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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 (**?**, Fig. 1).

Known knowns

Known unknowns

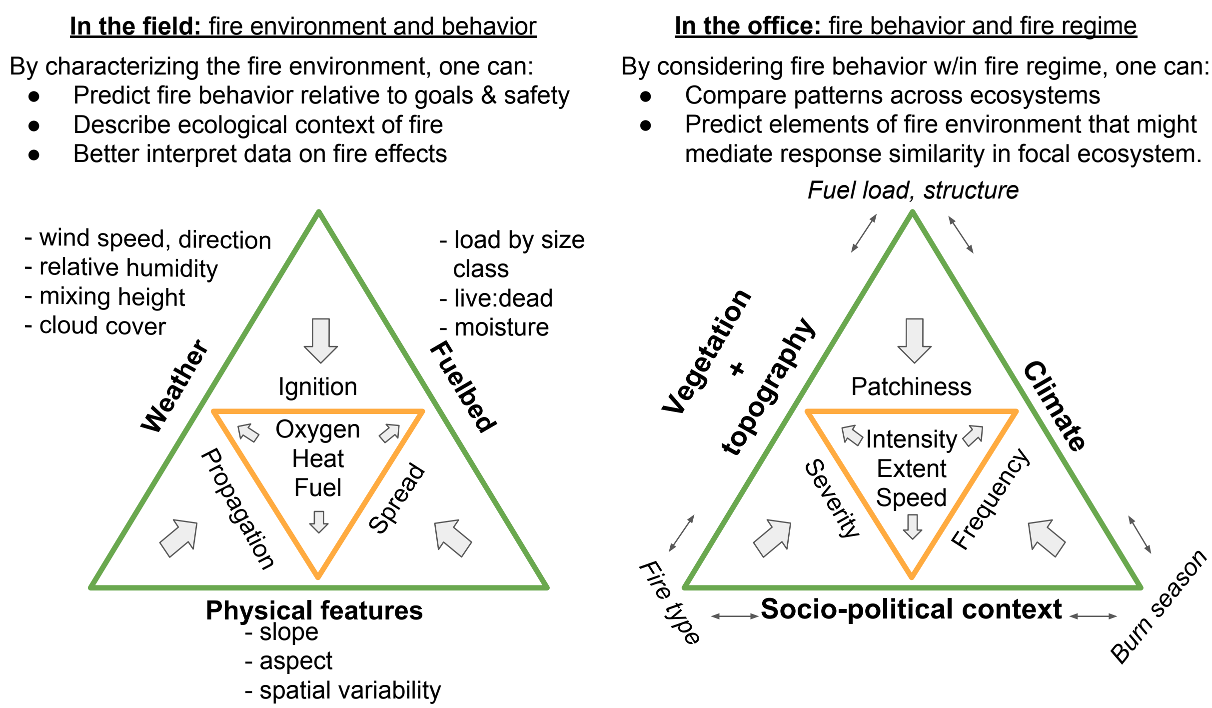

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Figure 1: Two arenas of wildland fire science—the field and the office. This figure helps fire professionals from each arena identify characteristics of the fire environment or fire regime that dominate their colleagues' perspective.

Unknown unknowns

Contents

Part I

Prescribed fire science

Fire science basics

In a given year, about 3% of Earth's terrestrial surface burns (**?**). All this fire affects air quality, alters vegetation, and drives processes such as climate and nutrient cycles (**?**). 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 ignition pattern used to set it can affect the intensity of the prescribed

