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User Guide to the FireCLIME Vulnerability Assessment (VA) Tool: A Rapid and Flexible System for Assessing Ecosystem Vulnerability to Climate-Fire Interactions

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Abstract

Decision makers need better methods for identifying critical ecosystem vulnerabilities to changing climate and fire regimes. Climate-wildfire-vegetation interactions are complex and hinder classification and projection necessary for development of management strategies. One such vulnerability assessment (VA) is FireCLIME VA, which allows users to compare management strategies under various climate scenarios and gauge the potential effectiveness of those strategies for reducing undesirable impacts of climate on wildfire regimes and resulting impacts of wildfire on natural ecosystems. Developed as part of the SW FireCLIME science-management partnership, FireCLIME is meant to be quick, flexible, and amendable to a range of data inputs (literature review, expert, and modeling or monitoring activities). These inputs allow users to easily compare various fire-climate outcomes for one or more ecosystems of interest. Users can use literature, hypothetical scenarios, or quantitative data to implement the FireCLIME VA tool. This tool, unlike other vulnerability assessment, is best used iteratively to explore a range of possible scenarios and management strategies.

Keywords: forests, climate change, vulnerability assessment, natural resource planning, fuel treatments

Cover—Fire effects monitoring crew observes a prescribed fire in the Jemez Mountains of New Mexico. Photo by R. Loehman.

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Contents

I. INTRODUCTION

Climate changes are pervasive, with cascading effects already observed throughout global ecosystems, including threats to biodiversity, ecosystem functioning, and human well-being (Hughes 2000; Williams et al. 2008). Additional impacts across a wide diversity of ecosystems, taxa, species, and human communities are expected in the future, as climate continues its rapid rate of change (Allen et al. 2015; Field et al. 2014; Williams et al. 2013). Many modeling and empirical studies predict changes in ecosystems and plant communities in response to changing climate at decadal and longer time scales (e.g., Lawler et al. 2006; Gonzalez et al. 2010; Rehfeldt et al. 2012). Superimposed on climate-induced range shifts (i.e., shifting bioclimatic envelopes) are severe large-scale disturbances (e.g., wildfires) that can reorganize ecosystems along much shorter time scales of weeks to months (Overpeck et al. 1990; Adams 2013). Among the most immediate concerns are impacts of warming weather and changing hydrology on wildfire. Already, forest ecosystems in the United States are experiencing longer fire seasons with larger and more severe fires that are associated with drier conditions (including drought) and warmer temperatures (Westerling 2016; Kitzberger et al. 2017). These regime changes pose serious threats to ecosystem integrity and resilience and pose profound challenges to ecosystem managers (Falk 2013; Haffey 2014).

Developing effective management strategies for ecosystem resilience to wildfire and climate change is a significant challenge in natural resource management. However, prediction of future climate-driven wildfire patterns is difficult because climate, vegetation, and disturbance interactions are complex and do not operate independently (Loehman et al. 2014; Loehman et al. 2018). Climate changes influence forests directly. For example, drought and heat stress have been linked to increased tree mortality, shifts in species distributions, and decreased productivity (Allen et al. 2010; Van Mantgem et al. 2009; Williams et al. 2012). Climate changes also indirectly influence forests via wildfires, through changes in fire timing and seasonality, frequency, behavior, and spatial burn pattern (fig. 1). For example, fire frequency, fire season length, and cumulative area burned are all projected to increase in the coming decades in the Western United States in response to warmer, drier conditions (McKenzie et al. 2004; Flannigan et al. 2006). In addition, trees stressed by climate changes become more prone to changes in growth and survivorship that potentially increase the expressed severity of fires, even under constant fire behavior (Van Mantgem et al. 2018).

Climate changes can alter spatial distributions and amounts of fuel as a result of shifts in biotic properties of ecosystems such as dominant vegetation type, biomass, or structural stage (Lenihan et al. 2003; Loehman et al. 2011). As a further feedback to the interlinked climate, vegetation, and fire system, changes in wildfire regimes are likely to alter vegetation composition and configuration (Lenihan et al. 2003; Loehman et al. 2011) and thereby alter subsequent fire behavior and occurrence via shifting fuel mosaics. Climate changes may also increase the frequency or magnitude of climate patterns and extreme weather events that affect fire behavior and fire occurrence (Kurz et al. 2008; Lubchenco and Karl 2012; Littell et al. 2009; Westerling et al. 2016). Fire-vegetation feedbacks can be positive (amplify fire), such as when severe fires convert forests to shrub-dominated systems with denser, more continuous surface fuels that dry readily in the open conditions, or negative, such as fires that convert subalpine or boreal conifer forests to early-seral vegetation dominated by less flammable deciduous species (Tepley et al. 2018).

