant material in the first place:

$$CO_2 + H_2O + \text{energy}_{solar} \rightarrow (C_6H_{10}O_5)_n + O_2 \quad (2)$$

Thus, burning plant biomass—i.e., *combustion*, Eq. 1—is just a natural decomposition process that breaks down vegetation.

Combustion can be divided into distinct phases:[1]

1. **Preheating—**Fuel particles begin to absorb heat. Dehydration begins at 100°C—moisture is driven out of fuel particles. This is an *endothermic* part of the process, meaning it depends on heat from an external source. Often the energy source is an approaching flame front, so the heating rate increases as the flame front approaches. Flame contact leads to rapid heating.
2. **Pyrolysis—**The thermal degradation of matter. Around 200°C, chemical bonds in the fuel start to break down. The fuel particle begins to lose mass as previously solid components like cellulose volatilize. Around 500°C, any remaining material essentially turns into charcoal.
3. **Ignition—**The endothermic reaction that required heat input transitions to an *exothermic* reaction that releases heat. More than just reaching a threshold temperature (e.g., *kindling temperature*, as in Eq. 1), this phase means the reaction is releasing energy faster than the surrounding environment can absorb it.
4. **Flaming combustion—**The reaction zone—the surface of the fuel particle between 200–500°C—is engulfed in flame as the heated gases released by pyrolysis mix with oxygen in the air and ignite.

[1] It is important to keep in mind that *combustion in the wildland environment is not linear*. Because vegetation has all sorts of sizes, arrangements, and chemical and moisture contents, wildland fuel particles heat unevenly and release gases and energy at different rates (Sullivan and Ball, 2012; Finney et al., 2013). In fact, fire ecologists have used an overly-simple model of combustion for decades (Sullivan, 2017a), which often focuses on changes in temperature. But combustion is better understood as the exchange of energy between the environment and plant matter at the surface of fuel particles, known as the *reaction zone*. These review papers really get into the complexities of wildland fuel combustion: (Sullivan and Ball, 2012; Sullivan, 2017a,b).

5. **Glowing combustion—**Remainder of solid fuel particles continue to break down, even after all the gases have been released and burnt off as flames. Also known as *smoldering*.

6. **Extinction—**Combustion finally ceases, but not necessarily because all of the fuel is gone. Once the reaction no longer produces energy faster than it can be absorbed by any moisture or inorganic materials nearby, the reaction will slow and the fuel particle will cool enough to stop combustion if no more energy is added.

Heat transfer

No matter how hot a fuel particle burns, wildland fire cannot spread unless heat energy transfers to another fuel particle. The transfer of heat energy from combusting fuel to adjacent particles is called *propagation*. Heat transfer in the wildland fire environment follows three standard physical processes (Fig. 3):

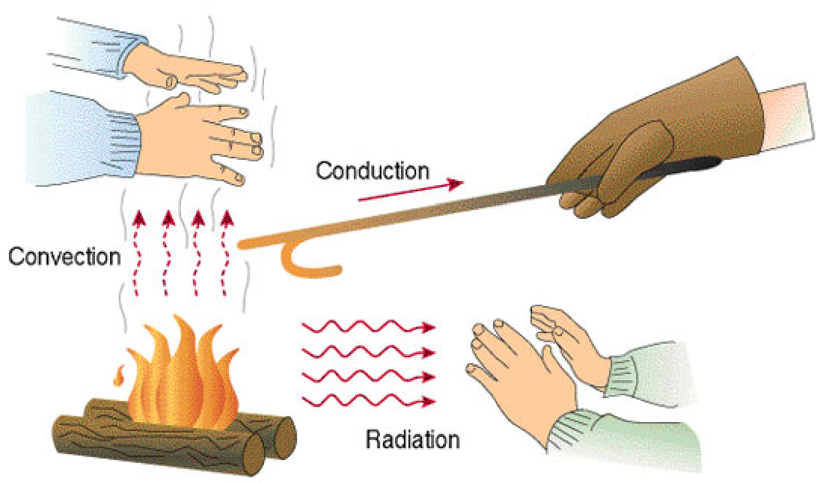


Figure 3: The three basic mechanisms of heat transfer. Convection is often the most important mechanism in wildland fire: buoyant hot air moves uphill or is pushed ahead of the fire by wind to preheat fuels prior to contact with flames.

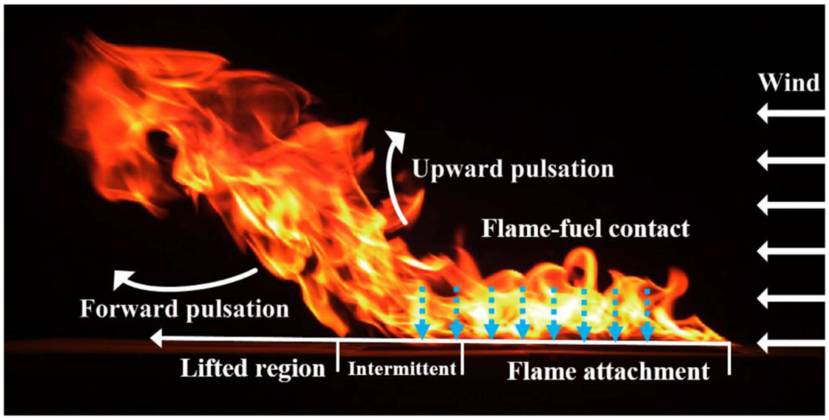
- **Conduction—**The transfer of heat through direct contact, from molecule to molecule within an object. Since plant matter generally conducts heat poorly, especially when dry, conduction in the wildland fire environment is primarily limited to carrying heat through soil and large-diameter fuels like logs.

- **Convection—**The transfer of heat through air flow is important in determining the direction of fire spread.[2] *Free convection* is the buoyant rise of heated air; *forced convection* is hot air moved by wind.

[2] As further evidence of the complexity of the wildland fire environment, convection can also *cool* fuel particles that are being heated by other processes, and the relative influence of heat loss vs. heat gain increases with the surface area:volume ratio of the fuel particle (Finney et al., 2013).

- **Radiation—**The transfer of energy via electromagnetic waves.While radiation can occur over relatively long distances, it requires unhindered line-of-sight movement and is thus limited to much shorter ranges in dense fuels.

Figure 4: Flame pulsation



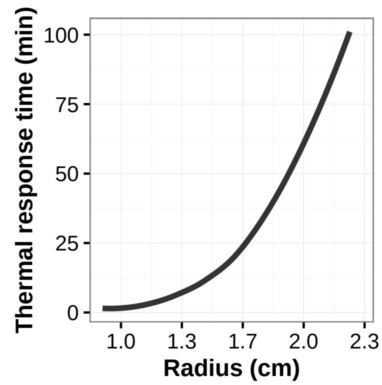
Two other heat transfer mechanisms are also important in the wildland fire environment:

- **Direct flame contact** is critical to propagation as it can ignite particles ahead of the flame front (Fig. 4). Flames can be pushed forward by wind, or even by a fire's own fluid dynamics. Brief, fine-scale turbulent pulsations created by fresh air flowing into the reaction zone as buoyant hot air lifts away can create horizontal vortices that push flames down, into contact with pre-heated fuel particles. The flame contact rapidly bringing them up to ignition temperature.[3]
- **Solid fuel transport** is the physical movement and deposition of burning fuel particles:
  - Large burning particles can break apart as pyrolysis degrades them; these burning chunks can fall or roll and cause ignition downhill.
  - *Firebrands*, or burning embers, can get carried by wind and fall far from the original fire. When firebrands land in a receptive fuelbed that is dry enough to ignite, they start *spot fires*.

[3] Finney et al. (2015); Tang et al. (2017); Morandini et al. (2018)

Wildland fuels

Wildland fuels are comprised of plant material. There are many species of plants, and they take many forms. Thus many properties describe wildland fuels: vegetation type (e.g., grasses, brush, coniferous or deciduous trees, logging slash, etc.); arrangement and structure (e.g., horizontal or vertical, continuous or discontinuous); particle size, along with surface area to volume ratio; particle density (loft, or packing ratio); whether the vegetation is alive or dead, standing or fallen, and whether it was derived from leaves or stems. But since fire spread depends on the transfer of heat energy through the environment, the diversity of plants can be functionally reduced to just a few categories of wildland fuel based on their thermal properties.



Data: Fosberg (1973)

Figure 5: The non-linear relationship between fuel particle size and heat transfer rate. Small increases in fuel particle radius leads to disproportionately large increases in thermal response time—the speed at which the material changes temperature. Thus, a fuel particle with radius 1 cm has a response time of 1.4 min, while the response time jumps to 56 min for a particle of 2 cm radius.

Fuel size classes

The primary categorization is *size class*, which is given by a fuel particle's diameter. Different diameters produce different surface area:volume ratios, which affects heat transfer rates: both how quickly the particle gains heat during pre-heating (Fig. 5), and the rate at which heat is lost while smoldering prior to extinction. Fuel size classes are referred to by their *lag times*, which refers to how quickly fuel particles gain and lose heat and moisture. The size classes of fuel are 1-hour, 10-hour, and 100-hour, which correspond to diameters of $<$ 0.6 cm, 0.6–2.5 cm, and 2.5–7.6 cm, respectively (Fosberg and Deeming, 1971).[4]

It is often sufficient to differentiate fine fuel (1-hr) from coarse fuel (10-hr and above). Physically, fine fuels are "thermally thin", with low surface area:volume ratios that take on heat quickly and evenly, and have often fully combusted by the time the flame front passes. In the field, the fine/coarse distinction might apply to grasses vs. larger shrubs, trees, and downed woody debris.[5]

Fuel moisture

Fuel moisture is an important property, and wildland fuel moisture dynamics follow the size classes described above. But first it is important to distinguish between living versus dead vegetation. There are two reasons fuels ought to be considered a class by themselves (Finney et al., 2013):[6]

- Moisture in living plant tissue is under the biological control of the organism (ecophysiology), whereas dead fuel moisture is a passive interaction between plant tissue and the environment.
- Live tissue moisture often exceeds levels that will support combustion—in terms of heat flux, this moisture absorbs energy, making living plant tissue more of a sink than a source of combustion energy. And live tissues retain this moisture until their cells fail, slowing dehydration.

Within dead fuels, the concept of lag times applies to fuel moisture gain and loss as well as heating and cooling: dead fuel moisture depends on the moisture content of the air around it. All dead fuels passively gain and

[4] The metric delineations might seem odd, but the original categories were in inches: $<$ 0.25, 0.25–1, 1–3. Some recognize a 1,000-hr class for very large fuels.

[5] In prescribed fire, fine and coarse fuels are often managed separately—undesired woody plants might be targeted for heating, while desired species are to be protected, and keeping a pile of woody debris from igniting in the first place is the best way to ensure it doesn't kick up embers hours after everyone has gone home.

[6] Fire scientists have struggled to account for live vegetation. In the parlance of wildland fire science, live fuels are often *not available to burn* because they are insufficiently *cured*, i.e. they haven't been dried out through exposure to warm air or radiation. Because many management fires occur outside of dry, dormant seasons or in fuelbeds dominated by invasive species, prescribed fire managers (and scientists) must think beyond dead fuels alone.

lose moisture by exposure to the atmosphere, and fine dead fuel moisture changes faster than coarse fuels.

Several environmental variables affect fuel moisture transfer rates. Sources of moisture include the atmosphere itself—humidity and precipitation—and contact with other sources capable of holding and releasing moisture, such as soil and forest duff. When these sources are steady, fuel particles eventually reach an *equilibrium moisture content* with the surrounding air—gains and losses of moisture via diffusion with the air are net neutral. Fine fuels reach equilibrium moisture content within a matter of hours, while coarse fuel can take days or weeks to become available for combustion if they got soaked through. Drying increases with exposure to both wind and solar radiation (Byram and Jemison, 1943).

The fuelbed and fire types

Wildland fuels occupy a three-dimensional space called the *fuelbed* through which flame fronts spread from particle to particle. As such, the structure of plant biomass in this three-dimensional space has a major effect on fire. Within the landscape, the type of vegetation—grassland, brush, or forest—determines the type of fuel available to burn. Within the combustion reaction zone, the arrangement and density of fuel particles regulate the flame triangle—fuel availability, oxygen flow, and how quickly heat transfers to new fuel particles.

Three broad fire types are defined by the fuel layer through which fire spreads (Fig. 6): *ground fires* burn through organic material below the soil surface, such as peat and heavy forest duff; *surface fires* burn through herbaceous and brushy aboveground plant biomass rooted in, or laying on, the soil surface; and *canopy fires* burn through the foliage of standing trees; *torching* is when the canopy of a single tree burns, while fire propagating from one canopy to another *running crown fire*. Although fire rarely starts in the canopy, canopy fuels can be ignited by extremely high surface flames or via *ladder fuels*—hanging branches, vines, or shrubs and trees of younger age classes that carry fire into the canopy after first being ignited on the surface. These canopy dynamics are a vivid illustration of the importance of *horizontal continuity*—how far apart the trees are—and *vertical continuity* between surface and canopy fuels, but these dynamics are at play in determining surface fire spread and behavior, as well.

