Developing Fuel Treatments for a Future Climate

Best Practices and the Use of Climate Projections

Executive Summary

This best practices guide outlines an approach for identifying fuel treatment alternatives that will be more effective under a changing climate. It outlines the decision framework for determining which fuel treatments are appropriate to alter for a future climate, reviews global climate models and their limitations, identifies sources and uses of downscaled climate data that are appropriate for local-scale land management practices, explains how to use future climate data in widely-utilized fire behavior modeling and fire weather analysis software, and summarizes both the decision-process and the caveats of this process for both planners and fire management personnel. This is meant to be a guide only, and should be adapted locally with appropriate expertise.

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Developing fuel treatments: past, present, or future conditions?

Fuel treatments are widely implemented across the United States and beyond to meet numerous land management objectives, including restoration of ecosystem processes, maintenance of wildlife habitat, and eradication of invasive species. Chief among fuel treatment objectives, however, is fuel reduction leading to the modification of wildland fire behavior and impacts. The effectiveness of a fuel treatment in meeting this objective is dependent upon several factors, including the time since treatment (and the potential regeneration of some fuels), the fuel conditions at the time of the fire, and the fire behavior for a given site under variable weather conditions. Over the past two decades, fire managers and fire researchers have utilized increasingly sophisticated models to project both the potential fire behavior for a given set of conditions and the potential effectiveness of a fuel treatment in altering the behavior of a fire as it moves across the landscape. These are now integrated into the freely available software programs Behave, FARSITE, and FlamMap, and are frequently used for both risk assessment and mitigation planning by fire professionals and fire-prone communities throughout the US.

Fire managers in the US and globally have observed increased wildfire activity over the last couple of decades, and numerous scientific studies have found that increases in fire activity, including ignitions, severity and duration, are partially attributable to changes in climate. Many of these same studies also project that wildfire activity will likely continue to increase during the 21st century given climate projections, with various local effects. For fire and fuels managers, this increased fire activity provides no end to the already complex challenge of managing wildfire. One manner in which increased fire activity specifically impacts fire and fuels management is through fuel treatment effectiveness. To-date, there have been no scientific studies addressing the effectiveness of fuel treatments under a changed climate, but anecdotal evidence from wildfire suppression suggests that fuel treatments become less effective in warmer, drier conditions. For example, during the 2007 Zaca Fire in the Los Padres National Forest of California, an experienced Fire Behavior Analyst noted that numerous fuel treatments and riparian zones that had effectively reduced fire behavior during past wildfires did not perform in the same way during the Zaca Fire. Record low fuel moisture coinciding with warmest March-August in the 118-year observational record likely played a role in reducing the effectiveness of fuel treatments in mitigating fire behavior, and this contributed to the Zaca Fire burning over 240,000 acres over a two-month period.

For fire and fuels managers, the influences of climate change on extreme fire weather and fuels conditions associated with it pose a considerable challenge to implementing and maintaining effective fuel treatments. One solution is to develop and implement fuel treatments that are specifically designed to be effective under future extreme conditions. This process traditionally uses historical data from Remote Automated Weather Stations (RAWS) or nearby observer stations to quantify historical extremes (e.g., 90th percentile conditions for the historical period). While global climate models (GCMs) are not intended to predict the weather for a given future day, they can provide a scientifically credible description of the range of weather conditions for a future period under enhanced greenhouse conditions. This means that GCM output, when used in combination with RAWS observations, can be used as inputs to fire behavior models when proposed fuel treatments are tested, often as part of the planning process prescribed by the National Environmental Policy Act (NEPA).

This guide is meant to provide a step-by-step understanding of how fuel treatments can be developed to remain effective under future conditions, specifically, through the mid-21st century. It explains the acquisition and use of GCM output that has been transformed to an appropriate scale for land management and made available for use in a common weather file format. It also illustrates how fire and fuels managers can produce and utilize quantitative outputs from fire behavior modeling software to support alternative scenarios in their Environmental Assessments that address fire danger and fire behavior in a changing climate.

The Decision Framework

Determining fuel treatment extents and intensity is a complicated process. There are numerous local concerns that influence this process, from population density and politics to fuel type and weather patterns. The decision framework presented here is not meant to simplify those local influences, but rather to serve as a guide for asking questions specifically related to planning and implementing treatments for future effectiveness.

1) **What is the primary objective of the fuel treatment?**
2) **What leg of the fire behavior triangle is the primary driver of fire activity?**
3) **What aspects of fire behavior are most critical within the treatment?**
4) **How is climate most likely to alter fire activity in your area?**
5) **What fuels are on the site now versus what is likely to be there in the future?**
6) **What is actually feasible for treatment implementation? What are the limiting factors?**

Let's go through these in more detail.

What is the primary objective of the fuel treatments?

Fuel treatments often have a number of objectives. Ultimately, what is the primary condition under which the fuel treatment is considered successful? This will help to determine alternative for the treatment under future climate conditions. These might include the following common measures of success.

i. *Stopping a wildfire without any additional resources.*

If the objective of the fuel treatment is to stop an advancing flaming front without the aid of additional active suppression efforts, then the treatment must be intense enough to mitigate all wildfire behavior under the most extreme conditions.

ii. *Altering fire behavior without any additional resources.*

If the objective of the fuel treatment is to alter fire behavior and create a transition zone, with the expectation that the fire is most likely to continue past the treatment, then fuels must be targeted specifically to facilitate this transition. For example, at strategic locations, the goal of the treatment might be to facilitate what would very likely be an active, running crown fire to a surface fire.

iii. *Providing a safe working zone for fire suppression resources.*

If a fuel treatment is located at a strategic point where fire suppression resources are likely to try and hold a fire line as a flaming front advances, the fire behavior within the fuel treatment must be below a safe working threshold for fire resources. This may mean that the fuel treatment is considered a safety zone, or it may mean that resources have an easy and durable escape route from the site, such as a major road or highway unlikely to be cut off. Fuel treatments with this objective may also serve as an anchor for a backfiring operation, so the treatment needs to produce the type of fire behavior that is desired during a burnout.