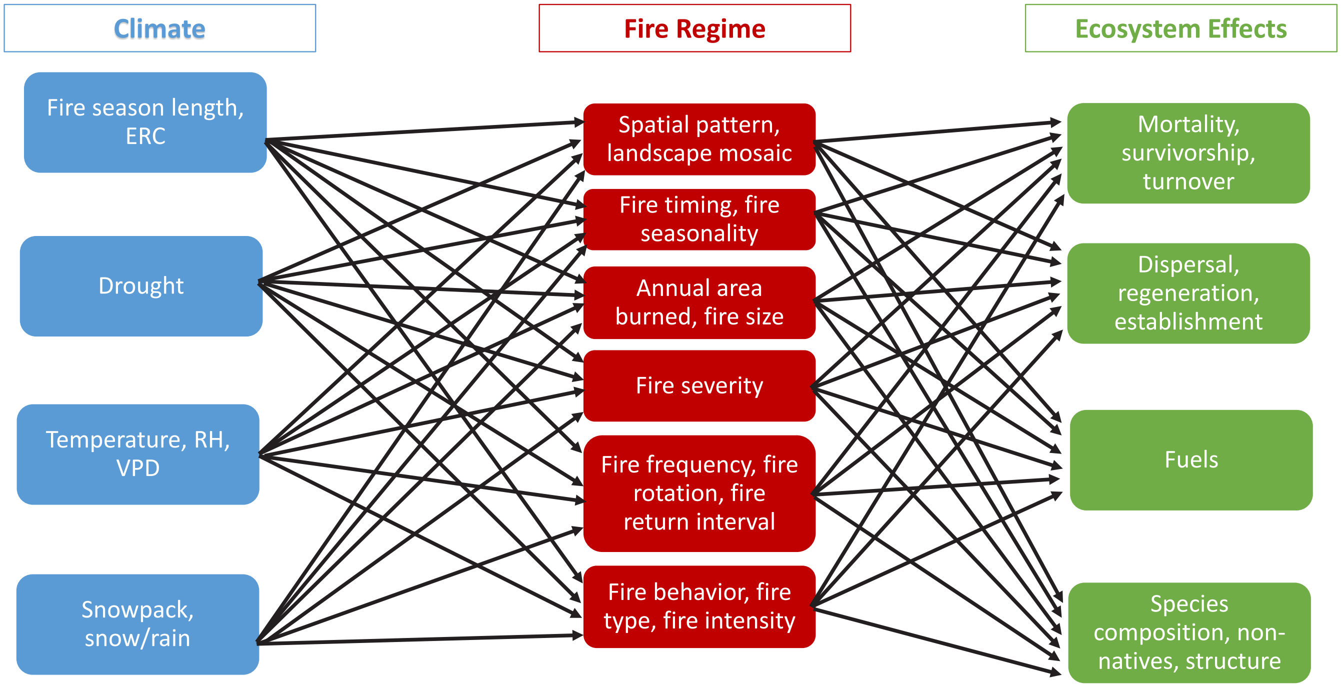

Figure 1—Diagram showing the inherent complexity in the climate-fire-ecosystem system. This diagram represents a simplification of the overall system in that it shows only the directional Climate→Fire regime→Ecosystem effects. Climate also has direct impacts for ecosystems and feedback exists between resulting ecosystem change and subsequent fire regime change (see text). This complexity challenges efforts to produce standard applications that can predict outcomes under various climate scenarios.