Fire behavior

Fire behavior describes energy release by the combustion of vegetation, and is controlled by the three factors in the Fire Behavior Triangle (Fig. 7). With knowledge and experience, wildland fire professionals can

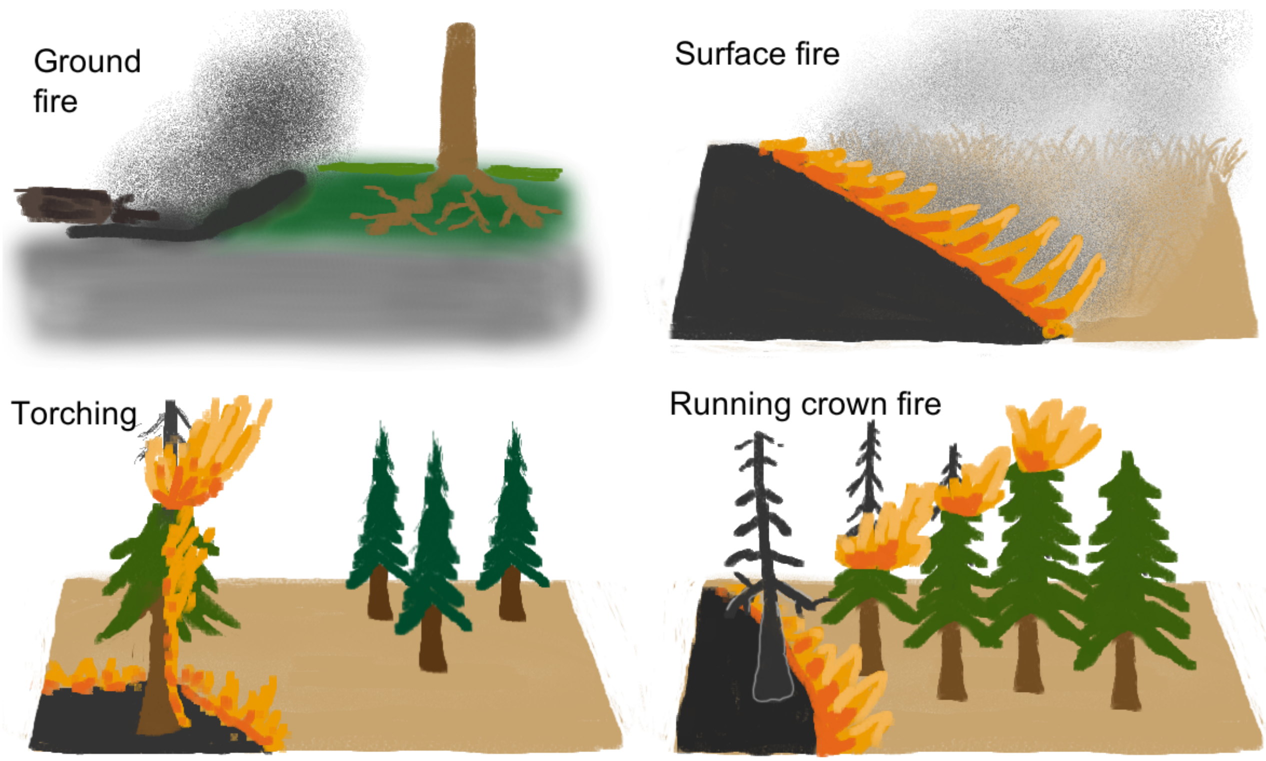


Figure 6: Four types of wildland fires. *Ground fires* burn underground through organic material like peat, while *surface fires* move aboveground through fuels on the soil surface. Fire can transition to tree canopies, as well. *Torching* occurs when the canopy of a single tree burns, while *running crown fires* involve canopies of multiple trees.

learn to anticipate how environmental factors influence fire behavior in a particular fuelbed.

Direct observations include how fast a fire moves, how long fuels burn, and the length of flames. Indirect observations include how much unburned fuel is left behind, or how high up trees are scorched by flames.

Two standard descriptors of fire behavior are rate of spread and intensity. *Rate of spread* is simply how fast the flame front moves through the fuelbed. *Intensity*—which is not directly observable —refers to energy release; specifically, *fireline intensity* is the amount of heat released per length of flame front within a period of time (Rothermel, 1983). *Flame length* is directly related to the rate of energy release and thus serves as an observable proxy of intensity (Rothermel, 1983). Both fireline intensity and flame length increase with fuel load and decrease as fuel moisture increases (Kreye et al., 2013).

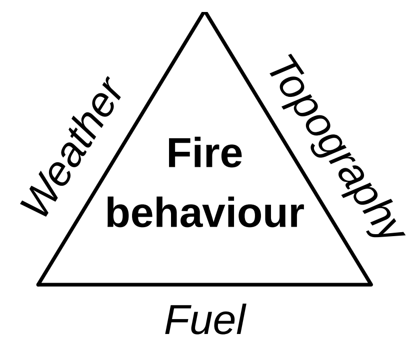


Figure 7: Topography, weather, and the fuelbed are the three major drivers of wildland fire behavior.

When fuels are constant, variability in fire behavior is driven primarily by wind and the flatness or steepness of the terrain, or *slope*. Wind and slope are important because they affect heat transfer and facilitate pre-heating, which is the critical mechanism for flame propagation (Sanchez Tarifa and Munoz Torralbo, 1967). Wind pushes heat ahead of the flame front and hot air rises upslope, both of which increase convective heat transfer (Sharples, 2008). Both also reduce the angle between the flame and surface fuels, increasing the probability of heat transfer via flame contact. The effect is for fires to move faster with the wind, or up a slope, and more slowly against the wind, or down a slope, than in the absence of either.

Wildland fire anatomy

Because the effects of slope and wind on heat transfer are predictable, one can also predict the shape and direction of wildland fire spread through a given fuelbed. Fire behavior also varies predictably at different points along the fire perimeter relative to wind direction and slope.

Assume a single-point ignition in a flat grass fuelbed. Without wind, the flame front would slowly spread at a constant rate in all directions. Heat transfer is limited to particles very near the reaction zone. A fire under a no-wind scenario appears as a slowly-expanding circle. But if a wind were to rise, heat transfer rates will vary between the upwind and downwind directions and the shape of the fire becomes elliptical as different parts of the fire spread at different rates (Fig. 8).

While fire *spreads* outward as a flame front via propagation, *fire growth* is driven by increases in burned area, including the spot fires that accelerate the increase in burned area beyond the spread of individual flame fronts. On level terrain with a continuous, even fuelbed and constant wind, the shape of a fire's burned area depends primarily on wind speed. The

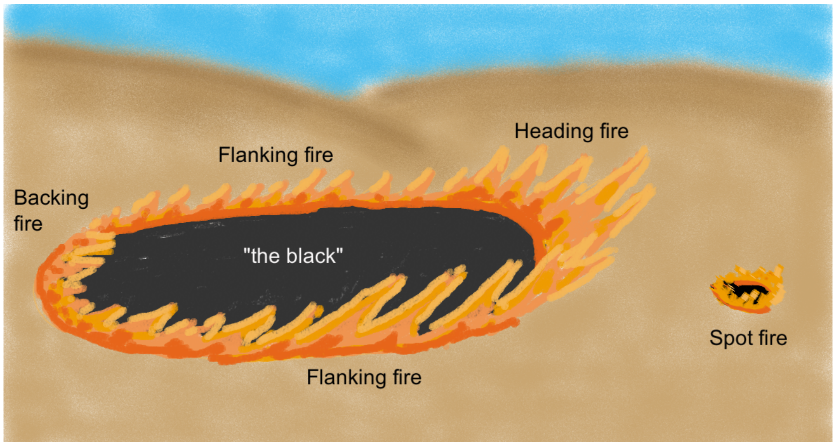


Figure 8: The anatomy of a surface fire. Here the wind moves from left to right, giving the fire an elliptical shape as the *heading fire* moves fastest with the wind, and has the longest flames. Conversely, the *backing fire* moves the slowest, creeping into the wind. On each side, *flanking fires* spread perpendicular to the wind at a rate between the backing and heading fires; they are aerated by the wind but are neither moving fully against it nor with it. The burned area in the center of the fire is often called "the black" and is an important safety zone for fire personnel due to the lack of remaining fuel. The spot fire was ignited by a *firebrand*, or ember, carried ahead of the main fire by the wind.

higher the wind speed, the longer and more narrow the burn perimeter.

A brief description of the anatomy of a wildland fire:

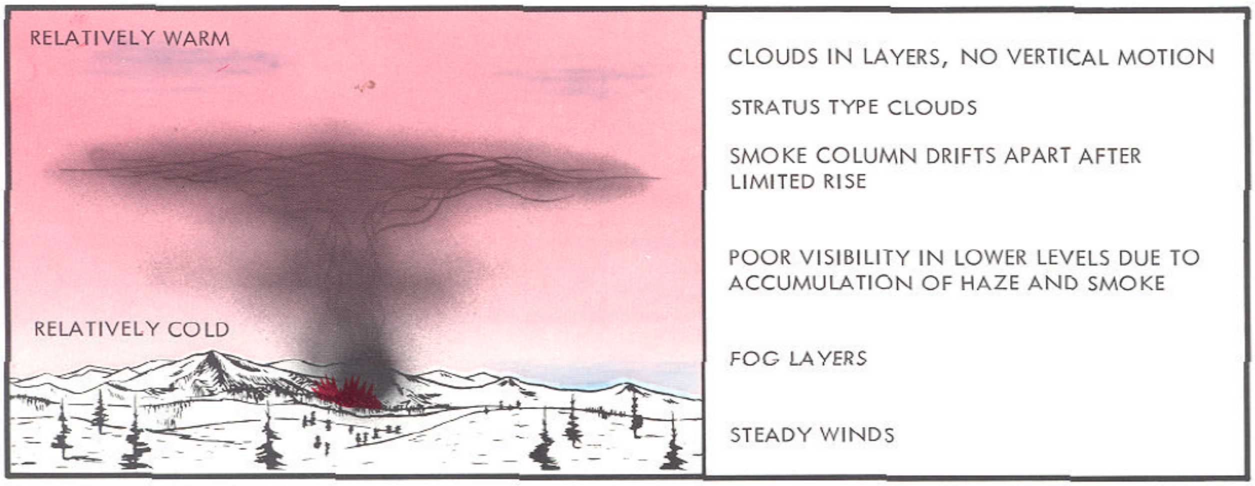
- **Head(ing) fires** move with the wind. Wind drives convective heat transfer by pushing warm air ahead of the fire, which accelerates preheating, propagation, and fire spread.
- **Backing fires** crawl into the wind. Blowing heat back over previously burned areas instead of into unburned fuel reduces preheating.
- **Flanking fires** are the sides of the fire that burn parallel to the wind. The lower intensity of flanking fires can be important tactically for wildland firefighters, as it is easier to fight these flames directly and work toward the head fire, reducing the total area burned.[7]
- **Spot fires** start via *firebrands*—burning embers carried ahead of a flame front by wind or convection.
- The **smoke plume** consists of the "gases, smoke, and debris that rise slowly from a fire while being carried along the ground because the buoyant forces are exceeded by those of the ambient surface wind (NWCG, 2019)." Plumes that develop strong updraft are called *convective columns*, highlighting their effect on fire behavior (Fig. 9). Many fire-atmosphere interactions that relate to convective lift aren't directly visible. Plume structure provides insight into atmospheric conditions and plume properties such as color and roiling indicate fire behavior.

Figure 9: Such a large smoke plume has developed over this wildfire that it has altered cloud formation at its top, several thousand feet above the fire.

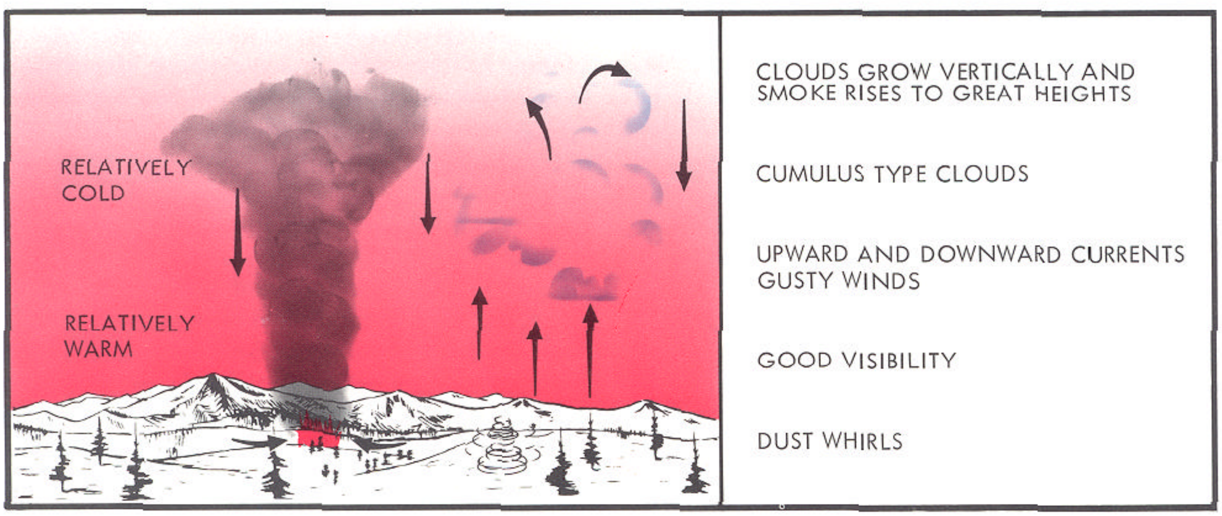
[7] Because a wind shift could easily turn a flanking fire into a head fire, it is important that personnel working on a flanking fire do so from the burned area within the perimeter, which serves as a safety zone.