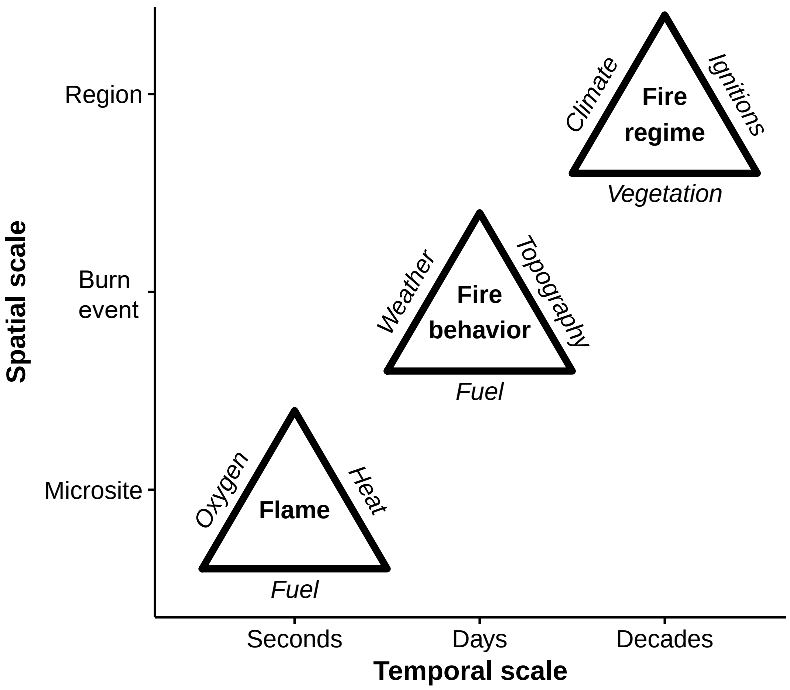


Figure 2: Three scales of wildland fire. Modified from **?**.

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:

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

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.
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*.

[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 (**??**). In fact, fire ecologists have used an overly-simple model of combustion for decades (**?**), 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: (**???**).

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):

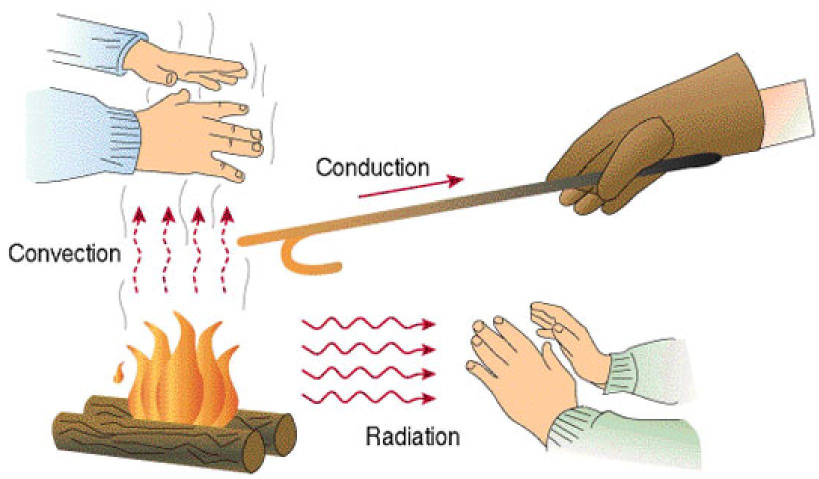


Figure 3: The three basic mechanisms of heat transfer. Convection is often the most important mechanism in wildland fire: buoyant hot air moves uphill or is pushed ahead of the fire by wind to preheat fuels prior to contact with flames.

- **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.
- **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.

[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 (**?**).

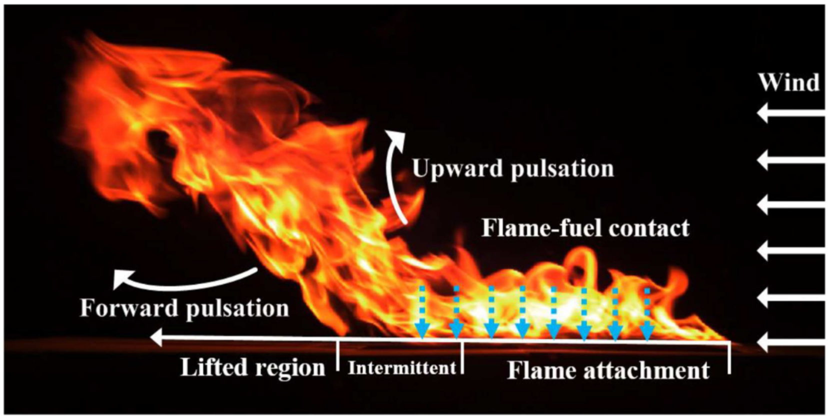


Figure 4: Flame pulsation

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] ???

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.