Despite these complexities, managers must develop long term plans and make site-specific decisions regarding the management of natural resources and wildland fire based on best available information and large-scale management objectives. One process used to support management decisions in light of uncertainty is vulnerability assessment (VA). Vulnerability assessments identify the relative susceptibility of resources to negative impacts as a result of a perturbation. Though VAs vary considerably in form and mechanics, all consider the degree to which a resource is affected by a potential disturbance or set of disturbances and the capacity of that resource to resist or cope with the resulting impact. The flexibility of vulnerability assessments has led to their use in a wide variety of studies focused on species, ecosystems, and resources (e.g., Foden et al. 2018; Friggens et al. 2013; Furness et al. 2013). Vulnerability assessments are used widely by resource managers to identify relative strengths and weaknesses among a suite of resources and to prioritize management actions. Designed to communicate and compare complex interactions and uncertainties, VAs are useful for comparing outcomes under varying environmental conditions or management practices. To date, VAs have not been used to evaluate the interactive effects of climate and fire regime changes on landscape components (though Thorne et al. 2018 do include wildfire as a stress factor in their assessment of forest vulnerability to climate change). Given the benefits of using VAs for management decision-making under uncertain futures, we have developed a tool to assess vulnerabilities and resiliency within the climate-fire-ecosystem complex. This tool, the FireCLIME (Fire-Climate-Landscape Interactions in

Montane Ecosystems) Vulnerability Assessment (VA), provides a flexible and rapid method for managers who wish to assess climate-related vulnerability in dynamic ecosystems. The FireCLIME VA can be implemented using information from a variety of data sources (literature, management plans, and modeling). The modules help identify effective management strategies for reducing climate-fire impacts (see *Section II. Instructions*).

The sections below describe the design and implementation of the FireCLIME VA. We developed the VA as part of a coupled research-management partnership (Joint Science Fire Project #15-1-03-26) to improve understanding and management of ecosystems in the Southwestern United States; thus, our examples and background information describe climate-fire-ecosystem dynamics in this region. However, as noted, the VA can be applied to other systems where these dynamics are of interest. The Southwestern United States is a highly relevant region in which to develop this tool because its fire-prone and fire-adapted ecosystems have been heavily impacted by a history of management, and climate impacts across all ecosystems are pervasive (Box 1).

Box 1—Ecological Consequences of Anthropogenic Changes to Fire Regimes in the Southwestern United States

Although wildfire is an integral part of Southwestern ecosystems, pre-European era fire regime characteristics, including fire frequency, have been altered by more than a century of livestock grazing, logging, and fire exclusion (Swetnam and Baisan 2003). As a result, many forests, particularly dry conifer forests adapted to frequent (typically, fire return intervals < 35 years), low-severity fire, are currently more dense, with increased surface fuel loads and reduced structural and spatial heterogeneity, than in the past (Covington et al. 1997; Allen et al. 2002; Schoennagel et al. 2004; Reynolds et al. 2013). Altered fuel characteristics—e.g., higher loading, increased horizontal and vertical continuity—along with increased seasonal temperatures and decreased moisture increase the likelihood that fires in these forests will be more intense with larger patches of high-severity fire than occurred historically (Littell et al. 2009; Abatzoglou and Kolden 2013; Abatzoglou and Williams 2016; Keyser and Westerling 2017; McKenzie and Littell 2017; Schoennagel et al. 2017; Holden et al. 2018; Keyser and Westerling 2019) and further reduce biodiversity and ecological function (Turner et al. 1994; Allen et al. 2002). Anthropogenic-related climate change is also associated with increased fire season length (the time between the reported first wildfire discovery date and the last wildfire control date) (Westerling et al. 2006; Miller et al. 2011) and increased regional fire synchrony in association with prolonged droughts (Westerling and Swetnam 2003; Heyerdahl et al. 2008; Littell et al. 2016).

FireCLIME VA Tool Overview

Fire-climate interactions are complex and mediated by climate effects on vegetation productivity and resulting fuel loads, fuel conditions, and environmental conditions at the time and place of ignition (fig. 1). The FireCLIME Vulnerability Assessment (VA) tool scores ecosystems based on current and future expected climate-fire-vegetation relationships as they relate to user inputs about desired future conditions to provide inference into which management strategies may be most effective for reducing risk under changing climate conditions. By identifying which fire regime and ecosystem components are most likely to be affected by climate, and which treatments are able to mitigate impacts, the FireCLIME VA can provide information critical for planning under changing fire regimes and fuel conditions.

Application

As designed, the FireCLIME Vulnerability Assessment Tool (FireCLIME VA_beta) works across multiple ecosystem types and multiple spatial scales (e.g., regional or local). The tool is amendable to different data sources (e.g., published literature and expert knowledge) and can be used with or without climate model inputs. The FireCLIME VA tool requires detailed but widely available information on climate trends and ecosystem and fuel properties (table 1), but does not require site-specific quantitative data on these trends and properties. The tool can be used to make several types of comparisons (fig. 2) and vulnerability is measured in context of potential departure from desired future conditions (DFC), where DFC is defined by the user. By using the FireCLIME VA, managers can calculate the relative vulnerability of different ecosystems to similar fire-climate scenarios (for example, “Which of my forest types is most vulnerable to change?”), compare multiple climate and management scenarios (“Which treatments are most effective for reducing vulnerability under future climates?”), and identify the critical drivers of climate-fire and fire-ecosystem responses (“What aspects of the fire regime are most sensitive to climate change?”).