Fire-atmosphere interactions

Fires interact with the atmosphere. Crucially, these interactions are often simultaneously the least visible factors affecting fire behavior and the most important factors affecting the safety and effectiveness of prescribed burns. Thus it is important for all prescribed fire professionals to know how to read the signs that indicate how a fire is interacting with the invisible atmosphere.



Visible indicator of a stable atmosphere.



Visible indicator of a stable atmosphere.

Schroeder and Buck (1970)

Figure 10: An illustration of general indicators of *atmospheric stability*—the resistance of the atmosphere to mixing via vertical movement of air. A stable atmosphere resists mixing, which limits convective lift of smoke and generally subdues fire behavior. An unstable atmosphere is receptive to rapid convection and smoke lift, which increases ventilation of the combustion reaction zone and increases fire intensity.

Atmospheric stability refers to how resistant the atmosphere is to vertical air movement, one of the controls on fire behavior (Schroeder and Buck, 1970, Fig. 10)). Hot combustion gasses and heated air are buoyant, and naturally seek to rise until the air expands and cools. In an unstable atmosphere, warm air rises easily, which increases convective airflow away from the combustion zone. One cannot directly observe instability, but meteorologists can measure and predict associated variables. US fire weather forecasts include the *Haines Index*, an index of the potential for rapid fire growth derived from correlations between observed fire behaviour and atmospheric stability (Haines, 1988).

An *inversion* is a departure from the typical pattern in which air gets colder with distance from the Earth's surface. *Surface inversions* are deep layers of cool air near the surface, also known as *night inversions* because such cooling often occurs at night (Schroeder and Buck, 1970). Inversions form low, stable barriers of air that prevent mixing, convection, and smoke dispersal. Although inversions are prominent in mountainous regions, night inversions often form over broad areas without topography.

The effect of an inversion on fire behavior is sometimes most noticeable as the inversion lifts. By suppressing convection, inversions have the obvious effect of reducing the intensity of wildland fire burning under it, perhaps a prescribed fire lit during the morning. But as solar heating in the morning warms the surface, warm air begins to circulate in the near-surface atmosphere and starts to mix with higher layers. This convection and mixing weakens the inversion until it lifts entirely, allowing convective currents to reach to the top of the *troposphere*, the lowest layer of the atmosphere that interacts with the Earth's surface. The consequence for fire behavior is greater intensity as convection develops.

The fire regime

The fire regime of an area is the product of climate, vegetation, and the pattern of ignitions averaged over a given period of time (Fig. 11). Many of the specific parameters of fire regimes—fire frequency, spatial extent, seasonality, intensity, and fire type—can also describe individual fire events.

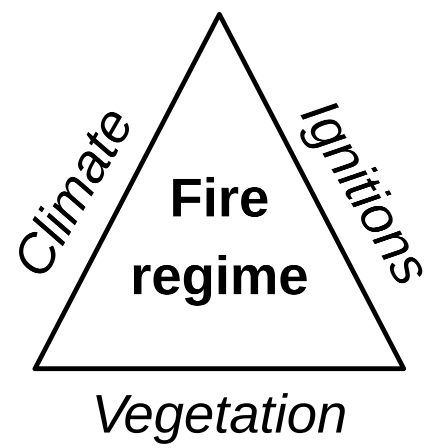


Figure 11: The three sides of the Fire Regime Triangle. See Fig. 12 for specific components with each side of the triangle.

While the term *fire regime* typically refers to a "core group of parameters describing which fires occur when and where according to frequency, size, seasonality, intensity, and type" (Krebs et al., 2010, p. 61), many parameters are a product of two or more sides of the Fire Regime Triangle and are controlled at multiple temporal scales.

The importance of the fire regime concept to wildland fire science and management can hardly be overstated. The fire regime concept underpins the objectives of fire management policy as well as the strategy and tactics of prescribed fire operations (Fig. 1). Thus, to be useful, wildland fire scientists must target data collection to measure components of the wildland fire environment that relate to the targeted components of the fire regime. Let us focus on the *core parameters* of fire regime—the physical parameters of a specific fire, or the typical fire in an area.

Two physical characteristics are important to fire regime: *fire type* and *fire intensity*, which describe the distribution of energy released to the environment, and where it might expose soil, plant organs, and organisms to

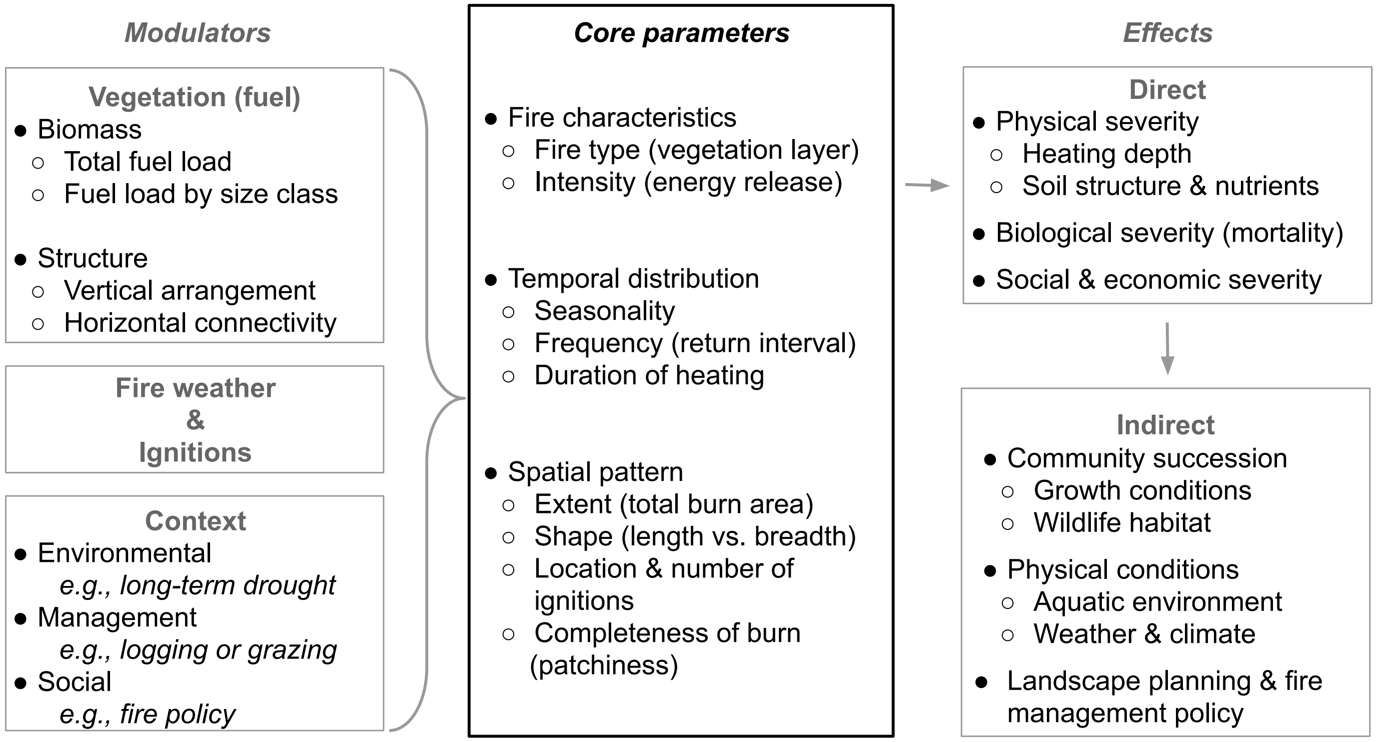


Figure 12: The fire regime concept can be divided into core parameters—those that describe the physical characteristics of either one fire event, or the typical fire event—as well as biological, meteorological, and social factors that modulate fire events, and direct and indirect effects of fire. Figure from McGranahan and Wonkka (2021), inspired by Krebs et al. (2010).

heat. Recall that fire type refers to the vegetation layer that burns (Fig. 6), and intensity refers to the energy released by the combustion of wildland fuel.

There are three components to the timing of fire:

➥ **Seasonality** describes when in the year a specific fire occurs, or when the typical fire is likely to occur. It is broadly categorized as occurring in dormant or active seasons. Seasonality affects burn severity through direct and indirect interactions with *phenology*—the timing of organisms' life histories relative to the climate. Generally, physiologically active organisms are more sensitive to fire damage.

➥ **Fire frequency** typically means the number of fire events per period of time, while a similar term, *fire return interval*, expresses time between fire events. Both are measures of the amount of time between fire events, which affects both how long fuels have to accumulate and vegetation succession since the last disturbance.

➥ **Duration of heating** refers to how long soil or organisms are exposed to elevated temperatures from combustion. Many organisms have traits or behaviors that help them survive short periods of exposure to even high heat, but surviving long exposures to even moderate heat often requires specialized adaptations. Sometimes even just the difference between a fast-moving head fire or a slower backing fire creates variability in heat exposure in grassland. Smoldering chunks of coarse fuels can hold heat against the soil.

It is also important to consider the spatial pattern of fire. A simple measure is *extent*, or the total area burned. *Completeness of burn* refers to how much area within a fire perimeter actually burned. A fire with low burn completeness will have unburned areas where fire did not spread. Such areas might have been protected by fuel gaps created by streams or wetlands, rocky features, areas of intense herbivory, roads or trails, or defensive firebreaks. The resulting landscape is a patchwork of burned and unburned areas; thus *patchiness* also describes the degree to which a fire did not burn completely.

Accounting for environmental variability

One of the most basic principles of the scientific method is to focus on the variable of interest, and hold everything else constant. This is fairly easy in controlled experimental environments. For example, if a researcher wants to determine whether road dust effects photosynthesis in crop plants, they would find seeds from the same source, plant them at the same time in the same type of soil, give them the same water and fertilizer and the same amount of light in a greenhouse, and measure photosynthesis after applying dust to a randomly-selected group of plants (Fig. 13). If there are differences in photosynthesis between the two groups, it is reasonable to assume that the differences are due to the dust, because everything else was held constant.

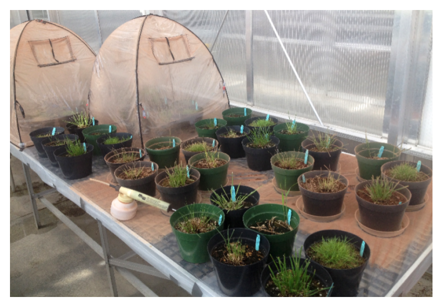


Figure 13: Controlled application of dust on plant leaves in a greenhouse.

But working out in the natural environment at the scales that land is managed is different. The environment is inherently variable—only the most highly-managed field or pasture has exactly the same time of plants in the same type of soil on the same slope and with the same amount of moisture. Wildlands and other areas managed for wildlife, native plants, and general biodiversity conservation are notoriously variable in terms of topography, soil, hydrology, and plant communities.

Fuels

Fuel for wildland fire consists of vegetation. Recall from Eq. 1 that combustion is essentially the decomposition of plant matter—originally produced by photosynthesis—in the presence of oxygen and sufficient heat. Because a high degree of variability in fire behavior can be attributed to variability in fuels, making good fuel measurements is essential to predicting how a prescribed fire will burn and explaining variability in the effects that fire produces.

Broad considerations

Fuels and the fire regime

The primary consideration of fire regime in planning fuels measurement is identifying the *fire type* by determining which vegetation layer(s) carries the fire (Fig. 12). Under all but the most extreme conditions in densely-wooded vegetation, prescribed fire management is typically focused on surface fires that consume herbaceous vegetation rooted in—or laying on—the soil surface. [8]

[8] Note that in woodlands and savannas, the fuelbed often contains leaf litter that fell from tree canopies, which are considered surface fuels once they have fallen.

Next, one must determine if live fuel is a consideration (we assume here that it is). How to determine if live fuels are relevant? Consider the conditions below. If any apply to a burn or study, one should likely be measuring live and dead fuels separately:

Checklist for live fuel relevance

- ✓ Prescription for growing season burn
- ✓ Vegetation dominated by exotic cool-season (C_3) grasses
- ✓ Management and/or research objectives focus on any C_3 grass
- ✓ Research objectives include parameterizing custom fuel models and/or modeling fire behavior

However, if none of the above conditions apply, one is probably not missing out on much information by not dividing the fuelbed up into live and dead components.

There are two basic types of information on fuels the fire scientist ought to obtain *by fuel class*[9]:

- Fuel load
- Fuel moisture

[9] While these would typically also be described by size class, in the workshop we are considering only 1 hr fuels, so we will consider each in terms of live and dead components.

Sampling approaches

There are two broad categories of sampling methodologies, each with pros and cons specific to wildland fuel sampling, although the pros and cons likely apply to other sampling contexts, as well:

- **Destructive—**Samples are collected by physically removing material from the environment.

Pros: Most accurate; probably needs fewest observations. Raw data in desired units (mass/area for fuel load, % H_2O for fuel moisture).

Cons: Removes from the fire environment the very thing one seeks to describe within the fire environment. Time consuming. Requires weighing and drying equipment. Data not instantaneously available.

- **Non-destructive—**Sampling consists of observations that do not require the material to be disturbed.