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 (**?**).[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]

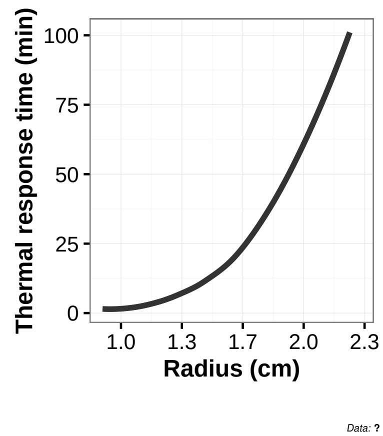


Figure 5: The non-linear relationship between fuel particle size and heat transfer rate. Small increases in fuel particle radius leads to disproportionately large increases in thermal response time—the speed at which the material changes temperature. Thus, a fuel particle with radius 1 cm has a response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

[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.

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 (**?**):[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.

[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.

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 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 (**?**).

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 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 un-

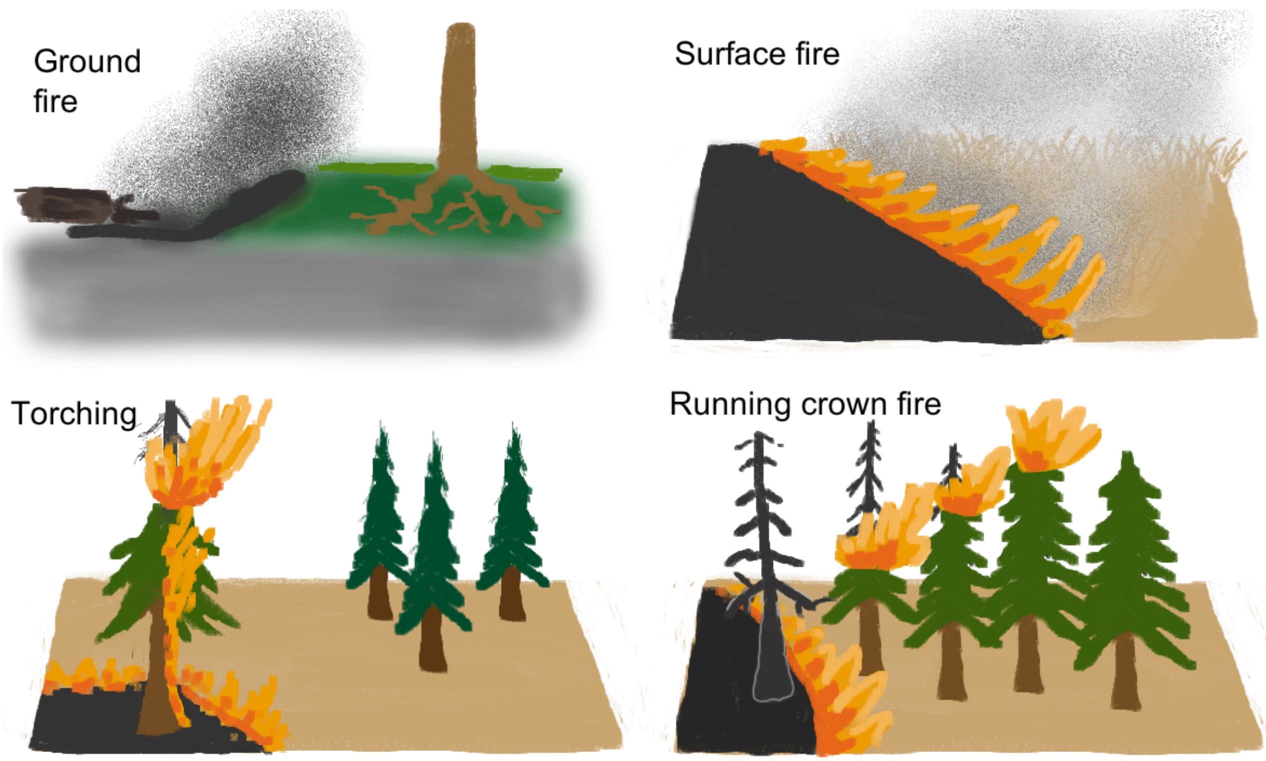


Figure 6: Four types of wildland fires. *Ground fires* burn underground through organic material like peat, while *surface fires* move aboveground through fuels on the soil surface. Fire can transition to tree canopies, as well. *Torching* occurs when the canopy of a single tree burns, while *running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

burned 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 (**?**). *Flame length* is directly related to the rate of energy release and thus serves as an observable proxy of intensity (**?**). Both fireline intensity and flame length increase with fuel load and decrease as fuel moisture increases (**?**).