Output from the tool includes scores for overall vulnerability of an ecosystem (risk of departure from DFC) and scored values of impact relating to fire regime change and ecosystem response (see Section III. Interpretation). Several measures specific to individual component impacts are also produced, which can be used to identify components with the greatest likelihood to be negatively affected by expected changes in climate-fire processes (fig. 3). Finally, for each question, users are asked to rank their confidence for each response based on the amount of information available to answer the question and the robustness of that information. Confidence scores are then presented in charts so that users can quickly assess which components and scores are based on adequate knowledge and which may need further information.

Table 1—Types of data needed to complete FireCLIME VA.

Data inputs	Purpose
Climate scenarios	Identifies potential exposure via change in climate variables with direct influence on fire behavior
Historic fire and management regime	Provides basis of comparison and initial conditions that might influence vulnerability
Current conditions	Identifies status and conditions that may indicate increased sensitivity (reduced resilience)
Desired future conditions (DFC)	Identifies basis by which vulnerability is measured. All entries are based on whether changes will bring component further or closer to DFC.
DFC: Fire regime	Identifies management objectives in order to structure analysis of whether exposure leads to undesirable outcomes
DFC: Ecosystem	Identifies management objectives in order to structure analysis of whether exposure leads to undesirable outcomes
Response of fire regime, ecosystem and fuel components to climate	Responses translate to potential exposure, sensitivity, and adaptive capacity of each component, which are tallied to quantify impact and ultimately vulnerability
Information on Treatments	Identifies the purpose and parameters of treatments in order to structure analysis of treatment effectiveness