Pros: Doesn't remove any fuel from the fire environment. Most often requires less sample processing time & effort, and data can be instantaneously available.

Cons: Likely requires more observations to minimize variability. Raw data rarely on a meaningful scale; often needs a conversion factor that in turn must often be derived from separate calibration efforts.

Whether one implements destructive or non-destructive sampling has profound implications on the nature of the sampling protocol and the data it produces, including the transferability of data to other events and locations and even whether the data are useful for the stated purposes. Consider just a few examples of how different wildland fire professionals might need different types of data on different time scales:

- *The burn boss wants to make tactical decisions on fuel conditions such as a minimum or maximum fuel load, or minimum dead fuel moisture.* They will need this information the day of the burn—they cannot wait for samples to be clipped, dried for 48 h, and weighed. On the other hand, an estimation based on a representative but limited sample is probably sufficient. The values likely do not need to be applied to other locations.

- *The biologist has designed a monitoring program to assess shrub mortality across several sites with different amounts of smooth brome.*

Whether that smooth brome was green or not at the time of the fire—and how much of it there was—is likely important information. On the other hand, categorical assessments of live:dead biomass based on non-destructive observations is probably sufficient. An estimation of live fuel moisture based on a representative but limited sample would probably be icing on the cake.

➥ *A graduate student has a hypothesis that connects fire behavior to fuel parameters.* It is important that multiple pre-fire measurements be taken around each fire behavior observation point, and continuous variables are best. On one hand, statistical analysis can take fuel load on any scale, so a rapid, non-destructive quantification method will be fine. On the other hand, reviewers are likely going to want to be able to connect these data to actual values, and managers will need those values to apply the findings well, so it is best to have a plan for calibration. An accurate measure of fuel moisture is important, but the data aren't needed until well after the fire, so there is plenty of time to dry and weigh clipped samples.

These questions help guide a responsive and informative sampling plan:

Ask first:

✓ *Who* is expecting the data and *what* are they going to use it for?
✓ *When* are they expecting it?

Then determine:

✓ *What* will be reported
✓ *How and when* data will be collected

Measuring fuel load

Destructive sampling

Clipping is the most straightforward form of measuring fuel load in grasslands. A representative sample point is identified, a known area determined, and all vegetation—representing combustible fuel—is removed by hand and stuffed into a paper bag (Fig. 14). Once dried and weighed, the mass of the material in the bag is easily expressed as the fuel load for the known area from which the sample was collected.

Clipping Clip all material to within about 2 cm or 1 inch of the soil surface. The main idea is to gather as much combustible material as possible while being as consistent from sample to sample. Clipping and scraping right down to bare mineral soil when one can will produce a different picture of the available fuel load than a quadrat with a thicker mat of wet

Figure 14: On the left, a 0.25 m^{-2} quadrat is about to be clipped with sheep shears (this might sound silly, but they are the secret weapon for efficient grass clipping).

litter that is unlikely to burn anyway (Fig. 15). Better to be consistent from quadrat to quadrat. Deposit clipped material in a paper bag clearly labeled with a marker.

Figure 15: Even a hot fire can't burn it all off.

Drying Clipped biomass samples are typically dried in forced-air ovens at at least 60degC.[10] The aim is to dehydrate clipped biomass to the point that the samples reach an equilibrium moisture content with the air in the oven—as the weight of samples at such a state would no longer loose mass, complete drying of samples is often referred to as "constant mass." With herbaceous samples, this often occurs within 48 hours.

[10] There is debate around the minimum temperature required to adequately dehydrate samples, although differences have the most effect on determining moisture content, not dry mass. Thus this debate is discussed in the fuel moisture section below.

Weighing Weigh dried biomass samples on a digital balance shortly after removal from the oven, before they absorb moisture from the cooler ambient air. The primary concern with weighing is accounting for the mass of the paper bag. One can either dump the bag contents into a tared container on the balance, or weigh the sample in the bag and subtract the mass of the bag. There are many arguments for the latter—it is often faster and less messy—but it is prone to error if different types of bags are used. A best practice for data management is to enter a code for the bag type when entering mass data for each sample, or group of samples with a common bag type, and assign the mean mass of several empty bags to each code when subtracting bag weights prior to analysis.

Nondestructive sampling

Nondestructive sampling of fuel load—i.e., measurements taken without physically removing material from the fuelbed—has several distinct advantages. Chiefly, nondestructive sampling leaves the fuelbed intact, which ensures that the amount of fuel recorded in the data is actually the amount of fuel available to burn. If too many clipping samples are taken from too small of an area around a fire behavior sensor, the removal of fuel could reduce intensity and rate of spread. Fire behavior data from that sensor would not represent the rest of the fire.

The most common technique for non-destructive sampling of aboveground vegetation in North American rangeland is known as the Robel pole (Fig. 16). Initially presented by Robel et al. (1970), the point was to make a measurement that combined the height and density of prairie vegetation to assess wildlife habitat. The pole itself was 3 cm in diameter, 150 cm long, and painted in 1 dm (10 cm) increments. Observers stood the pole upright in the vegetation, stepped back 4 m, and bent down such that eye level was 1 m. The lowest increment on the pole that was 50% obscured by vegetation was recorded; this came to be known as the *visual obstruction reading*, or VOR.

Crucially, the VOR had "a striking relationship between the visual ob-

Figure 16: Two views of a Robel pole in place: Left, in very low biomass due to repeated grazing following a patch burn; Right, in tall, fully-headed out smooth brome grass in an idled CRP field.

struction measurements and the weight of vegetation clipped from each transect (Robel et al., 1970, p. 296).” From their analysis of data averaged at the transect level,[11] the relationship between the non-destructive VOR measured from the Robel pole and actual vegetation biomass (g m^{-2}) could be well explained ($R^2 = 0.97$) by the linear relationship

$$\text{biomass}_{g\ m^{-2}} = 113 \cdot \text{VOR}_{dm} + 1.9 \tag{3}$$

[11] Standard practice has become to collect four VOR measurements around each pole placement, typically from the four cardinal directions, and average those readings for a single observation. This works well for fuel load measurements around fire behavior sensors not oriented along transects.

The utility of VOR in estimating herbaceous biomass has been confirmed several times since the Robel pole was introduced. Two studies in particular compared VOR to other non-destructive methods, and found it to be the most accurate in both hayfield/pasture situations and native rangeland (Harmoney et al., 1997; Ganguli et al., 2000). Vermeire et al. (2002) fit a new linear equation to a combined dataset from shortgrass, mixed-grass, and tallgrass prairie (1000-7000 kg ha^{-2}; $R^2 = 0.93$):

$$\text{biomass}_{kg\ m^{-2}} = 183 \cdot \text{VOR}_{cm} + 538 \tag{4}$$

While they note that users can get better accuracy by creating location-specific calibration equations by comparing VOR measurements to their own clipped quadrats, this general equation provides a good estimate across grasslands in general.

Differentiating fuel components

Often information is needed on specific parts of the fuelbed. When live fuels are a consideration, live and dead components must be assessed separately. Managers and researchers are often interested in litter separate of the total fuel load. Below are approaches for each.

Live vs. dead

The most accurate method to report live and dead components of the fuel load are to measure each separately. “Hand sorting” is the process of placing live and dead fuel in their own bags for separate weighing. Samples can be sorted as they are clipped, or prior to drying; the sooner it occurs, the easier it is to distinguish live material from dead.

But hand sorting is very time-consuming, and fortunately alternative methods have been developed. The *constituent differential method* from Gillen and Tate (1993) uses known values of wet weight (mass in the field, just after clipping) and dry weight (mass after drying) for pure sub-samples of live and dead biomass to determine the fractions of each in combined samples. When fuel samples are clipped on the same day as a burn, the pure sub-samples of live and dead fuel can also be used for fuel moisture measurements.

Live:dead fractions can also be estimated via visual categorization. This is a more rapid technique that does not require any clipping from the fuel load, although its accuracy can be improved via calibration with clipping data from a local stand similar to the fuelbed. Visual categorization based on color tends to over-predict curing, because fuels start to *look* cured before their moisture content has actually gotten below the moisture of extinction (Kidnie et al., 2015).

Litter

Destructive sampling Perhaps the best way to measure litter separately when clipping plots is to clip all standing plant material down to the top of the litter layer—not to within 3 cm of the soil surface right away—then collect the litter into a separate bag. Any remaining standing material can then be clipped to 3 cm of the soil surface and added to the first bag.

Figure 17: Measuring litter depth with a ruler.

Non-destructive sampling Specific litter depth measurements can be made with a ruler (Fig. 17). Do not rely on a separate reading on a Robel pole, which is likely too coarse—in terms of both the diameter of the pole pushing down litter, and the width of the increments—to provide a sufficiently precise measurement. Find an average of multiple depth readings taken from a focal area (e.g., a quadrat). Then, if necessary, additional work can likely be done to calibrate the average depth to biomass on a per-area basis.

Measuring fuel moisture

As with fuel load, the most reliable measurements of fuel moisture content are made by clipping physical samples. There are two differences to consider when clipping for fuel moisture samples: Less material is needed, making it less disruptive to the overall fuelbed, and fuel moisture samples must be weighed before drying as well as after. Critically, *the pre-drying mass should be taken as soon after clipping as possible*, to prevent moisture loss (Fig. 18). If samples are at risk of going for more than an hour or so before pre-drying mass can be determined, they should be handled in sealed, non-permeable containers like zippered baggies or bottles and kept out of direct sunlight and hot environments until they can be weighed.

Figure 18: Green, live grass material is weighed separately prior to drying.

There is debate around the best temperature to sufficiently dry samples intended for fuel moisture measurement. On one hand, Gillen and Tate (1993) only set their drying ovens to 45°C; this is likely too low to be recommended for measuring fuel moisture content. Matthews (2010) compared the moisture content of dead grass fuels after 48 h in ovens set at 60°Cand 105°C, and found they averaged 10% and 8% moisture, respectively, which could be a meaningful difference if, for example, dead fuel moisture is being used as an input for fire behavior calculations.[12] On the other hand, further work suggests drying temperature is less important, given the amount of variability inherent among samples, especially for live fuels (Jolly and Hadlow, 2011).

If day-of fuel moisture measurements are required, there are a few options. Firstly, smaller sample volumes can be sufficiently dehydrated in a microwave oven to get a reasonable estimation of fuel moisture. Secondly, there are technologies that use electricity to determine the moisture content of plant material—many such devices are used in the grain industry, for example, to monitor moisture content. Campbell Scientific manufactured a moisture meter specifically for wildland fuels (Fig. 19), but unfortunately only a limited number were produced and new units are not available.

[12] For example, a BehavePlus calculation for tallgrass prairie (fuel model 3) that assumes a 10 mph wind on flat ground indicates fire will spread 8 m min^{-2} faster at 8% fine dead fuel moisture than at 10% (83 vs. 75 m min^{-2}, respectively).

Figure 19: The Campbell Scientific DMM-600 duff moisture meter uses electricity to instantaneously determine the moisture content of a sample. In addition to forest duff, it is effective for live fuel moisture in grassland fuels (McGranahan, 2019). Unfortunately the manufacturer's website indicates the product has been retired.

Fire weather

Weather is the most variable component of the fire behavior triangle (Fig. 7). Understanding effects of weather on fire behavior is key to safely conducting any fire management—wildland fire use or suppression—and provides important information to understanding variability in fire behavior even if fuels are relatively similar.

Wildland fire weather information can be divided into two components (Teie, 2018):

- **Strategic weather—**Information on general trends for a day, extending to several days.
- **Tactical weather—**Local observations made at the scene (Fig. 20). Typically includes air temperature (often called *dry bulb*), relative humidity, and a wind vector (direction, average sustained wind speed, peak gust).

Figure 20: Devices like portable weather meters make it easy to quickly collect fire weather information to support tactical decisionmaking and ecological research.

Below we describe how to acquire and use both types of data in a prescribed fire operation. From an operational perspective, strategic weather information consists of forecasts and tactical weather information comes from belt weather kits and local automated weather stations. Researchers have access to the same forecast data but also historical data at multiple scales, from automatic weather stations that log data and are networked, to broad-scale, gridded historical weather data products.

Strategic weather

Strategic weather products consist primarily of forecasts available from a number of sources at several different spatial and temporal scales.[13]

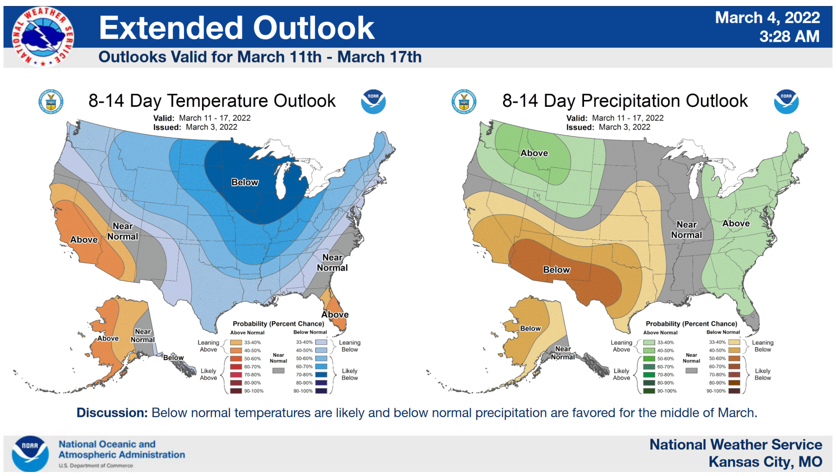
Forecast products

The National Weather Service (NWS) provides several products either specifically for, or very relevant to, fire weather. We discuss a few here, starting at spatially-broad and long time scales, working to local predictions for specific time periods at a specific point on the landscape.