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 preheating, which is the critical mechanism for flame propagation (**?**). Wind pushes heat ahead of the flame front and hot air rises upslope, both of which increase convective heat transfer (**?**). 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.

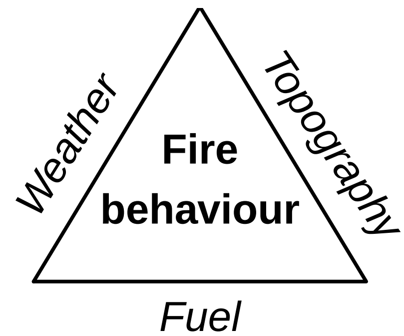


Figure 7: Topography, weather, and the fuelbed are the three major drivers of wildland fire behavior.

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

A brief description of the anatomy of a wildland fire:

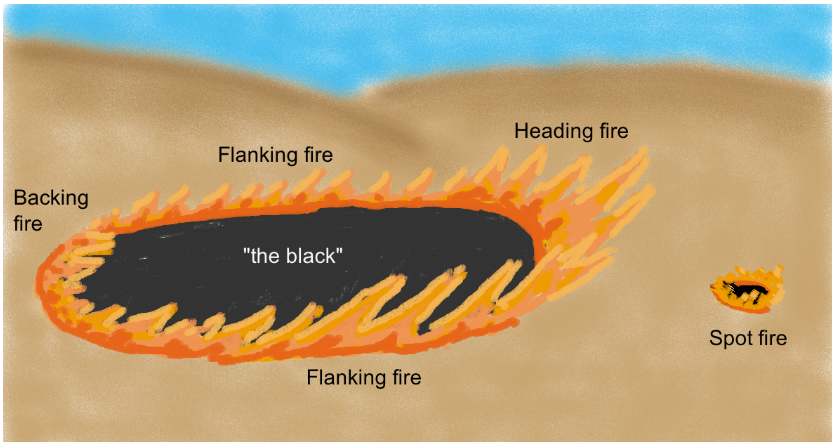


Figure 8: The anatomy of a surface fire. Here the wind moves from left to right, giving the fire an elliptical shape as the *heading fire* moves fastest with the wind, and has the longest flames. Conversely, the *backing fire* moves the slowest, creeping into the wind. On each side, *flanking fires* 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 centre 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.

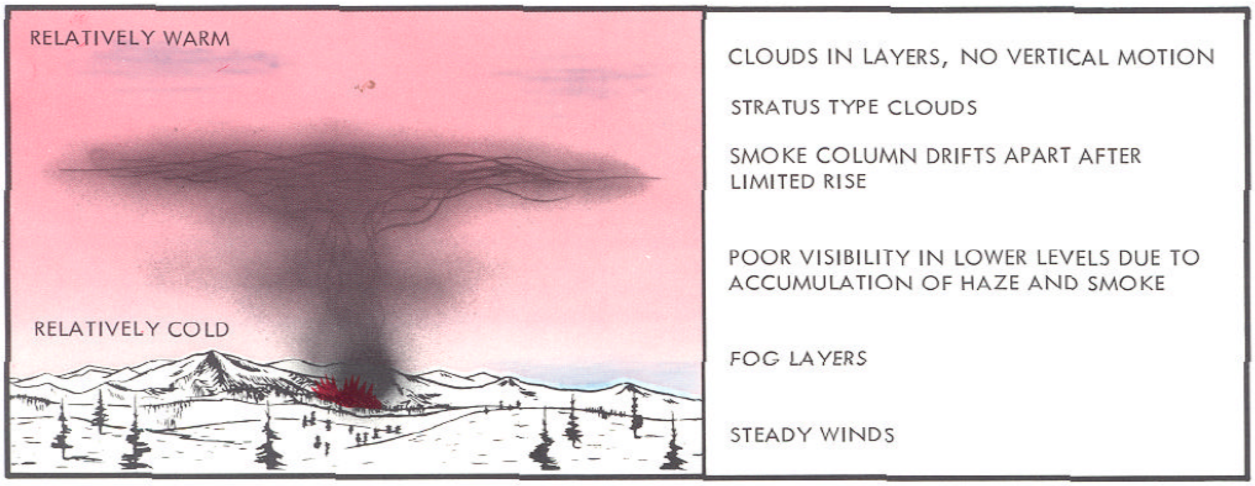
- **Head(ing) fires** move with the wind. Wind drives convective heat transfer by pushing warm air ahead of the fire, which accelerates preheating, propagation, and fire spread.
- **Backing fires** crawl into the wind. Blowing heat back over previously burned areas instead of into unburned fuel reduces 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 (**?**)." 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.