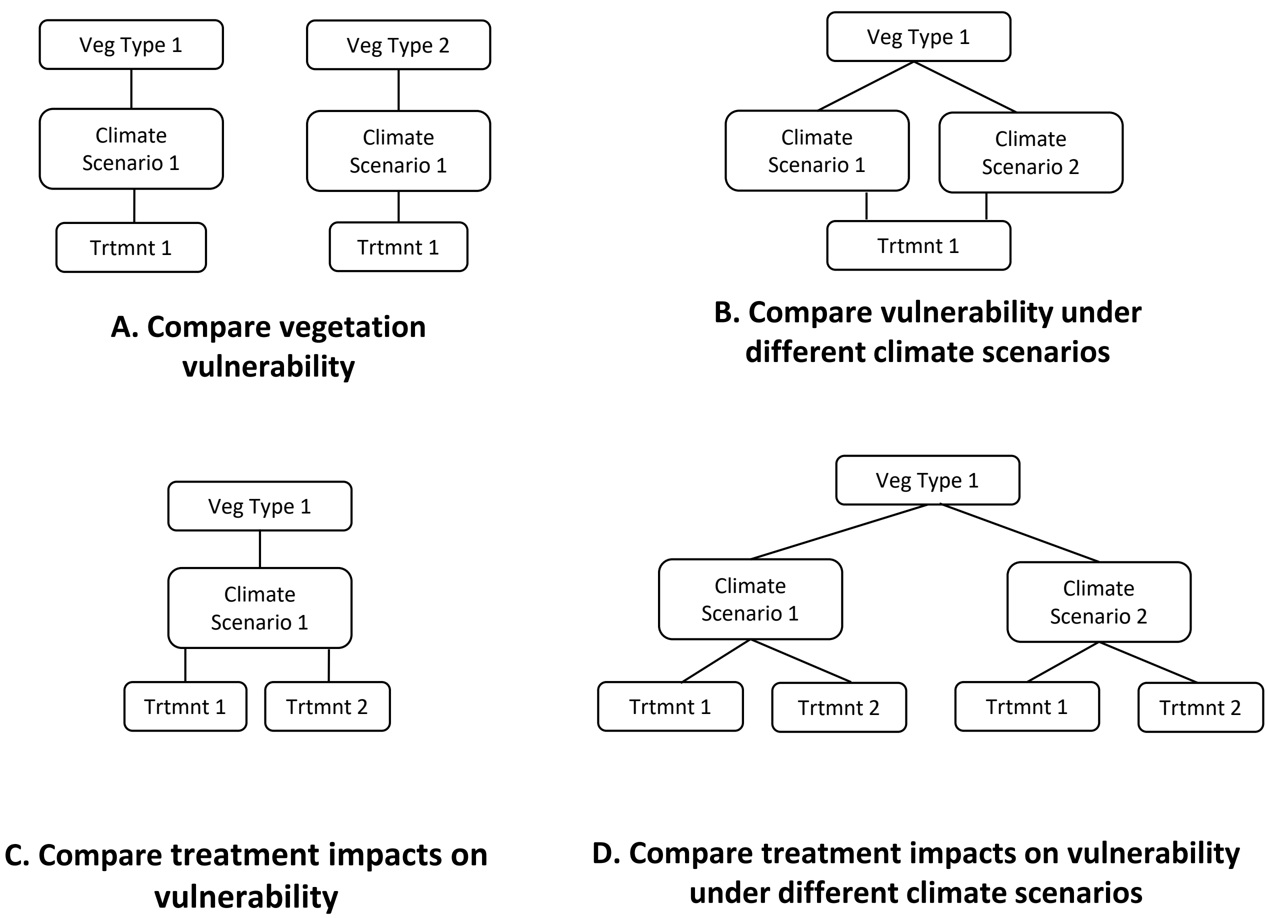

Figure 2—Examples of comparisons that can be made using the FireCLIME VA.

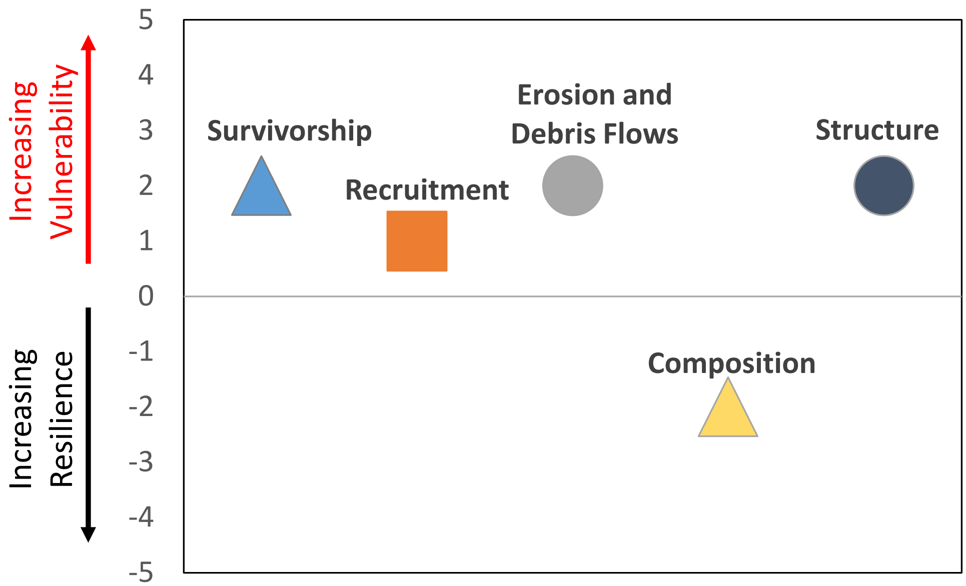

Figure 3—Example FireCLIME VA tool components chart showing the relative vulnerability/resilience of ecosystem components. In this example, composition appears most resilient to future expected changes in climate and fire regime.

Development

The inherent complexity of interactions among climate, fire, and vegetation/fuels challenges efforts to anticipate outcomes of management actions under future climate change. In light of these challenges, a science management partnership, SW FireCLIME (Southwest Fire-Climate-Landscape Interactions in Montane Ecosystems) was launched in 2015 (https://www.firescience.gov/JFSP_advanced_search_results_detail.cfm?jdbid=%24%26J7%3BT0%20%20%0A) to develop new knowledge and tools to identify management solutions despite uncertainties in future conditions. As part of underlying efforts to develop the FireCLIME VA, scientists identified the key interactions among climate conditions, fire regime components, and ecosystem effects (fig. 1). These components were then narrowed down to seven key climate variables, four fire regime characteristics, and eight landscape responses (table 2) through feedback during manager workshops and the application of a criteria-based selection process. We then used the resulting key variables to develop a tool that could quantify the effects, negative or positive, of climate on fire regime change and of fire regime change on ecosystem components. The definitions below highlight the relevance of each component to fire-ecosystem vulnerability.