What leg of the fire behavior triangle is the primary driver of fire activity by season?

Not all types of wildfires and fire regimes will benefit from the placement of a fuel treatment on the landscape, and not all fuel treatments will be effective during the entire year. The concept of fuel treatments stems from fuel being the primary driver of fire behavior on the landscape, but in many locales both topography and wind can drive more extreme fire behavior. Where this is the case, it is critical to determine a) whether or not a fuel treatment can successfully modify fire behavior, and b) what time of year it is most likely to be effective.

One of the best examples of understanding and identifying timing comes from southern California, where there is a bimodal fire regime. Topography is always a factor in this region, as some of the steepest and most complex terrain in North America is associated with the Transverse Ranges. During the summer months, fuel-driven fires can burn for several weeks, primarily due to the challenging terrain, inaccessibility, and abundant available fuels. During the fall months, however, a completely different fire regime is associated with some of the largest and most destructive fires in US history. During autumn, pressure gradients across the southwest region produce what are known locally and to firefighters everywhere as Santa Ana winds. These gale-force offshore wind events can produce the type of flame lengths and long-range spotting that make fuel treatments completely ineffective, and fires move so quickly that suppression resources are less likely to use the fuel treatment as an anchor point or a defensible working zone. In Southern California, fuel treatments that are effective during summer-month, fuel-driven wildfires are far less likely to be effective during autumn Santa Ana wind-driven fires. In the same way that this bimodality is recognized and incorporated into fire suppression training, it is also critical for planning and implementation of fuel treatments. From the perspective of planning fuel treatments for a future climate, it is critical to identify how individual seasonal drivers will be impacted differentially by climate change, and to use climate projections for the correct seasons.

What aspects of fire behavior are most critical within the treatment?

Climate change not only impacts drivers of fire behavior by season, it will also impact the specific aspects of fuels that determine fire behavior. In addition to identifying the objective of the fuel treatment as described above, part of planning and implementing of effective fuel treatments is to identify what specific characteristics of fire behavior the treatment is meant to modify. For example, if the objective of the fuel treatment is to pre-position a fireline that will be utilized by suppression resources for direct attack during an incident, the fire behavior metrics that may be most important are flame length and fireline intensity. For objectives where the fuel treatment will be a passive modifier of fire behavior (i.e., suppression resources are less likely to be on site during an incident), metrics like rate of spread and crown fire potential may be more critical. Since climate change may differentially impact fire behavior, it is useful to identify the most important fire behavior metrics and focus on those in assessments of future fuel treatment effectiveness.

How is climate most likely to alter fire activity in your area?

Climate change is incredibly complex and often misunderstood. Most frequently, the changing climate is discussed in terms of warming and typically described by increases in mean annual temperature, or other seasonal averages. When seeking to mitigate the impacts of climate change, it is important to understand in how climate change is likely to manifest, and what its direct and indirect impacts will be, for your specific region.

There are four key characteristics of climatology that are important to keep in mind when thinking about, understanding, and contextualizing climate change:

1) Departures from historic normals
2) Seasonality
3) Frequency and magnitude of extremes
4) Direct and indirect effects

Departures from historic normals are the most common way that climate variability change is described. Historic normals are calculated from a period of historic data; in the US, the National Oceanic and Atmospheric Association usually describes climatic normals, or averages, by the most recent three decades of data (e.g., 1981-2010). The two most common variables described are temperature and precipitation, although other variables like snowfall are also considered.