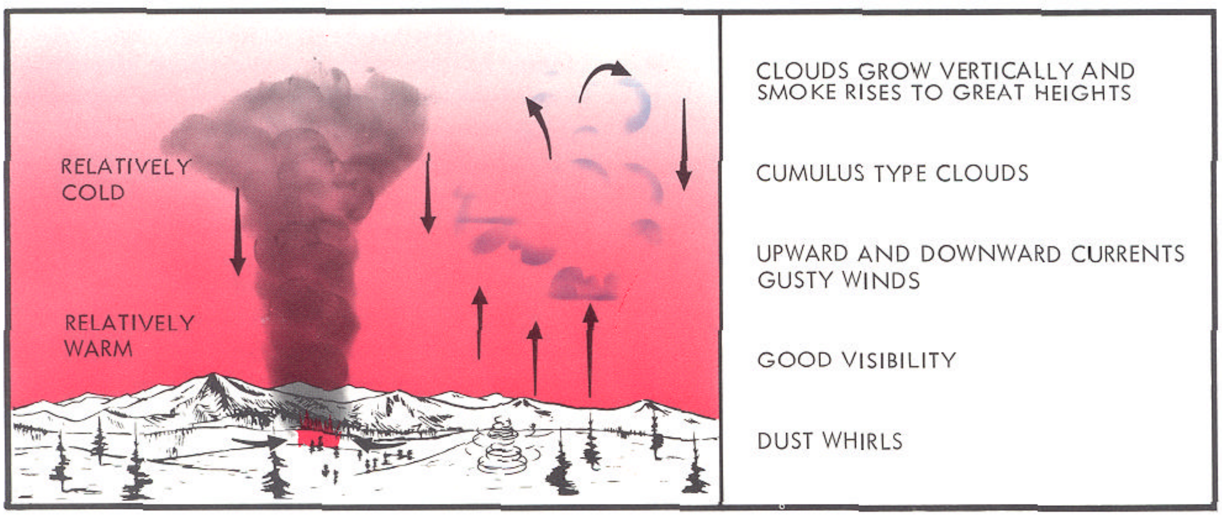
[7] Because a wind shift could easily turn a flanking fire into a head fire, it is important that personnel working on a flanking fire do so from the burned area within the perimeter, which serves as a safety zone.

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.

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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 (**?**, 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 (**?**).

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 (**?**). 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.

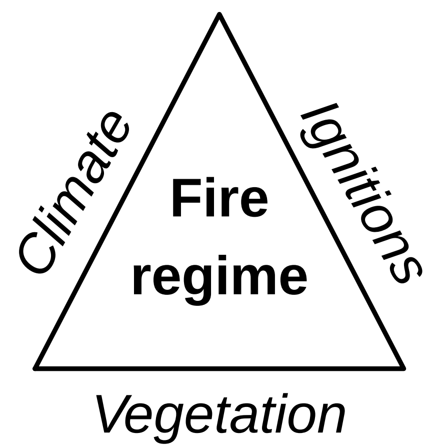

Figure 11: The three sides of the Fire Regime Triangle. See Fig. 12 for specific components with each side of the triangle.