[13] We focus here on shorter-term products from the National Oceanic and Atmospheric Administration's National Weather Service (weather.gov), but NOAA's Storm Prediction Center and Climate Prediction Center also offer longer-term outlooks relevant to fire planning. Additionally, the National Interagency Fire Center's Predictive Services provide a lot of fire-specific weather information at both national and regional levels (predictiveservices.nifc.gov/weather/weather.htm). The information is geared towards wildland fire suppression but is also useful for prescribed fire operations.

Basic weather products

NWS provides extended outlooks at a national scale (Fig. 21). Each NWS office also provides a daily Area Forecast Discussion that not only explains how current regional atmospheric patterns affect the area's weather, but also some of the considerations taken into account by local forecasters as they assess model output.



https://www.weather.gov/media/eax/DssPacket.pdf, 4 March 2022

Figure 21: An example of national 8-14 day temperature and precipitation outlooks provided by the Kansas City, MO NWS office.

Zone area forecasts—accessible by searching a town name at weather.gov—are local forecasts generated at the county or municipality level by regional NWS offices. Zone area forecasts provide a 7-day weather forecast and current conditions at the nearest NWS observation point, typically the closest airport. These pages also provide hourly weather forecasts that illustrate predicted trends in several weather variables hour-by-hour over the next few days (Fig. 22).

Specific fire weather products

National fire-related forecast data are compiled at weather.gov/fire (Fig. **??**). Some regional NWS offices provide fire-specific forecast information. Several regional offices around the country provide text-based Routine Fire Weather Forecasts that give strategic fire weather forecasts for smaller zones within the area (Fig. 24). But not all offices provide fire-specific data, and not all regions provide the same information or even for the whole year. For example, Bismarck, ND regional office has a page dedicated to fire weather in western and central North Dakota, but it isn't maintained during winter months. And compare differences in output between Figs. 24 & 25 due to different local environmental contexts.

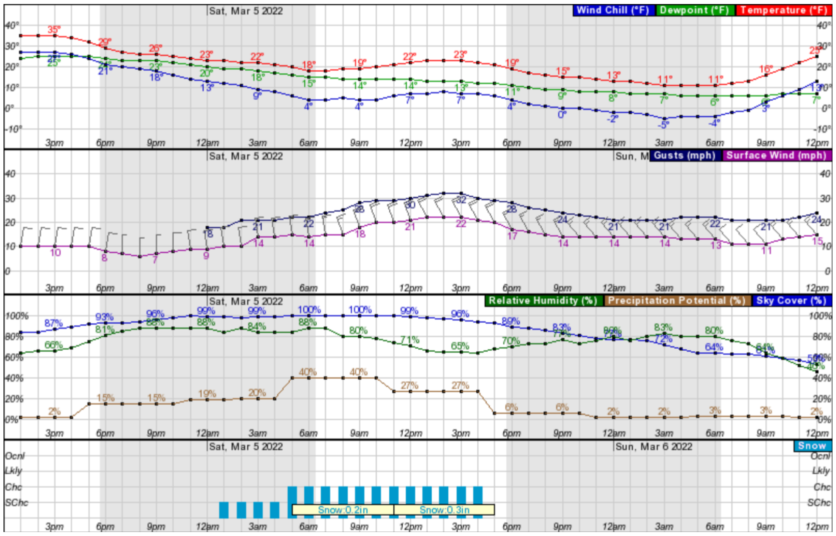


Figure 22: An example of predicted hourly trends in several basic weather variables for two days in Hettinger, North Dakota. All regional NWS offices in the country provide this product. While searched best by town names (weather.gov), one can edit the latitude and longitude fields in the URL by hand to generate an hourly forecast for a specific point and bookmark it for future use.

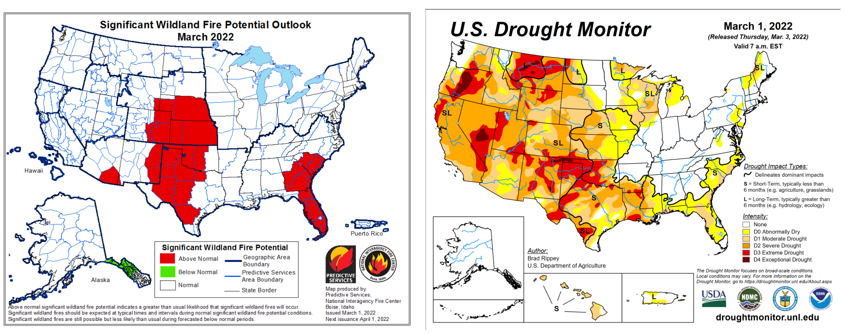


Figure 23: Two examples of national fire-related forecast products conveniently posted at weather.gov/fire, but produced elsewhere: the wildfire potential outlook product is generated by the National Interagency Fire Center's Predictive Services while the drought monitor comes from the University of Nebraska–Lincoln.

```
SDZ039-050015-
Kingsbury-
Including the cities of De Smet, Arlington, and Lake Preston
511 AM CST Fri Mar 4 2022

.TODAY...
Sky/weather.........Mostly cloudy.
Max temperature.....43-48.
Min humidity........55-60 percent.
20-foot winds.......Southeast winds 14 to 19 mph with gusts to
                    around 28 mph.
Haines Index........3 or very low.
Hours of Sun........2 hours.
Precipitation.......None.
Mixing Height.......Around 2300 ft AGL (Ave 12-6 pm).
Transport Winds.....Southeast around 18 mph (Ave 12-6 pm).
Smoke Dispersal.....Around 43000 or good (Ave 12-6 pm).
Max GFDI Index......Moderate.
```

Figure 24: An example of a Routine Fire Weather Forecast for Kingsbury County, South Dakota. Note that because much of South Dakota wildland fire occurs in rangeland, many NWS offices in the state calculate a Grassland Fire Danger Index (GFDI).

Spot weather forecasts A spot weather forecast is a ”special forecast issued to fit the time, topography, and weather of a specific incident.”[14] The forecast includes information similar to the routine fire weather forecast (Fig. 24), but a specific NWS forecaster concentrates predictive weather models on a specific location provided by a request filed by a qualified user at weather.gov/spot. Requests include the geospatial location and date along with some site-specific information, such elevation above sea level, fuel type, slope and aspect, and size of burn. The results include a description of general weather patterns expected for the day, as well as specific predicted values for fire-related variables at critical points in the day (Fig. 25).

[14] NWCG (Spot Weather Forecast 2019)

```
FNUS75 KBYZ 180932
FWSBYZ

Spot Forecast for Ft Keogh Nicks Plots...USDA ARS
National Weather Service Billings MT
332 AM MDT Fri Jun 18 2021

Forecast is based on ignition time of 0900 MDT on June 18.
If conditions become unrepresentative...contact the National Weather
Service.

Please contact our office if you have questions
or concerns with this forecast.

...FIRE WEATHER WATCH IN EFFECT FROM SATURDAY AFTERNOON THROUGH
SATURDAY EVENING...

.DISCUSSION...
Mostly sunny skies are expected at the burn site today. Look for
northwest winds to prevail this morning and gradually turn
more to the north into the afternoon. RH will drop in to the teens
by 330 pm. Winds will be northeast overnight, gradually turning to
the southeast late.

Please note the Fire Weather Watch for Saturday. Saturday will
see highs around 90 and RH dropping into the teens with a frontal
passage in the afternoon producing wind gusts from the northwest up
to 30 mph which will continue through Saturday evening. BT

.TODAY...

Sky/weather.........Sunny.
CWR.................0 percent.
Max temperature.....81-85.
Min humidity........15-19 percent.
Wind (20 ft)........
 Slope/valley.......Northwest turning gradually to the north at 7 to 12 mph.
 Ridgetop...........Northwest around 11-15 mph.
Mixing height.......7800 ft AGL.
Transport winds.....Northwest around 8 mph.
Haines index........4.
```

Figure 25: An example of a Spot Weather Forecast for a summer prescribed burn generated by the NWS regional office in Billings, MT. Note that because the Billings office covers mountainous areas, forecasters account for topographical effects on wind by breaking wind predictions down for slope/valley and ridgetop positions. Note also that the forecast was generated at 03:33, and the forecaster calls attention to a fire weather watch in effect for the next day, with a description of the anticipated weather changes. As the ignition time approached and observed winds were higher than predicted, the NWS staff member who generated the spot forecast contacted the burn boss via the cell phone number provided in the request. After a discussion with local fire management officials about existing fire danger conditions and the expected trend towards extreme weather, this prescribed fire operation was postponed. It is impossible to determine whether this burn would have been a success or a failure had the burn boss proceeded. But by working with the NWS and county officials, the burn boss was certainly aware of the current and forecast conditions when considering the Go/No-go decision.

The official NWS spot forecast process is not the only way to obtain location-specific information. Regional offices that provide fire services also provide fire-specific products in the hourly weather forecast format (Fig. 26). Even managers who obtain official spot weather forecasts can complement that information, which focuses on weather at critical times of the day, with hourly predictions of the same fire-specific variables.

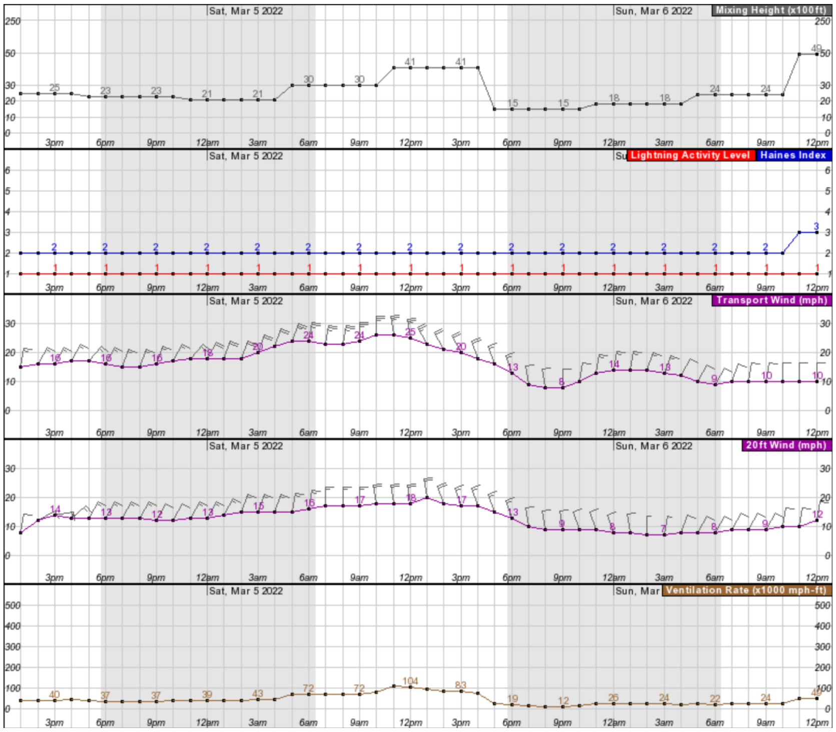


Figure 26: An example of predicted hourly trends in several variables specific to wildland fire for two days in Chadron, Nebraska. Not all regional NWS offices in the country provide fire products, and the specific fire products provided varies among offices. The hourly weather format can be "hacked" to provide location-specific information by hand-editing the longitude and latitude fields of the URL for an hourly weather product found for a local town.

Tactical weather

Fire managers and researchers alike rely on real-time fire weather observations taken during the operational period.

Spinning weather

The tried-and-true methods of taking fire weather measurements are included in the *belt weather kit*, a standard package of field-ready instruments for measuring and recording air temperature, dew point & relative humidity, and wind speed & direction (Fig. 27). Using the belt weather kit is sometimes called *spinning weather* in reference to the sling psychrometer that is used for measuring dew point and relative humidity.

While the belt weather kit has been technologically superceded by portable handheld weather meters (Fig. 20), it remains important to understand the operation of the belt weather kit because both methods have their own sources of error and opportunities for malfunction or damage. And one never knows when the batteries on the electronic meter will fail. Finally, there is debate on which method is "best." When both options are available, fire weather observers are advised to use both the belt weather kit and an electronic meter at least at the beginning of the observation

Figure 27: Standard items in the belt weather kit for making fire weather observations in the field.

period and make a note of which method was used to collect each value.

Common tactical weather variables include:

- **Air temperature—**Often called *dry bulb temperature* because ambient air temperature can be read from the unaltered thermometer on the sling psychrometer. Air temperature is not a direct factor in fire behavior, but it helps managers understand trends in fuel moisture and crew well-being.
- **Relative humidity (RH)—**As a measure of the capacity for the air to absorb moisture, RH is a critical variable in how quickly fuel dehydrates, and thus fire intensity. Exposure to low RH desiccates fuels ahead of flame fronts and makes crew members more susceptible to dehydration. RH is calculated by comparing measurements from a sling psychrometer via a psychrometic table or slide rule (Fig. 28, *top*).
- **Wind—**Wind is often reported as a *vector* consisting of velocity and speed. As ventilation increases oxygen available to the combustion reaction zone, wind increases fire intensity and drives rate of spread. Wind speed is often reported as *sustained*—an average value or range of wind speed over a minute or two—and *gusts*—peak velocities that are substantially above the average or beyond the range of sustained winds. Handheld anemometers measure wind speed (Fig. 28, *bottom*). A compass aids in determining wind direction.