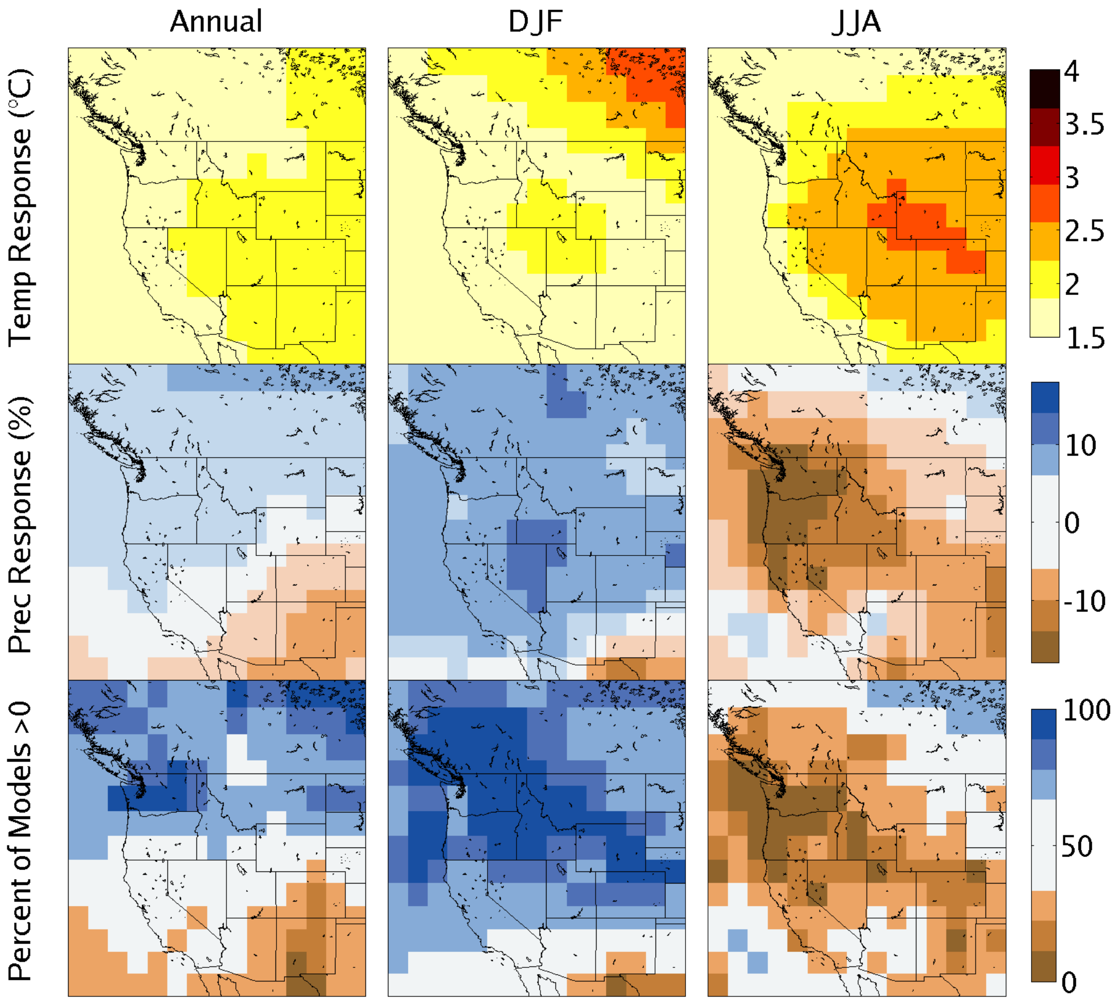

Figure 1. The change in annual (left column), winter (middle column), and summer (right column) temperature (top row) and precipitation (middle row) for the western US between the late 20th century (1970-2000) and the mid-21st century (2031-2060). Changes are the average of 15 GCMs, and the bottom row shows the level of model agreement for precipitation.

Seasonality describes seasonal changes in climate over the course of the year. This seasonality in turn, helps to shape the time of the year that fuels are most receptive to fire. Climate change is projected to impact the seasons differentially, in terms of both "shifting" the timing of seasons, potentially altering the length of the fire season, and the magnitude of changes during different times of the year. For example, across much of the western US, the winter months are projected to warm at a different rate than the summer months. This means that while the warmer summer temperatures will likely contribute to increased fire activity, perhaps the more important contributor will be the warmer winters, through a decrease in accumulated snowpack (because fewer days are cold enough to turn any precipitation to snow). Understanding which seasons are the most important for the fire behavior that the fuel treatment is meant to modify (Early fires in the spring? Late fires in the fall?) is critical to using the correct climate data for an analysis.

Understanding *frequency and magnitude of extremes* is more critical to fire management than understanding climate normals. Fires are less extreme when climatic conditions are normal; by definition, they tend to occur more frequently, more extensively, and with more devastating impacts when conditions are extreme. Some of the largest, most destructive wildfires in the last century have occurred during highly anomalous climatological and meteorological conditions, including extreme heat, extreme drought, and extreme high winds. One of the most important aspects of climate change is that as the climate generally warms, there in an increase in both the frequency and the magnitude of extreme events. This means there are likely to be longer, hotter and generally more severe heat waves, and that while many regions of the US are projected to receive more precipitation, it will fall in a fewer number of days, create higher potential for flood events. Even a 1-degree mean increase in temperature can be associated with a 4-5 degree increase in the 97th percentile high temperatures.

Direct and indirect effects of these projected changes in climate will be many. Direct effects are the direct outcome changes in atmospheric conditions, for example, increased fire danger through warmer and drier weather. Indirect effects are more complicated, and are much more difficult to project, as they can be two or three dominos down the line. For example, a reduced winter snowpack in the mountains may lead to earlier green-up and subsequent curing of grasses, allowing fire season to initiate earlier. Riparian zones that were historically too wet to burn even in the late part of summer may be sufficiently dry to burn, reducing the number of natural fire breaks on the landscape. Warmer temperatures may allow bark beetles to thrive on greater areas, producing incredible standing fuel loads, and ultimately altering the dominant vegetation types when those stands burn or fall.

What fuels are on the site now vs. likely to be there in the future?

One of the most difficult effects of climate change to predict will be the redistribution of species across the landscape, and the subsequent changes in fuel loading. This is particularly hampered by the ongoing spread of invasive species introduced by humans. But for many sites that sit at climatic thresholds, a small change in climatic patterns may produce a transition to a new dominant ecotype and fuel load. If your potential fuel treatment site is located at a transition interface between forest and shrubland, what is the likelihood that transition zone will be located in the same location in 20 or 30 years, or will it have moved uphill? If your fuel treatment is planned for a north-facing aspect that is currently heavily timbered, will that timber still be thriving in a few (warmer) decades, or is it likely to transition to a lower density as conditions change? These are challenging questions to answer, but will ultimately impact the longevity and effectiveness of your treatment.

What is actually feasible for treatment implementation? What are the limiting factors?

Since every fuel treatment implemented must first go through the planning and review process outlined in the National Environmental Policy Act (NEPA), there are limitations to what can reasonably be accomplished. Whether the limitations are based on proximity to private lands or other multiple-ownership challenges, financial constraints, or public perception hurdles, limiting factors tend to be highly localized and often at odds with treatment objectives. More often than not, fuels managers would like to treat more fuels while constrained to treat less.

One of the goals of this guide is to provide quantitative support for treatment alternatives that would otherwise be considered outside the constraints of feasibility for fuels management. Often, the fuel manager is asked to identify the minimum extent and intensity treatment alternative that will still effectively modify fire behavior. However, this assessment has traditionally been made utilizing climate data collected over the previous several decades. Because climate change will alter the effectiveness of fuel treatments in modifying fire behavior, the minimum extent and intensity of treatment required to produce the desired results are also altered under the future climate. The next chapter provides an overview of the process for incorporating future climate data.