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" (**?**, 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

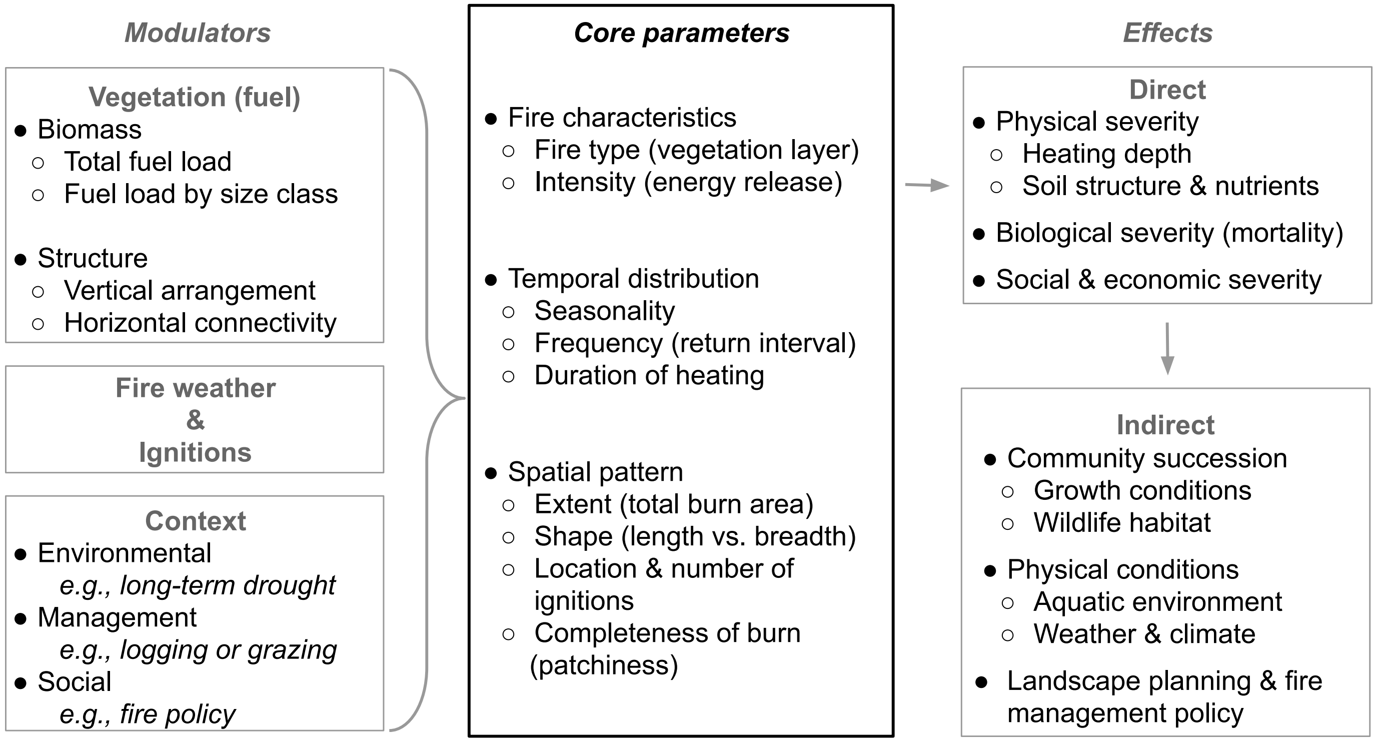

Figure 12: The fire regime concept can be divided into core parameters—those that describe the physical characteristics of either one fire event, or the typical fire event—as well as biological, meteorological, and social factors that modulate fire events, and direct and indirect effects of fire. Figure from **?**, inspired by **?**.

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.

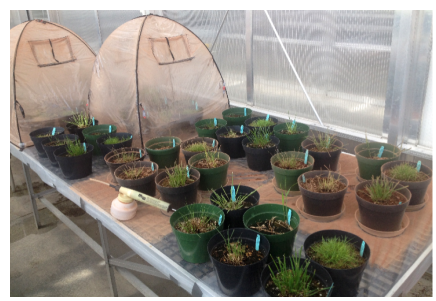

Figure 13: Controlled application of dust on plant leaves in a greenhouse.

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

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

picture of the available fuel load than a quadrat with a thicker mat of wet 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.

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.

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

[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.

History of fire in grasslands

Fire has been an intrinsic component of grasslands and other rangeland ecosystems since these biomes developed and spread around the world. Grasslands as we know them today—including both the vegetation and characteristic animal communities—emerged after the last Ice Age, and have burned regularly and naturally since. Many grass-dominated landscapes owe their existence to fire, especially in the US Great Plains (**?**), where precipitation is substantial enough to support woody plant species capable of converting these landscapes to shrublands, woodlands, or even forests without regular burning.

Figure 16: Topography, weather, and the fuelbed are the three major drivers of wildland fire behaviour.

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

Bibliography