TL: Joe Haupt, CC BY-SA 2.0; TR: Neal Herbert, US DOI, public domain; BL: USAF, public domain; BR: USDA, CC BY 2.0

Figure 28: Methods of taking fire weather observations. **Top:** Sling psychrometers allow one to calculate instantaneous relative humidity by determining how quickly evaporation produces a cooling effect. Left: An antique sling psychrometer with a wooden handle for spinning two thermometers, one open to the ambient air (“dry bulb”) and one with a “wet bulb” wrapped in a soaked wick that cools while the water evaporates while the device is spun rapidly. A table or slide rule in the belt weather kit converts the difference between the final temperatures into dew point (DP) and relative humidity (RH). Right: Belt weather kits include a small sling psychrometer with a chain connecting the thermometers to a chain, and smartphone apps quickly calculate DP and RH. **Bottom:** Two methods for determining wind speed. Left: Analog wind meter, standard in the belt weather kit. Right: A Kestrel brand all-in-one portable weather kit. Such units take digital measurements of many parameters of use to wildland fire professionals.

Automated weather stations

Additionally, hourly weather observations made by the NWS and even Remote Access Weather Stations managed by state and federal agencies are all available together online at MesoWest mesowest.utah.edu.

Historical weather data

Point-level data Many of the same resources for getting real-time observations from remote weather stations provide a means to access historical records. Substantial requests for historical MesoWest data can be managed via their “official” API service https://developers.synopticdata.com/mesonet/, the *mesowest* R package, and the *MesoPy* python package.

Local data One of the best resources for historical weather in the US is gridMET (Abatzoglou, 2013), “a dataset of daily high-spatial resolution (4-km, 1/24th degree) surface meteorological data covering the contiguous US from 1979-yesterday. (climatologylab.org/gridmet.html)” Values represent data extremes (maximum temperature, minimum RH) interpolated for grid cells across the US via models using data from several weather observation networks. The gridMET dataset includes several fire weather variables (e.g., dry bulb temperature, relative humidity, dew point, and wind vectors) as well as indicators of potential fire behavior including products from the National Fire Danger Rating System (100-hr fuel moisture, Burning Index & Energy Release Component). In addition to the steps listed on their website, gridMET data can be accessed via the `climateR` R package and Google Earth Engine.

Figure 29: Topography, weather, and the fuelbed are the three major drivers of wildland fire behaviour.

Wildland fire behavior

Broadly speaking, there are two main reasons a wildfire professional might be interested in fire behavior:

Firstly, a prescribed fire burn boss or wildfire incident commander is likely to want to know how intense and fast-moving the day's fire will likely be, so they can safely plan where and how crews will operate. Most of this information will come from predictions based on models that use fuel and weather data, but leadership often expects updates as the day goes on to see if anything unexpected is occurring.

Secondly, researchers can use data on fire intensity to inform why organisms responded the way they did to the burn. Sometimes well-done fuel and weather sampling allows for this information to be modeled, as well, but direct measurements are the most accurate.[15]

[15] In the best of all possible worlds, good measurements of fuels, weather, and fire behavior support validation of model results, increasing capacity to anticipate fire behavior so as to maximize the safety and effectiveness of future operations.

Broad considerations

Observation and measurement

While there are many ways to measure and quantify fire behavior, most observations relate to two broad categories of fire behavior:

- **Rate of spread** describes how fast flame fronts move through fuel beds—and is theoretically easy to observe and measure as the time taken for flames to move between two points of known distance.
- **Intensity** describes how much energy is released by the fire. Intensity is best measured over a specific period of time and expressed as a rate, often on a per-area basis. While energy flux is tough to observe, *flame length* is a visual measure of intensity.[16]

[16] Note the emphasis on *flame length* instead of *flame height*. It is important to note that because wind tends to push flames down, the flame parameter best associated with fireline intensity is true flame length—the distance from the base of the flame in the fuelbed, to its tip—and not just flame height, which does not increase in proportion to wind speed precisely because the wind lays the flame down.

The mechanisms behind these two properties are related and in fact, rate of spread is an input for many calculations of fireline intensity. Rothermel (1983) derives the value for fireline intensity from two measurable variables: the amount of energy available for release within the unburned fuel (heat per unit area), and how fast the flame front moves through the fuel (rate of spread). And Byram (1959) provides an equation to calculate intensity I:

$$I = H \cdot w \cdot r \quad (5)$$

where

H = heat yield, obtainable by putting fuel clipped before the fire in a bomb calorimeter, or using default values for different types of plant material;
w = mass of fuel consumed, determined by subtracting post-burn fuel from pre-burn fuel load measurements; and
r = rate of spread

Factors that affect fire behavior

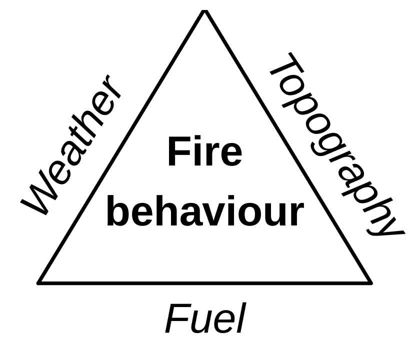


Figure 30: Topography, weather, and the fuelbed are the three major drivers of wildland fire behaviour.

Weather, fuel, and topography all interact to determine the outcomes of fire spread (Holsinger et al., 2016, Fig. 30). Sampling fuels is discussed in Chapter I, while weather measurement is discussed in Chapter I. Here we briefly review the role of topography.

Fire moves more quickly upslope—and more slowly downslope—relative to flat ground, just as head fires move faster with the wind and backing fires more slowly against the wind. Because hot air rises, fuels on a slope above an actively-burning fire get a head start in pre-heating, whereas fuels below the [17]

The implications for topography on prescribed fire management are perhaps more apparent than prescribed fire science. Managers must always take slope effects into account—especially when firing or staging equipment—and be able to foresee whether a strip laid at the bottom of a hill will rush upward faster than a torch operator might expect, or whether flames and smoke at the top of a hill will make control more difficult.

But all observers need to take note of the slope when making fire behavior observations. Consider how a steep slope might affect conclusions about a correlation made between fire behavior and fuel properties; flame length would be longer than those same fuel conditions on level ground. Thus, to the extent possible, slope effects should be controlled for by taking fire behavior observations on level ground.[18]

[17] In fact, wind and slope are treated as *additive factors* in many fire spread models, which means that their effects can generally be swapped for one another—what wind does to a fire on flat ground, slope will do about the same—or they can cancel each other out—a downslope wind can move a fire downhill faster than it would move in the absence of wind.

[18] Although of course in some landscapes, level areas are the exception rather than the rule. In cases where it is inappropriate to *control* for slope effects, they can be *accounted* for by measuring the slope with an inclinometer or taking a precise GPS reading for the sample area and finding its slope later in a Digital Elevation Map in a GIS.

The role of temperature

First off, **does anything stand out as *not* being discussed much in the list above?** Notice that no mention is made of temperature or heat, despite the obvious fact that fire is hot. It turns out that *temperature*—defined as a measure of the average kinetic energy of the particles in a sample of matter—is actually a poor response variable to describe the behavior of fire in the wildland environment. Temperature has two major limitations:

- **Temperature has no spatial or temporal component.** Consider an electric radiating space heater, plugged in and cranking out the same amount of heat energy each second it is turned on. How "hot" the heater feels depends on how close one is to it. Even if the heater were on wheels and moved across the room, ensuring every point in the room gets to be the same distance from the heating element at some point, the speed at which this process occurs is determined by an external force—maybe how hard someone is pushing the heater—that is not quantified by measuring the temperature. Similarly, the speed at which a flame front moves through a grassland depends on external factors—energy and moisture content of fuels, slope and wind—that are not reflected in the measurement of temperature at a given point at a given time.
- **Temperature is subject to the material measured.** How "particles in a sample of matter" move depends greatly on the properties of the material, irrespective of heat energy input. Even very close to the space heater, the kinetic energy of particles of asbestos insulation will respond much differently than a block of iron. In the wildland fire environment, the value of a temperature data point has almost as much to do with the properties of the device used to make the measurement as with the properties of the fire.

Despite all of this, various measurements of temperature are probably the most frequently-reported data in the fire ecology literature. Temperature is intuitive and relatively easy to measure. Below, the discussion on measuring fire behavior focuses on using conventional methods to measure temperature in the wildland fire environment in new ways that increase the information value of the data they produce.

Measurement

Almost certainly, the most common device for measuring temperature in the wildland fire environment is the thermocouple.[19] The primary advantage of thermocouples over most other temperature sensors is that they can operate under exposure to extremely high temperatures, like wildland fire, and they aren't terribly expensive. But the thermocouple itself is a specific component; a thermocouple alone isn't enough to measure anything. In wildland fire science, the phrase "we used thermocouples" almost always refers to a system of thermocouples and the electronics necessary to process signals from the probes and record the data. Here we focus on each in turn.

[19] Another common approach is the use of temperature-sensitive paints that discolor at various temperatures. One can place heat-resistant tiles with a series of these paints before the fire, and by ascertaining which paints were distorted and which were not, one can narrow the range of temperature exposures down to the ranges tolerated by those paints.

Introducing the thermocouple

The Seebeck effect The physics behind the thermocouple are pretty simple: When a wire is heated at one end, a temperature gradient forms along the wire and electrical signals are generated that can be detected at the other end. This is called the *Seebeck effect*. The signals vary according to the material in the wire. Therefore, when two wires made of different metals are exposed to the same heat source, there is a detectable difference in their electrical responses. This difference scales predictably with the common temperature of the heated ends. Thus, a thermocouple is simply two wires of different metals, joined at one end to detect temperature (the *hot junction*), and ready to be connected to a device capable of detecting the signals at the other (the *cold junction*). But as stated above, the detecting device is a separate part of the system. And even the wires are just conduits for the signal between the hot and cold junctions—apart from the heated tip, thermocouple wires are wrapped in thermal insulation to isolate all but the tip from heat exposure. Let's narrow our discussion down to the hot junction, the business end of the thermocouple.

Considerations at the hot junction

The hot junction can take various forms, with differences in their performance in the wildland fire environment (Fig. 31). The differences arise from the varied applications of thermocouples—from residential thermostats to monitoring industrial furnaces and boilers. In some cases, the hot junction consists of a *probe*, a rigid sheath that encloses the wire connection. In other cases, the junction is simply a bare *bead* in which a small weld, made to ensure the wires are connected, remains exposed just beyond the insulation.

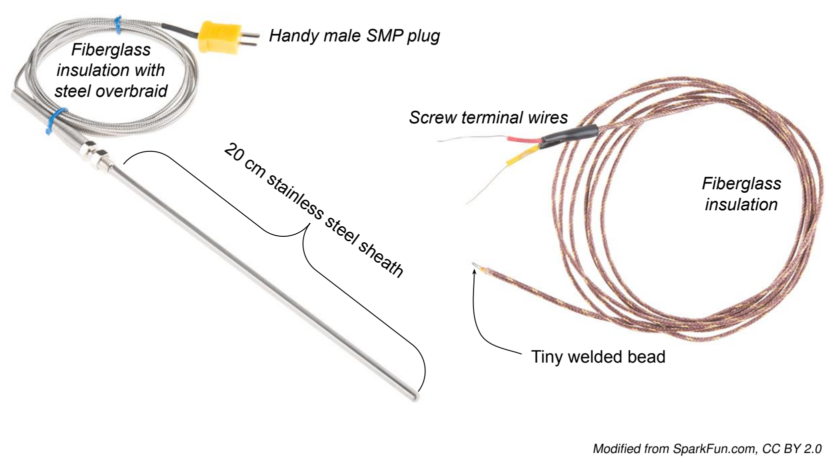


Figure 31: Two types of hot junctions, with different thermocouple features identified. On the left, the hot junction of a K type thermocouple is enclosed in a 20 cm × 5 mm stainless steel sheath. On the right, the hot junction consists of a simple exposed welded bead. Note that all combinations of hot junctions, cold junctions, and everything in between are available.

Surprisingly, it does not appear that the relative merits of probes vs.

beads for wildland fire science have been reported on, although the probe seems to introduce some confusion into what is actually being measured.[20] The additional layer between the heat source and the hot junction introduced by the sheath might also complicate things. We suggest using exposed bead thermocouples.

[20] For example, Coates et al. (2018) observed different temperatures from 28 cm probes laying horizontally along the soil surface to those standing vertically, which they attributed to the different "orientation" of the probes. But since the hot junction is at the end of probe, they've really just compared two points at different heights above the ground. That temperature in the wildland fire environment changes with distance above the soil surface has been known for decades (e.g., Trollope, 1984).