Climate Variables

The VA tool includes climate components that (1) are identified as important in studies of Southwestern climate-fire interactions, (2) have sufficient data or information within scientific literature to enable judgment of impacts, and (3) are of relevance to fire management (table 2). In the Southwestern United States and elsewhere in fire-prone ecosystems, these components of the climate system significantly impact wildfire regimes in multiple and complex ways. For instance,

Table 2—Components used in the FireCLIME VA to measure climate-fire-related impacts to ecosystems at a landscape level.

	Landscape components		
Climate	**Fire regime**	**Ecosystem**	**Fuel properties**
Fire season length	High severity patch size	Survivorship	Fuel loading
Energy Release Component (ERC)	Fire frequency	Recruitment	Horizontal continuity
Drought frequency and duration	Soil burn severity	Erosion and debris flows	Vertical arrangement
Average summer temperature	Annual area burned	Species composition	
Relative humidity		Stand structure	
Snowpack or Snow Water Equivalent (SWE)			

drought increases water stress in plants and their susceptibility to fire-related mortality and contributes to drier fuels, but it ultimately reduces primary productivity and thus fuel loads (Littell et al. 2016; Sun et al. 2015). In the FireCLIME VA, the first step asks users to identify the expected change for the following climate variables.

Drought frequency and duration: Drought directly and indirectly influences wildfire regimes. Very dry forests in the Western United States are typically fuel-limited, so widespread fires occur during periods of increased productivity and fuel accumulation driven by increased growing season precipitation (Littell et al. 2009; Swetnam et al. 2003). Conversely, in more mesic forest types where sufficient fuel is typically available to carry fire but suitably dry conditions for fire spread occurred infrequently in the past (Schoennagel et al. 2004), persistent or frequent droughts may be sufficient to increase fire size and severity (O'Connor et al. 2014; Trouet et al. 2010). Drought conditions are associated with reduced live fuel moistures and increased fuel flammability; for example, prolonged dry weather conditions (about 40 days without precipitation) can dry live and dead fuels enough to carry large, intense fires once they are ignited (Riley et al. 2013; Schoennagel et al. 2004). However, persistent droughts can reduce plant growth and thus biomass (fuel) production, which paradoxically can reduce fire spread potential (Rothermel 1972; Westerling et al. 2003).

Average summer temperature: Summer temperatures can influence the timing of fires at regional scales (for example, regionally synchronous fires have generally occurred in the northern Rocky Mountains during years with relatively warm, dry summers) (Heyerdahl et al. 2008; Morgan et al. 2008), and fire starts and acres burned peak when temperatures are warmest, typically during July and August in much of the Western United States but as early as May and June in the Southwest (Westerling et al. 2003). Wildfire annual area burned (WFAB) is controlled by a number of climate variables including temperature, and in mountainous ecosystems in the Western United States, WFAB is high when year-of-fire temperatures are high (Littell et al. 2009).

Relative humidity: Relative humidity (along with precipitation, solar radiation, and temperature) relates to likelihood of fire where it influences fuel moisture in dead fuels such as litter and downed woody debris. In the absence of precipitation, dead vegetation (fuels) will dry out, converging toward ambient relative humidity over a period of days or weeks. The rate of change of the moisture content is dependent on the diameter of the fuel so that larger diameter fuels respond more slowly to changes in relative humidity (Fosberg 1971). Fire ignition is more likely when fuels are dry, and rates of fire spread are higher (Andrews et al. 2003; Rothermel 1972).

Fire season length: Fire season length (the time between the reported first wildfire discovery date and the last wildfire control date) impacts fire patterns by increasing the likelihood that ignitions—natural or human-caused—will occur during conditions conducive to fire spread. More spreading ignitions and longer periods of burning are likely to result in larger fires and increased annual area burned relative to contemporary recorded fire activity (Riley and Loehman 2016).