Using future climate data

To assess the effectiveness of fuel treatments under future climatic conditions, you must first have a source for future climate data. Global Climate Models (GCMs) are the initial resource, producing projections of daily weather for a specified period in the future (e.g., 2000-2100). GCM outputs are not meant to be actual forecast of weather for a given day, rather, they are meant to represent a probable range of weather over a decade or multiple decades under enhanced greenhouse conditions. Direct GCM outputs are not very useful for local scale land management, such as fuel treatment analysis, because they are available at very coarse spatial resolution; the average model output is approximately 2°x 2° resolution, or a 200km cell size. This resolution obviously fails to represent the local topography and microclimates that control fire behavior on the landscape.

GCMs are run with different 'scenarios' intended to provide potential pathways of future emissions of man made greenhouse gases and aerosols. The Intergovernmental Panel on Climate Change (IPCC), a collection of the world's top scientists and policy experts, defines the scenarios based on potential changes in global population, derivation of energy, land-use changes and globalization. For example, the B1 scenario from the 2007 IPCC report assumed that there would be very little increase in world population and almost no new industrialization in developing countries, in addition to developed, first-world countries reducing their greenhouse gas emissions. This is sometimes referred to as a "best-case scenario." On the other end of the spectrum, scenario A2 assumes rampant growth both in industrializing countries and in first-world countries, the so-called "worst-case scenario." In between is the A1B, or "middle-of-the-road" scenario. A new set of scenarios, called Representative Concentration Pathways (RCP), have been developed for the IPCC's Fifth Assessment Report due out in 2014. This means that the user must choose which scenario they would like to use climate projections from in their analysis. For users interested in examining

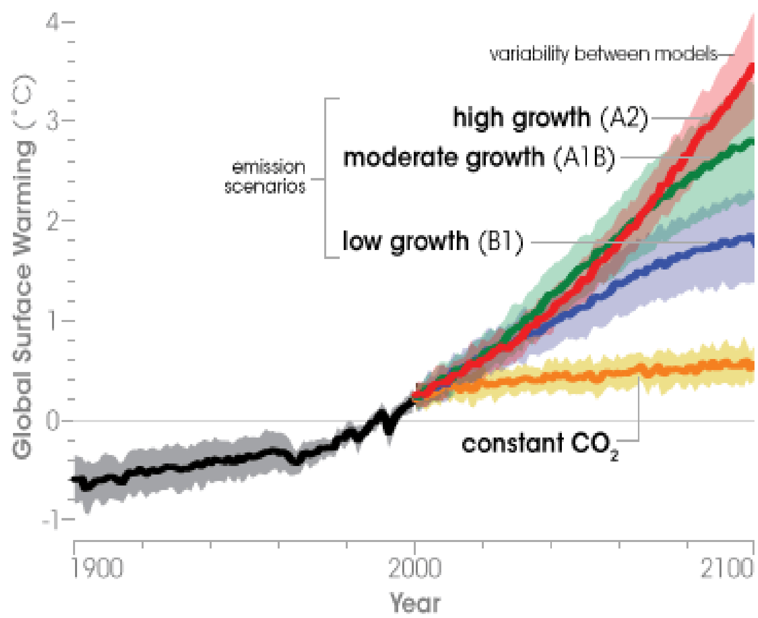

Figure 2. IPCC emissions scenarios used as inputs to global climate models from the 2007 report.

climate projections prior to mid-21st century, the choice of scenario may not be as important as other factors; however, users interested in longer-term horizons will want to pay special attention to scenarios.

To further complicate matters, there are many GCMs being run by scientists around the globe. Each GCM is constructed slightly differently; that is, the resolution of the model and the algorithms are slightly different. The ability of GCMs to simulate historical climate and changes in climate for a region can vary widely. The most common solution when using output from these models is to use a group, usually called an ensemble, of models. This approach is similar to conducting a scientific experiment across multiple samples. Typically, users select between 3 to 12 different models, and then look for agreement between the models as the most likely future. For example, in the figure on page 9, the ensemble shows that all of the models project a slight increase in winter precipitation for the Northern Rockies, so we can have greater confidence in this projection because so many of the models agree on it.

In order to make climate projections usable for local application, output from GCMs must be transformed into a fine-scale product. This process is called downscaling and includes a variety of different approaches with the overall goal of retaining the driving information from the GCMs while the practical considerations of users. Most downscaled datasets transform coarse-scale GCM output to gridded data at a resolution of 4km-50km that may still be coarse and may not be readily applicable into current operational based tools. New techniques from the University of Idaho have bridged this gap by downscale these climate model outputs to a resolution widely used by fire managers: that of the individual Remote Automated Weather Station (RAWS).

To-date, the University of Idaho has downscaled future climate projections from a variety of GCMs for 50 RAWS across Southern California, with potential to downscale additional RAWS in the future. These individual station datasets are available via an interactive search tool and map at http://nimbus.cos.uidaho.edu/JFSP/

Additionally, the University of Idaho has developed downscaled 4-km future climate projections for monthly temperature and precipitation for the continental United States, and daily temperature, precipitation, relative humidity, wind velocity and downward shortwave radiation for the western United States. These data complement the scale of the widely-used Parameter Regressions on Independent Slopes Model (PRISM) data from Oregon State University. There are two types of data available from the University of Idaho through an add-on tool to ArcGIS (found through INSIDE Idaho; http://inside.idaho.edu): 1) monthly data for the continental US (CONUS), and 2) daily data for the western US.

Comparing apples to apples: using modeled versus observed historical data

Users of climate model outputs will notice that outputs are provided for both historical conditions and future projections. For many users, the inclusion of data run under historical model forcing may seem counterintuitive: why would anyone want to use modeled historical data, when we have observed historical data from trusted weather stations all over the country?