Realities of thermocouple measurements To place a thermocouple probe in the wildland fire environment is to subject it to all of the physical processes to which everything else in that environment is exposed. Thus, the same heat transfer dynamics apply to the thermocouple as to a fuel particle—simultaneous heating and cooling via convection, radiation, and conduction.[21] This heat transfer is a combination of the properties of the media, the sensor, and the temperature gradient between them. A thermocouple placed 15 cm above the soil surface is responding to the kinetic energy of the air molecules around it. Likewise, a thermocouple placed in the soil is responding to the kinetic energy of the air, mineral, water, and organic matter molecules around it. In each case, the sensor's response to changes in the media's kinetic energy has a lag time that reflects the mineral content and thickness of its materials, e.g., the wires themselves and welded bead or probe sheath.

[21] Let's assume the proper materials have been selected such that ignition and a phase change, i.e. melting, won't be issues for our sensor.

Thus, two realities that affect all thermocouple measurements include:[22]

[22] For a third reality, see Fig. 38.

1. **Thermocouples always underestimate temperature.** Like all particles in the wildland fire environment, the sensors are subject to cooling processes at the same time as they are subject to heating.
2. **Thermocouples are always at least a little bit behind in responding to changes.** This lag time is often referred to as the thermocouple's *response time*.

Wildland fire scientists have generally come to terms with each of these realities. Regarding Reality 1, one assumes the recorded temperature is a relative value that scales consistently with the actual temperature; as such, for a researcher comparing measurements among different experimental groups, comparisons between observed temperatures are just as meaningful as if the actual temperatures are being compared.[23] (Think of two parallel lines on a graph, with the same slope but different Y intercepts.) Similarly, regarding Reality 2, fire scientists just try to use thin, responsive thermocouples and be consistent among observations so relative values can be used in place of actual heating rates and peak temperatures.

[23] When the true value is required, as can be the case in industry, two thermocouples of different diameters can be placed side-by-side and the actual temperature determined by extrapolating from the relative difference between the observed values (Walker and Stocks, 1968).

While such work-arounds are often fine for comparisons within studies that use the same type of thermocouple, one encounters substantial barriers when trying to compare across studies that use different thermocouple set-ups (e.g., probe vs. bead, K-type vs. another type, different wire diameters, etc). Imagine if other systems of measurement depended so much on the properties of the measurement device. Consider the frustration of using your ruler to determine you need a board 30 inches long and having the lumber yard cut one down for you using their ruler, only to find that it doesn't fit. It is already difficult enough to keep the units of length straight—inches vs. centimeters, yards vs. meters—it would be ridiculous if the same value resulted in different lengths because the measurements were made with two rulers of different thicknesses. But that is essentially the issue when comparing data collected with different thermocouple types.

Signal processing and data logging

Four basic but important steps occur on the other end of the thermocouple wires, at the cold junction:

- **Signal detection** Electrical signals in the wires are self-generated, so there is no power input required, but the voltage is low.
- **Reference temperature measurement** Converting the voltage differences in the wire to temperature requires the temperature of the cold junctions to be known.
- **Temperature conversion** An equation is used to convert the voltage differences to temperature.
- **Data storage** Most wildland fire science applications require thermocouple data—typically just a timestamp and temperature for each observation—to be stored for retrieval.

Many instruments are designed to operate thermocouples and most take care of all of the above steps internally. But there are several discrete functions being performed, and variability in each dictate the nature of the systems available to the user:[24]

- Voltages are very low and quality electronics often amplify incoming signals.
- Devices typically include a basic semiconductor thermometer to ascertain reference temperatures.
- Conversion equations are specific to the metal in the wires, so devices are either limited to the type of thermocouple they are compatible with or require the user to identify the thermocouple via software interface.
- Data storage requires either a removable card slot or onboard media and some means to interface with it.
- Integrated systems require a computer or microprocessor to coordinate all of these tasks, which in turn requires a power source (even though the signals from the Seebeck effect are self-generated!).

Here we review three broad categories of electronics available to the wildland fire scientist:[25]

[24] Understanding this variability allows the user to select or even assemble systems that focus on getting the right type of performance for a given budget.

[25] Note that reference to trade names or specific commercial products are not product endorsements, but are used only as examples.

Basic thermocouple dataloggers Among the lowest-cost options for thermocouple electronics are self-contained devices into which one plugs a thermocouple and downloads the data to a computer afterwards. Popular commercial solutions include HOBO products from the Onset Computer Corporation (onsetcomp.com; Bourne, MA), which include single-channel (one thermocouple per datalogger) and four-channel (four thermocouples per datalogger) options that have been updated to include real-time visual displays of temperature and memory and battery capacity (earlier versions where just little white buttons with an on switch and a blinking light). These devices are programmed, and their data accessed, via proprietary but zero-cost software.

- *Advantages:* Relatively low-cost and easy to operate; small and easy to protect from heat exposure; most compatible with a wide range of thermocouple types.
- *Disadvantages:* Still not cheap (US$150 or 305, 1 or 4 channels; logger only); use limited to logging temperature from thermocouples; restricted proprietary software for both operation and interface.

Multi-purpose dataloggers with thermocouple capacity Of course, the scientific and industrial worlds—and thus many lab cabinets—are full of datalogger options for applications that go way beyond wildland fire. Most users might not appreciate how many functions are included in the catch-all term "datalogger," which includes an onboard processor and several input/output options. Almost any microprocessor-driven datalogger system can be made compatible with thermocouples—thermocouple-unique tasks are the signal amplification and a program with the voltage-temperature conversion equation. Many such systems are commercially available and ready for thermocouples out of the box. For example, almost every CR model from Campbell Scientific (campbellsci.com; Logan, UT) will handle many types of thermocouples (Fig. 32).

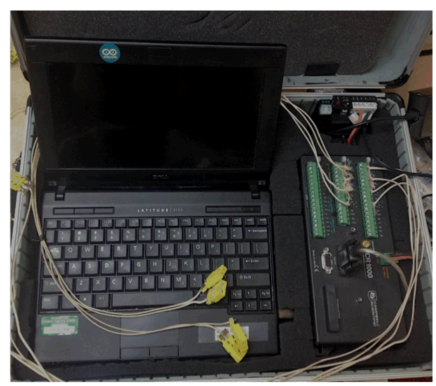


Figure 32: A Campbell Scientific CR1000 datalogger set up to read 8 thermocouple leads. While onboard data storage is available for CR dataloggers, this system is set up to display realtime data and write to the laptop via proprietary CS software.

- *Advantages:* Versatile systems for applications beyond fire science that include options for remote connectivity; often capable of handling many channels efficiently; usually many options for interface and data storage; often have more flexible programming options.
- *Disadvantages:* More—sometimes much more—expensive; often larger and more difficult to protect from heat exposure; often limited to proprietary programming languages.

Open-source DIY electronics systems Just as corporations like Onset and Campbell Scientific started with someone tinkering with electronics to accomplish a task, individual users can assemble their own custom systems based on low-cost parts running open-source code. The rise of the Maker's Movement and global connectivity via the Internet has produced many products and a community of developers relevant to wildland fire science. In particular, the low-cost, open-source Arduino platform (arduino.cc) is very user-friendly and accessible even to n00bs. In its most basic form, the Arduino system offers cheap microprocessors programmable via a free variant of the classic `C++` language (Fig. 33, *top*). As long as one isn't afraid to solder and code, there is hardly a limit on what the wildland fire scientist can build to custom specifications for a fraction of the cost of commercial systems.

The Arduino-adjacent Feather family of microcontroller products and peripherals from Adafruit Industries (adafruit.com; Brooklyn, NY) is particularly well-suited for wildland fire science because it is designed for mobility—small components that run on relatively small batteries (Fig. 33, *bottom*). The FeatherFlame system (McGranahan, 2021, diyfirescience.info) combines Adafruit products to amplify and process signals from up to 6 K-type thermocouples and store the data on a removable microSD card.

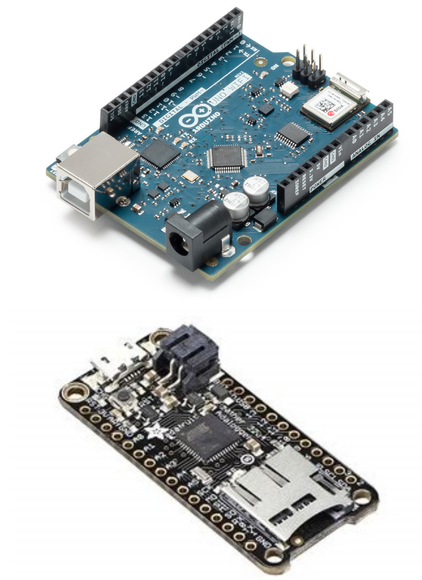


Figure 33: Two examples of open-source, DIY microprocessor systems. Top: A basic Arduino Uno. Bottom: A Feather M0 Adalogger from Adafruit Industries, with USB connections, JST battery terminal, and onboard μSD card slot. Both systems are programmed with a variant of `C++`; light versions of Python are available as well.

- *Advantages:* Maximum versatility in both hardware and software; often cheapest options available; small and easy to protect from heat exposure (and cheaper to replace).
- *Disadvantages:* Assembly required, and no customer support—following published projects requires basic soldering and coding skills, while substantial project customization and design require moderate skills in circuitry and coding; materials are developed for hobbyists and STEM classrooms and might not have the longest life in rugged conditions.

Thermocouple deployment

Where does one put thermocouples out in the landscape? The answer starts with the purposes of the data collection in the first place—who wants to know what about fire behavior? If some specific fire effects are going to be measured, it makes sense to place sensors near where those measurements will be taken, or where the heat input will occur: If one is studying grass bud mortality, one might put a thermocouple in the crown of the grass plant; if one is concerned about soil microbe mortality, thermocouples can be placed at or even below the soil surface. If general fire behavior measurements are desired, it is easy to use thermocouples to measure rate of spread by placing clusters in representative areas of the fuelbed.

The primary considerations are vertical and horizontal: At what height to put thermocouples, and how far apart? Unfortunately there are no standard protocols to guide either. Among published studies, the most common placement is right on the soil surface, followed by placements above the ground and somewhere above the ground (Fig. 34). There is

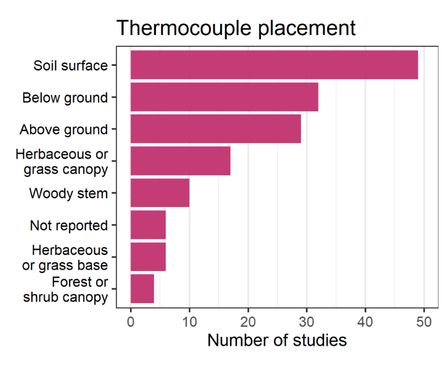


Figure 34: Frequencies of various locations thermocouples were deployed in the wildland fire environment, based on a review of 105 studies.

no standard for the height of aboveground placement, even though studies that report values for multiple intervals above the ground show wide variability. In terms of best capturing the “hottest” part of the vertical flame profile, something like 50% of the overall height of herbaceous fuelbeds is probably most appropriate. Heights like 15 or 20 cm are common in grassland fuels.

In terms of horizontal arrangement, many thermocouple sampling designs are limited by the number of thermocouples available, and just a handful are deployed per burn with little attention to their spacing. But if thermocouples are thoughtfully arranged, it is possible to analyze data in a manner that provides much more information on fire behavior than temperatures alone. Specifically, when thermocouples are spaced at known distances, the timestamps can be determine when flame fronts arrived at each sensor, and thus how quickly the flame front moved between sensors—*rate of spread*.

There are two options for measuring rate of spread with time-temperature data from thermocouples (Finney et al., 2021):

One-dimensional spread measures the linear rate of spread along a transect and is best measured under direct visual observation (Cruz et al., 2020). This is a common technique applied to specific parts of the fire, such as comparing head fire and back fire spread.[26] The technique requires knowing wind direction and the type of fire moving along the transect, and is most accurate when the angle of spread aligns with the angle of the transect.

[26] Fire behavior analysts often focus on head fires, specifically, because the *forward rate of spread* is a common output for fire behavior models and is most pertinent to tactical decisionmaking.

Two-dimensional spread requires neither knowing the wind direction nor alignment between sensor points and flame front.[27] Instead, trigonometry is used to determine spread through a non-linear array of sensors. When thermocouples are arranged in equilateral triangles such that individual sensors share common timestamps—as when connected to a multi-channel datalogger—one can calculate rate of spread through the array (Simard et al., 1984; Kidnie and Wotton, 2015). One can also nest several smaller equilateral triangles, or *microplots*, in a spatially-hierarchical design that facilitates geospatial analysis of fuel and fire behavior patterns (Fig. 35).

[27] While this technique does not require direct observation, determining what type of fire spreads through the array is best determined visually.

In plot-based studies ignited by a rapid ring ignition pattern, it is possible to calculate rate of spread based on the time taken for fire to spread through the entire plot (e.g., Trollope and Potgieter, 1985). Such a method does not require any equipment more fancy than a stopwatch.

Processing thermocouple data

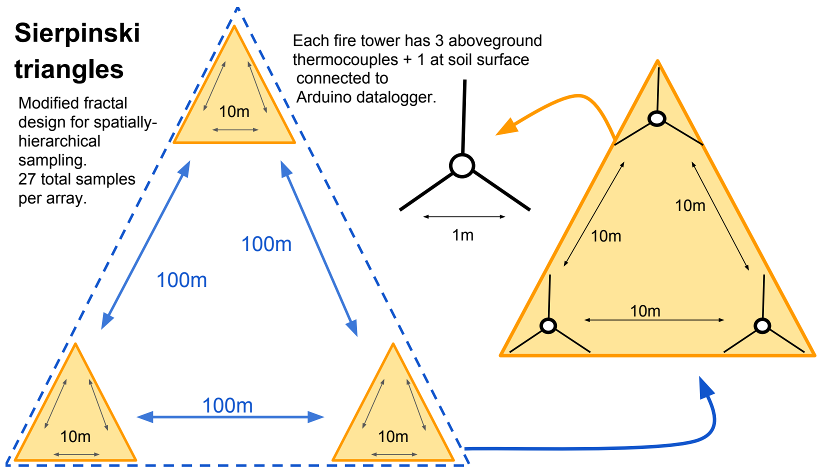


Figure 35: An example of an spatially-hierarchical arrangement of thermocouple sensors (McGranahan, 2021). Each 1 m equilateral triangle represents a *microplot* for which rate of spread can be determined; the fractal design of the Sierpinksi Triangle is intended to facilitate spatial analysis of patterns in fuel and fire behavior across multiple scales.

From logger to workspace

Raw thermocouple data are often a mess—mere seconds of meaningful data as the flame front passes buried in hours of ambient temperature records. But it is difficult to automate the extraction process because noise is often introduced into the data file (Fig. 36, *top*). This blog post describes how to use the **R** statistical environment to identify "rough windows" within the time-temperature curves for extraction (Fig. 36, *bottom*). Within these windows, minimum values, maximum values, and the data in between can be more reliably attributed to heating processes at the hot junction than noise at the cold junction.

Analysis

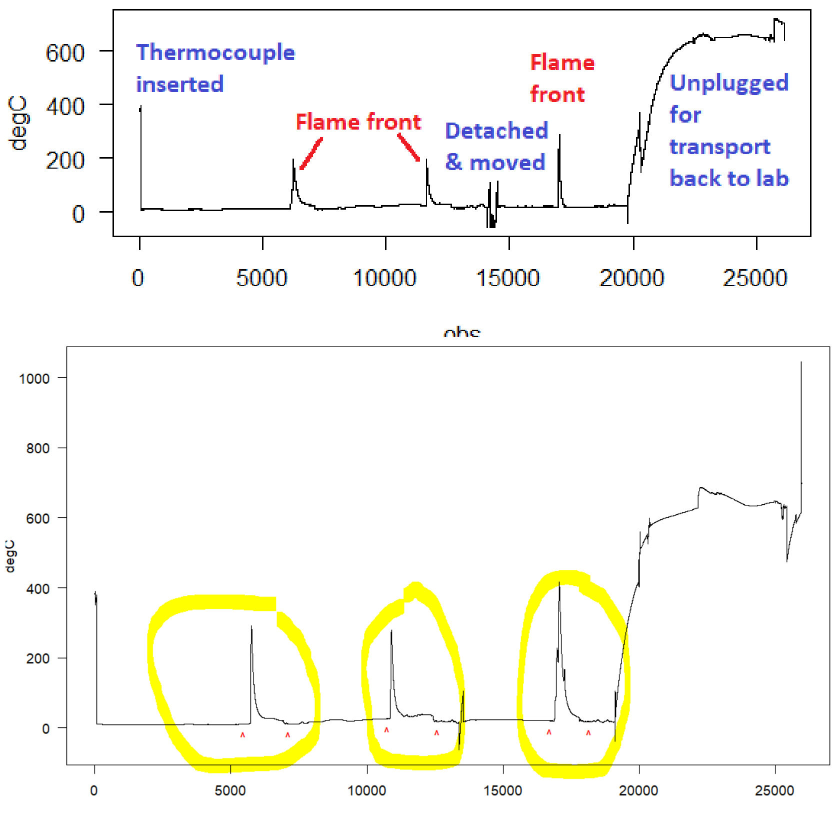


Figure 36: Top: An example of three meaningful heating events buried in hours of noisy data from a HOBO datalogger. Note that data associated with the heating events are never the highest or lowest values in the series. Bottom: Rough windows around heating events identified with an R script.

Because thermocouples measure temperature and fire is hot, it is not surprising that the most commonly-reported response variable from thermocouple data is maximum temperature (Fig. 37). But leveraging the *time* component of thermocouple data, rather than *temperature*, allows one to calculate less subjective measures of fire behavior. For example, rate of spread data can be combined with the other parameters in Eq. 5 to estimate intensity, and sidestep all of the issues around trying to use temperature as a fire response variable.

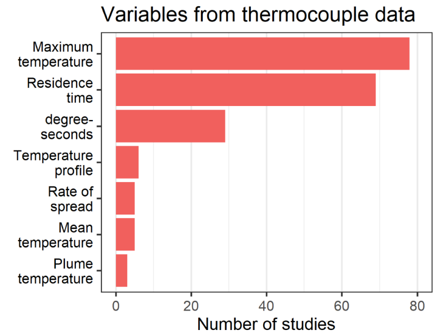


Figure 37: Frequencies of various response variables derived from thermocouple data, based on a review of 105 studies (McGranahan, 2020).

2-D rate of spread

With foresight in thermocouple deployment, it is possible to calculate rate of spread without knowing its direction. To facilitate measuring two-dimensional rate of spread, Simard et al. (1984) provided a series of equations that use trigonometry to calculate how fast a flame front moved through an array laid out as an equilateral triangle with sides D:

Let t_1, t_2, and t_3 represent arrival times[28] of flame fronts at vertices of equilateral triangle. If $t_1 \neq t_2$,

$$\theta = tan^{-1}\left(\frac{2t_3 - t_2 - t_1}{\sqrt{3}\cdot(t_2 - t_1)}\right) \tag{6}$$

and rate of spread r is

$$r = \frac{D \cdot cos\theta}{t_2 - t_1} \tag{7}$$

otherwise, if $t_1 = t_2$, $\theta = 90$ and rate of spread r is

$$r = D(\sqrt{3}/2)/(t_3 - t_1) \tag{8}$$

[28] There are a couple of approaches to determining arrival times, e.g., the timestamp for the first record of some level of heating (Kidnie and Wotton (2015) used 300°C), or peak temperature (McGranahan, 2021).

Heating curves

Fire ecologists often calculate a *heat dose* from thermocouple data that is intended to represent the amount of heat an organ, organism, or soil stratum is exposed to (Fig. 37). Time-temperature curves are ideal data for doing so, although unfortunately the data are often misapplied in calculations of heat dose (we aren't going to get into here, but see fig. 38 for a summary of the issue).

Once the beginning and end points of the heating curve are determined from the "rough windows" described above, one can extract several parameters useful for further analyses (Fig. 39). The heat dose is obtained by integrating the area under the heating curve (e.g., Engle et al., 1989). Beginning temperatures and rate of heating are useful parameters in soil heating models.

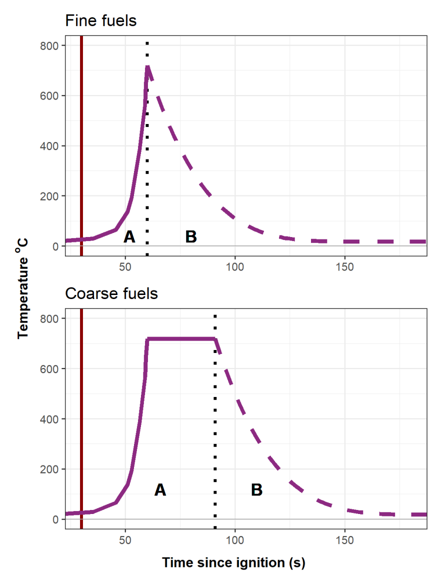


Figure 38: Examples of heating curves described by time-temperature data from fine and coarse fuels. While many ecologists use the entire curve to calculate heat dose, McGranahan (2020) describe how including the cooling portion of the curve (dashed segments) is a mistake because that reflects the cooling of the hot junction, not the physical presence of heat energy in the fire environment. Proper calculations of heat dose really ought to focus on the heating portion by truncating the time-temp data at the point it begins to reflect cooling (broken vertical black line).

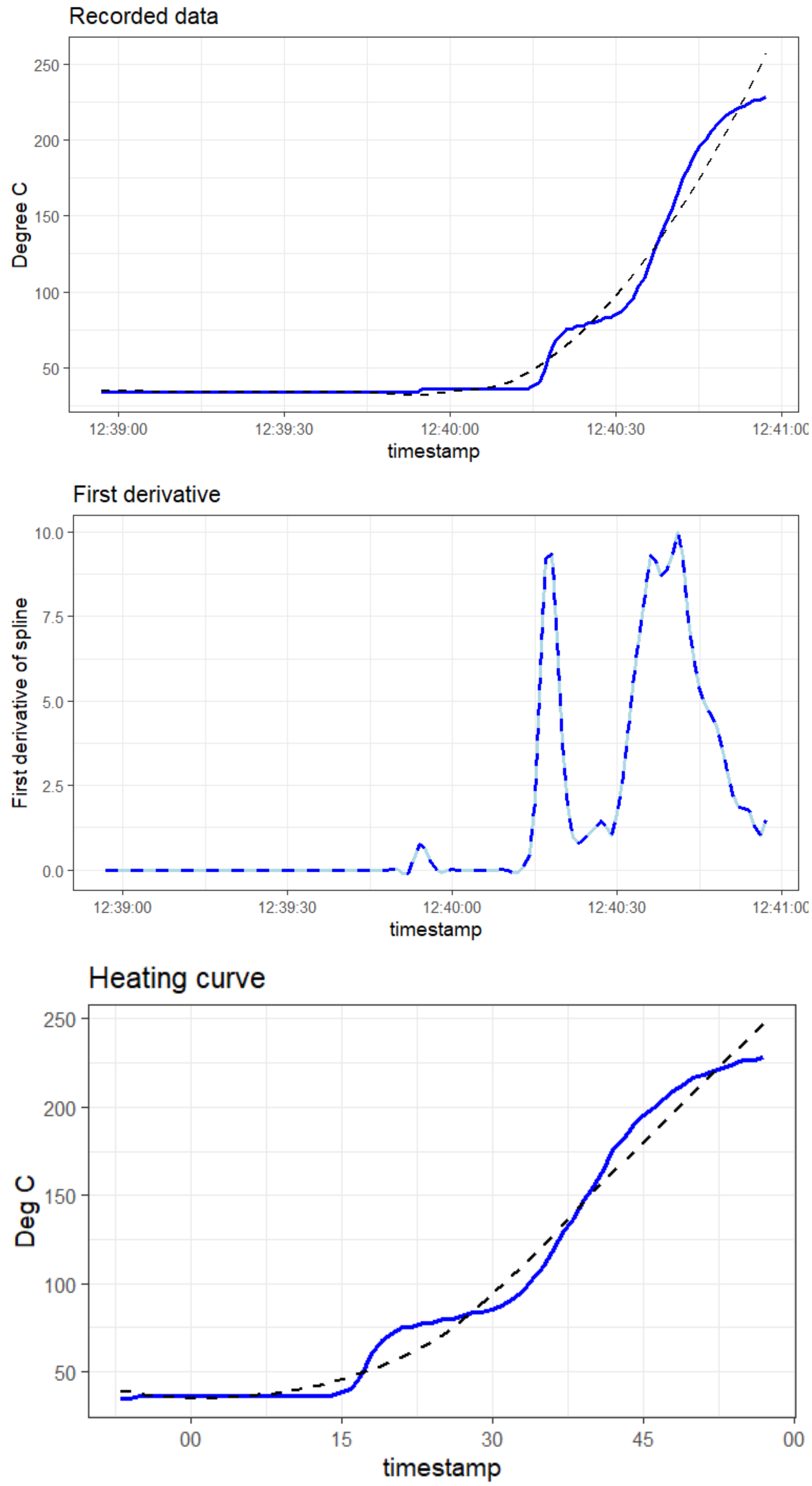


Figure 39: An example of steps to calculate parameters from heating curves. Top: A smoothed spline fit to the raw data from the rough window. Center: The first derivative of the smoothed spline identifies the point at which heating begins. Bottom: The curve is trimmed to begin at the first non-zero positive first derivative and a logistic curve fit to the raw data, under which the area is integrated between the endpoints of the heating curve. Table: Examples of heating parameters extracted from the final curve.

Start $°C$	Max $°C$	s to Max $°C$	Rate ($°C\ s^{-1}$)	Heat dose
34.4	228.4	1.1	181.9	6410.6

Part II

Prescribed fire operations

Fire management basics

As wind speed increases, so does the rate of spread in the same direction. It is essential to know the speed and intensity of a head fire when making tactical decisions. While lower-intensity head fires can be attacked directly—by specialised crews with hand tools and water hoses—fast-moving flame fronts with long flames must be attacked indirectly—by creating fire breaks and removing fuel between the barrier and the oncoming flame front.

Situational Awareness

LCES

Watch-out situations

Ten Standard Orders

Common denominators

Driving safety

ARRIVE ALIVE Always drive defensively. Reducing response vehicle speed can prevent rollovers. Red traffic signals and stop signs mean complete STOP. Insist that vehicle occupants use seat belts. Verify vehicle occupants are seated and belted. Evaluate road surface and weather conditions. Abide by federal and state motor vehicle laws. Lengthy response distances require frequent rest stops. Initiate standard vehicle backing operating procedures. Value occupant and public safety over time and speed. Enter dangerous curves and intersections cautiously.

Ignitions

Holding

Pumps and engines

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