The answer is simple: we want to compare apples to apples. When trying to describe the magnitude of a weather event, such as a drought or heat wave or snowfall, climatologists will describe this event as a *percent of normal*, based on historical conditions. For example, they might describe the April 1 Snow Water Equivalent (SWE), or snowpack, as being at 75% of normal, which conveys a level of drought or abundance that is more specific than simply saying it is “lower” or “higher” than normal.

In the same vein, when we are trying to project future climate conditions and the associated fire behavior, we want to describe the change in conditions as a departure from normal, again, with normal as the historic period. However, this is where the apple analogy becomes important and issues of scale come into play. Climate models simulate numerous years of data covering both historical conditions using observed levels of greenhouse gases and solar and volcanic forcing, and future scenarios. As individual models simulate their own natural variability including El Nino years, there is not a one to one correspondence between modeled climate and observed climate. Likewise, even though statistical downscaling methods ensure statistical matching between observations and modeled conditions, climate models represent a sample of observed conditions.

Because we wish to compare future conditions to historic conditions and look at changes relative to historical baseline conditions, we use the modeled historic data for this comparison. By doing so, we can be certain that changes we are seeing in climatic conditions and fire danger and behavior are associated with climate change, and not simply a function of comparing modeled future data to observed historic data that reflect differences in how models simulate climate of the given region. In essence, we want to compare apples to apples, instead of apples to oranges.

Using the data: what models

As described above, there are numerous global climate models being run by scientists across the globe. While the best approach when trying to understand the impacts of climate change is to use a multi-model ensemble, this is often not feasible due to limitations of time and other resources.

One solution to this challenge is to utilize a subset of models that represent the range of variability in projected conditions for the region of interest. The figure below represents the projected departure from summer temperature and spring precipitation normals for 2046-2065 in southern California from 13 different GCMs, as well as the multi-model ensemble mean (the large 'X'). It is immediately obvious that many of the models are in some agreement, and there is a mean likely trajectory associated with these 'middle of the road' models. It is also obvious that some models are more prone to project extremes: either an extreme on the low end that actually projects global cooling or an extreme on the high end that projects much greater warming than the bulk of the models.

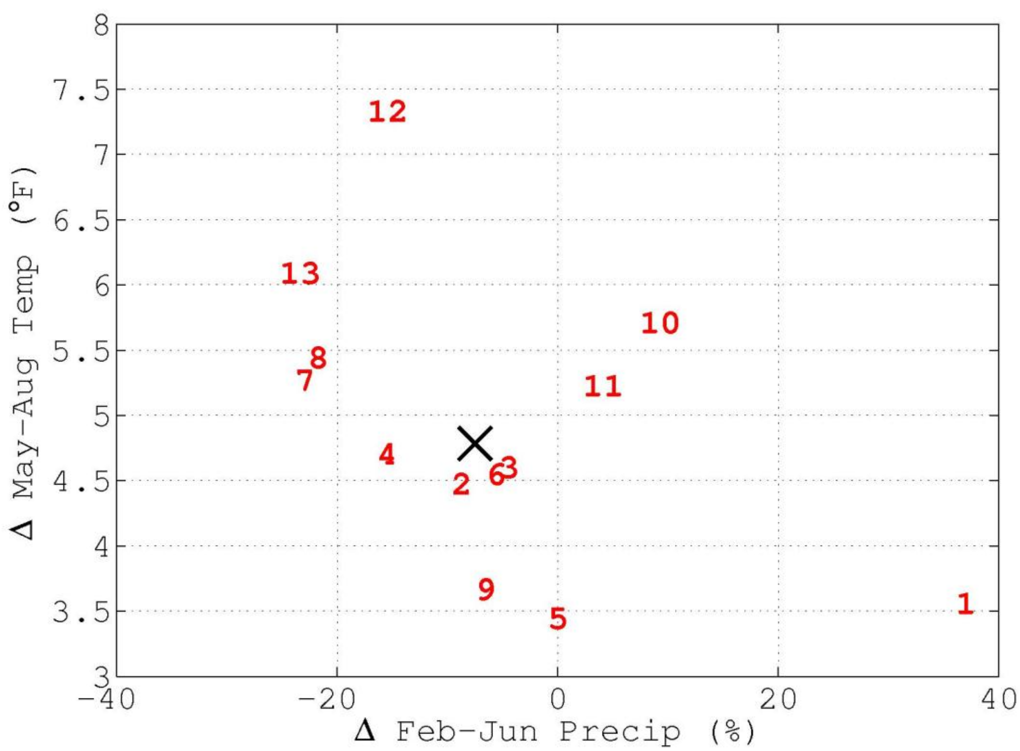

Figure 3. Projected departure from normal for summer temperature and spring precipitation for southern California for the 2046-2065 mid-21st century period for 13 different GCMs. The multi-model ensemble mean is represented by the black 'X.'

For risk management planning, one of the most common approaches is to identify the worst-case scenario possibility. For fire and fuels planning, this would mean the scenario that is likely to produce the most extreme fire weather conditions for the most extreme fire behavior potential. To help contextualize the worst-case scenario, it is also very useful to utilize a model that represents the mean or middle-of-the-road projection. By using the outputs of these two models at the minimum, risk planners can show both a most likely change in fire potential and a worst-case scenario change in fire potential that can help guide decisions about the types and intensities of fuel treatments would be most effective under the two sets of conditions. If users have additional resources, selecting additional models that represent the lowest-change models, or additional models that help to represent the range of variability in climate projections, will provide more context for what is possible. This is particularly important for public information sessions, where the public often asks for these exact two scenarios: what is the most likely outcome, and what is the worst-case scenario. In the case study we present in this Guide, we utilize a middle-of-the-road model and a worst-case scenario model.

Using the data: how to use in FireFamilyPlus

The downscaled RAWS data developed by the University of Idaho is available in .fw9 format from the project website (http://nimbus.cos.uidaho.edu/jfsp). Whether you are using this or other types of climate model data, there are a few key limitations and best practices to be cognizant of when importing it into FireFamilyPlus for analysis.

First, FireFamilyPlus was never designed for future dates. At the time of publication, version 4.1 was still being tested in Beta mode, and limits the inputs to the period 1970- present. Most climate model projection outputs are delineated for specific sets of decades; for example, the mid-21st century models project data from 2046-2065, while the late-21st century models project conditions for 2081-2100. FireFamilyPlus will not read in files that contain dates beyond present.

To get around this limitation, the easiest solution is to re-number the future years to years that are within the temporal limitations of FireFamilyPlus. For example, all of the projected RAWS data developed by the University of Idaho is for the mid-21st century model period, as it is the most representative future period for which we'd like assess fuel treatment effectiveness. This period was chosen both because there is greater model agreement (i.e., likely more accurate projections) for the mid-21st century as compared to the late-21st century.

To make the University of Idaho downscaled data more FireFamilyPlus-friendly, the future years are already converted to historic years. In this project, the mid-21st century years were narrowed to reflect the period of record when historic RAWS data were available for all 50 of the stations selected: 1996-2010. The mid-21st century period was placed 50 years ahead of the historic window: 2046-2065. Because of the limitations of FireFamilyPlus, the years designated within the .fw9 files for import were 1971-1990.

IMPORTANT: No matter what data are used for future climate conditions, users of FireFamilyPlus will need to be cognizant of its temporal limitations, adjust input dates accordingly, and remember their adjustment factor as they work within FireFamilyPlus.

Data import and use in FireFamilyPlus are no different than usage with other types of historical data from RAWS, WIMS, KCFAST or other sources. Station data should import with files.

A NOTE ON GREEN-UP DATES: One element of station data that is likely to be impacted by climate change are the seasonal bounds: the green-up date and first freeze date. Users may choose to simply stick with known historical green-up and first frost dates, or they can utilize FireFamilyPlus itself to analyze potential changes in these dates by creating a temperature climatology graph (i.e., mean high or low temperature for each day of the year) for the future period, and approximating earlier or later events.

Making weather fires for FARSITE, FLAMMAP, or ArcFuels

In the case study that follows, future climate scenarios are created to project fire behavior and burn probability in ArcFuels, an add-on tool for ArcGIS that calls FLAMMAP and FARSITE to run fire behavior scenarios specifically for different fuel-treatment alternatives. However, the wind and weather scenarios utilized in ArcFuels are the exact same files that are utilized in FARSITE and FLAMMAP, so any user familiar with this process need only use the modeled climate data in the same manner that they have been using historic observational data, but should compare historic conditions to future projected conditions using model outputs for both temporal periods (as noted above). More information on ArcFuels and an excellent instructional guide for interested potential users can be found at http://www.fs.fed.us/wwetac/arcfuels/.

General best practices for creating future wind and weather scenarios mirror recommendations made for assessing fuel treatment effectiveness based on historic range of variability. These best practices are addressed in previous chapters and elsewhere, but are summarized here. The highlights of these best practices include:

1. Select the appropriate seasonal boundaries for assessing fuel treatment effectiveness for the question being asked.
2. Select the appropriate percentiles for each meteorological and/or fire danger variable (i.e., a 97th percentile temperature is equivalent to a 3rd percentile relative humidity).
3. Select a range of percentiles and seasonal ranges to represent different likely scenarios that suppression resources will have to face. For example, in Southern California, the user might model both summer and autumn fire behavior to show the dichotomy of the

fire behavior associated with the fuel-driven summer fire regime versus the Santa Ana wind-driven autumn fire regime.

4. Utilize wind roses to represent wind speed and direction climatology to help identify wind speed and direction for scenarios.
5. Understand the caveats and limitations of creating scenarios, particularly as they relate to fire behavior.

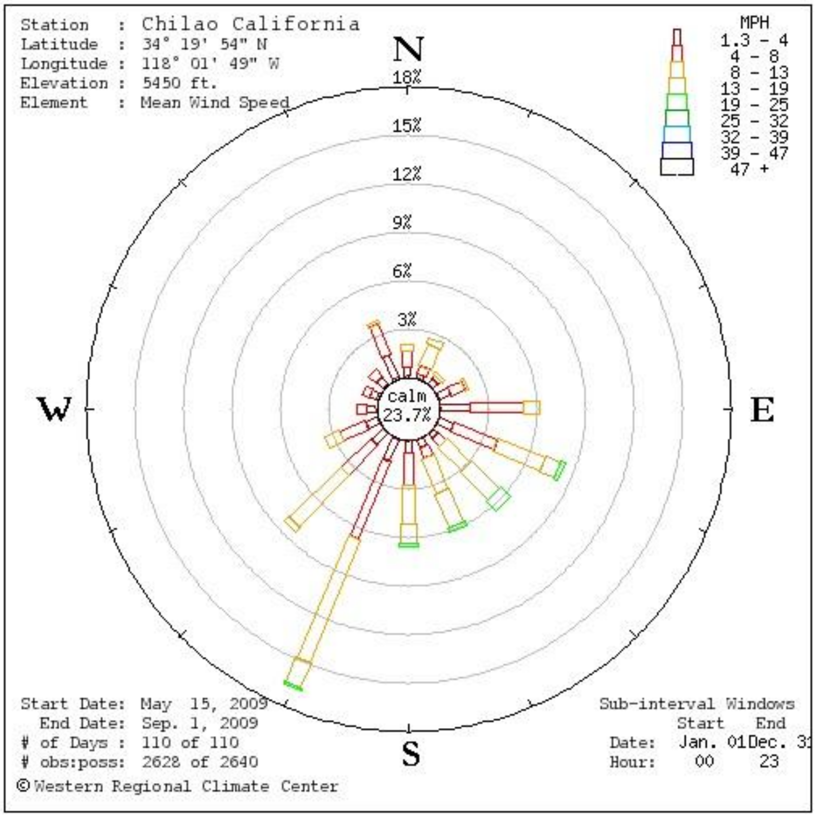

Figure 4. Wind rose used to determine prevailing winds at 90th percentile.

Using future climate data in fire behavior models to describe change

Any user of fire behavior models is likely fully aware of the limitations of such models. The most-commonly used software packages, including FARSITE, FLAMMAP, BehavePlus, and ArcFuels, all utilize the basic modeled relationships between environmental conditions and the resulting fire behavior for various fuel types that were first described by personnel at the Northern Forest Fire Laboratory (now the Missoula Fire Lab) in the 1970s. By definition, modeled relationships are simplifications that fail to fully account for the variability and anomalies that are observed in nature. With the complexity inherent in weather, fire, and fuels, models cannot yet provide the level of accuracy needed to forecast exactly how a fire is going to behave at a given point in time and space.

This lack of specificity in model accuracy is overcome by using probability-modeling approaches. For example, the development of FSPro has allowed long-term fire behavior analysts to model the likelihood of a fire extent reaching a given location using what is essentially a Monte Carlo-statistical approach: run the model one thousand times and quantify the proportion of times the fire reaches a given cell. These probabilities are used to generate a map highlighting probability of increasing fire extents.

In fire behavior modeling, there is often a tendency by the modeler to desire a specific value or metric as an output. For example, a fire behavior analyst might wish to identify locations where the flame lengths may exceed four feet in height, so that they can identify unsafe locations for direct attack by hand crews. This approach, however, can be problematic since it assumes quite specific weather and environmental conditions as inputs. In contrast, the user could assess changes in fire behavior by percent change from the baseline. For example, the user might run a comparative analysis and determine that the projected Rate of Spread is 50% greater/faster in a location for the mid-21st century as compared to historical conditions. However, this approach does not indicate whether that location meets some an effectiveness criteria for suppression, such as a maximum ROS of two chains per hour.

For fuel treatment effectiveness and climate change impact analysis, then, a multi-pronged approach may be the most effective for utilizing future climate information to assess fuel treatment effectiveness.

The NEPA approach: Assessment of percent change

For fuels planners looking to incorporate climate projections into NEPA planning documents, the percent-change change approach may be more compatible with the alternative scenarios format often utilized in the planning and review stages. For example, a planning effort that presents three scenarios, including No Change, Low-Intensity Treatment, and High-Intensity Treatment, would usually use historic wind and weather data in running the fire behavior models to identify the differences between the three treatment types.

In this scenario, a planner could run the No Change, Low-Intensity, and High-Intensity options each with the historic 90th percentile conditions, and then each with the projected mid-21st century 90th percentile conditions. This would allow the planner to conduct a percent change analysis showing projected increases or decreases in fire behavior and burn probability metrics without any treatment, and with each of the intensities. This allows decision-makers and the public to identify what intensity of treatment will produce the desired level of change in fire activity under future conditions, rather than historic ones. For example, Alternative C with mid-21st century climate data may produce the same reduction in crown fire as Alternative A with historic data. Communities and management units wishing to be proactive about the potential effects of climate change may wish to consider Alternative C in this scenario.

Table 1. Example fire behavior outcomes associated with incorporating future treatment scenarios.

Treatment Alternative	Percentile Scenario	Average Flame Length (ft)	Percent change from Historic-No treatment
No Change	Historic 90th	9.5	--
No Change	Mid-21st century 90th	13.6	43%
Low-Intensity	Historic 90th	4.1	-46%
Low-Intensity	Mid-21st century 90th	10.4	9%
High-Intensity	Historic 90th	1.5	-84%
High-Intensity	Mid-21st century 90th	3.9	-59%

The Suppression Planning Approach: Assessment of metric-dependent effectiveness coupled with FBAN expertise

While percentile changes in projected fire behavior are useful for planning and identifying treatment alternatives, they are less meaningful to fire managers who wish to characterize how fuel treatments might be utilized during a wildfire incident. For example, as fire managers update unit-wide Fire Management Plans, or work with local communities on Community Wildfire Protection Plans (CWPPs), their goal may be to identify safety zones for firefighters, escape routes for residents and equipment, or fuel treatments where direct attack can be initiated from scratch lines. In each of these cases, there is often a fire behavior threshold that defines safe versus unsafe.

Where there is a need to identify these thresholds from models, an expert fire behavior analyst, or FBAN, should be consulted to help with validating models. FBANs and other highly experienced fire managers can help a user to tune the model in order to match historical observations of fire behavior, and what they believe fire behavior would be in a given situation given their expert experience. For example, an expert FBAN may look at the flame length outputs for 90th percentile historical weather conditions for a given location and determine that the mean and range of potential flame lengths for the fuels at that location are actually much higher than as calculated by the model. This often happens on wildfire incidents, where observed fire behavior is far different than modeled. The fire behavior model is then systematically adjusted until the fire behavior outputs are accurate to what is being observed. These adjustments can then be applied using future climate scenarios to model what the actual fire behavior might be under the mid-21st century conditions, and maps developed with thresholds of interest to the potential user groups.

Putting it all together: Developing and Testing Treatment Alternatives for Future Climates

Fuel treatment effectiveness is highly variable over space and time. Fire and fuels professionals who seek to develop fuel treatments that will maintain a certain standard of effectiveness over time need to consider not only the changing fire weather conditions that will promote different fire behaviors, but also that changing climate is likely to alter vegetation communities and fuel structures. As such, we suggest the following decision-framework for developing and testing fuel treatments for future climates.

1) **Identify the primary objective of the fuel treatment.**

   Is the treatment expected to stop fire progression? Serve as a safety zone? Modify fire behavior for suppression resources to initiate direct attack?

2) **Identify what aspect of the fire behavior triangle is the primary driver of fire activity.**

   Are fires in this area predominantly wind-driven? Fuel-driven? Topography-driven? Each factors requires a slightly different approach to fuel treatment development. If there are seasonal fire regimes associated with different drivers, planners must recognize and address the dichotomy with realistic objectives. For example, given the dichotomous regimes of summer fuel-driven versus autumn Santa Ana wind-driven fires in Southern California, it is unrealistic to expect a fuel treatment designed to stop fire progress in a summer fire would meet this objectives during a Santa Ana wind-driven fire event.

3) **Identify which aspects or metrics of fire behavior are most critical within the treatment.**

   Associated with objectives, what metrics are most important? Reduced flame length to aid suppression? Minimizing crown fire as a source of embers that can ignite homes? Increasing rate of spread while reducing burning intensity in order to protect old growth or similar resources at risk?

4) **Identify the fuels on the site now versus likely to be there in the future.**

   Is the site currently a transition zone? Is there an invasive species that is likely to take over the site?

5) **Determine what is actually feasible for treatment implementation and identify the limiting factors.**

What are the local politics and fiscal realities? How much of that might be changed with a well-researched analysis using future climate data (e.g., public perception about treatment intensities)? How much is set in stone (e.g., financial resources)?

6) **Identify which global climate model outputs to use, and acquire downscaled data.**

Every land management agency now has climate experts to help these sorts of decisions. Use these experts and reports on global climate model outputs to choose ensembles, middle-of-the-road, and/or worst-case scenarios. When in doubt, try to use a range, or ensemble of models, that reflect both middle-of-the-road projections AND worst-case scenarios. The most widely used GCM emission scenario (which drives the models) is the A1B moderate growth scenario.

7) **Develop wind and weather scenarios for both historic and future conditions using best practices and modeled data so as to compare apples-to-apples.**

Use historic modeled data as a baseline against which to compare future conditions. Don't compare individual days or weeks of weather. Instead, compare percentiles from the historic period to the same percentiles for a future period (e.g., the mid-21st century). Base percentiles on appropriate periods of interest during the year (e.g., the primary fire season months) rather than the entire year. If GCM outputs for multiple future periods are available, the output period closer to the present is usually more accurate and more relevant.

8) **Model fire behavior for both historic and future conditions in a probabilistic analysis to identify likelihood of an outcome and range of variability.**

Run multiple iterations to develop a range of outcomes for the fire extent and behavior. Identify the range of probable values for each fire behavior metric of interest, and the highest likelihood (median value).

9) **Conduct percent change analysis to show the magnitude of change in projected fire behavior across the landscape associated with climate change.**

Quantify changes in fire behavior and potential as a percent difference from the historic, or baseline, period. This is more informative in particular for fire behavior metrics (e.g., fire line intensity) that may be more difficult to interpret meaningfully for suppression resources.

10) Conduct effectiveness analysis based on specific fire behavior thresholds with the help of an expert fire behavior analyst.

Fit models to observed fire behavior by “tweaking” inputs. For example, a slightly different fuel model than what was burned might be required to produce the same fire behavior as was observed given known weather conditions. Utilize the same alternative model to produce future fire behavior when focusing on fire behavior thresholds like flame length and rate of spread, particularly when the fuel treatment is likely to be actively used during fire suppression operations and such thresholds are critical. Fire behavior analysts and even experienced personnel who have observed fire behavior under a range of conditions near the site in the same fuel types can provide both estimates of expected fire behavior and validation for models.

11) Model relationships between treatment configurations and projected fire behavior to identify optimal fuel treatment intensities and characteristics.

To test different fuel treatment shapes, sizes and intensities, ArcFuels is a powerful and useful tool in the fuel planner’s toolbox. Because ArcFuels is actually just a script add-on to the regular ArcGIS interface, all of the usual tools in ArcGIS are also available in ArcFuels. The three primary tools used for testing alternative treatments are buffer, Editor, and the existing Modification tool in ArcFuels.

1) ***Buffer***
   Use the buffer tool to alter the size of fuel treatments. You can both reduce (via an internal buffer) or expand (via external buffer) the size of a treatment unit polygon or set of polygons to create several potential widths and areal extents.

2) ***Editor***
   Change the shape or spatial location and arrangement of fuel treatments.

3) ***Modification***
   Use the ArcFuels modification tool to alter intensities of treatments. Change the fuel model to one with different densities and flammabilities of fuels, reduce or increase the canopy cover, and modify crown characteristics such as Crown Bulk Density, Stand Height, and Height-to-live-crown. See ArcFuels for details and instructions.

12) Represent fuel treatment alternatives and fire behavior potential as ranges of variability associated with historic and future conditions.

It is unlikely that your projected future weather condition (e.g., 90^{th} percentile) will occur exactly during the fire incident. This is why it is important to have a range of expected conditions and the associated fire behavior. This range should be determined by both the range of potential fire weather conditions, and by the variability associated with randomness within this range (calculated by running the model multiple times).

Conclusion

Fuel treatments will continue to be a critical tool for fire and fuels management, but they will be more cost-effective and maintainable in the long-term if they are planned and implemented accounting for climate change. This guide is meant to provide some fundamental principles and resources for assessing fuel treatment effectiveness under climate change. It is not a step-by-step instruction guide, as most of the hands-on analysis is completed in ArcFuels, FlamMap, FARSITE, or other fire behavior modeling programs that have their own tutorials. Instead it is designed to present guidelines for testing and presenting fuel treatment alternatives that include future climate data, in a way that is scientifically sound and will be both admissible in NEPA documentation and assist in educating the public during outreach sessions on the need to plan pro-actively for climate change. With hundreds of millions of dollars spent on fuel treatments in the US each year, we hope this guide will help support long-term fiscal efficiency and reduced wildland fire damage in the future.