Snowpack or snow water equivalent (SWE): In mountains of the Western United States, snowpack controls the amount and timing of runoff, provides an important input to spring and summer soil moisture, affects temperature through surface albedo feedbacks, and influences fire activity (Pederson et al. 2011; Sheffield et al. 2004). Earlier snowmelt can lead to an earlier, longer dry season with more opportunities for large fires, and earlier snowmelt dates have been correlated with increased wildfire frequency (Westerling et al. 2006). Snowpacks keep fire danger low in semi-arid forests until the spring melt period ends, but once snowmelt is complete, forests can become combustible within a month because of low humidity and sparse summer rainfall (Running 2006).

Energy release component (ERC): The energy release component (ERC) is a part of the U.S. National Fire Danger Rating System (NFDRS) used to evaluate daily fire danger. The ERC serves as a proxy for fuel dryness or heat per unit area available to the flaming front (Cohen and Deeming 1985), and it captures effects of both seasonal climatology and daily weather on fire danger (Crimmins 2006). In general, the probability of ignition increases with ERC (Riley and Loehman 2016). In the Western United States, large fires tend to occur when ERC is above the 80th percentile, and the total number of fires and area burned increases exponentially with ERC percentile (Riley et al. 2013).

Fire Regime Components

The temporal and spatial patterns of wildfire (fire regime) have direct and indirect implications for ecosystems. Fire regimes are defined in terms of fire frequency, intensity, severity, size, pattern, and season (Agee 1998; Scott et al. 2007). The FireCLIME VA tool considers four primary components of fire regimes (table 2): annual area burned, fire frequency, mean high severity patch size, and soil burn severity (see Appendix 1 for definitions). Two of these components (fire frequency and annual area burned) are specific to the way in which a wildfire burns in an ecosystem, and two components relate to wildfire impacts (high severity patch size and soil burn severity). We considered these components best able to represent important processes within the ecosystem for several reasons. First, each component is ecologically important with known impacts within ecosystems. Second, they are commonly measured and used in management, indicating a high likelihood that there would be sufficient information for a user to determine impact. Finally, these fire regime components are likely to be influenced by climate.

Fire frequency: Fire frequency, or the number of fire events per unit time, is a key variable for measuring ecosystem vulnerability because it is one for which we have an extensive record (drawn from dendrochronology and other research). Fire history records allow for comparison of current conditions to the historical range of variability. In the Western United States, fire is typically most frequent in grasslands and open forests with an herbaceous component, less frequent in shrublands and mid-elevation forests, and least frequent in high elevation forests and wetlands. Fire frequency heavily influences which plant species or functional groups dominate in a given area. If fire is too frequent or infrequent to allow a species to complete its life cycle, that species will be excluded from the system (Hendrickson 1991). An example of this is the grass-fire cycle, in which frequent fires prevent open grasslands from succeeding to woody plant dominance (Bond et al. 2005). Depending on the regional species pool, fire can contribute to loss of woody species populations due to the increased frequency of fire areas invaded by nonnative grasses (D'Antonio and Vitousek 1992). The loss of frequent fire can also affect forest structure by allowing the densification of forests, which shifts the fire regime to higher intensity and more severe crown fires (Fulé et al. 1997). Therefore, fire frequency is often of concern to managers.

Annual area burned: Annual area burned is a useful measure of climate change impact on an ecosystem via wildfire because annual area burned is directly tied to climate conditions. In Southwestern ecosystems, annual area burned is strongly regulated by combinations of both fire-year and antecedent (preceding year) conditions, particularly drought (as expressed by the Palmer Drought Severity Index, PDSI) and seasonal precipitation (Littell et al. 2009). Area burned is sensitive to these climate drivers primarily because the combination of prior-season precipitation and current drought promotes fire spread over large areas. In most of the Western United States and in the Southwest, the total number of fires and annual area burned have increased since 1984 (Dillon et al. 2011; Dennison et al. 2014), causing concern among managers. The impacts of such increases can be variable; increases in annual area burned may reduce tree mortality for some frequent fire ecosystems, or drastically increase mortality if fire intensity is outside of the historic range of variability. Projections of future area burned indicate substantial potential increases in wildfire area burned by mid-century, depending on the strength of the relationship of annual area burned with seasonal climate (Kitzberger et al. 2017). Options to regulate annual area burned will be needed where climate-related changes will negatively impact DFC.

High severity patch size: Burn severity, essentially fire-caused mortality, is a crucial fire regime variable because it can determine the future trajectory of the ecosystem. Further, the pattern and size of high burn severity patches are critical for understanding the magnitude of effects due to fire in an ecosystem. The size and severity of burn patches can affect tree seedling recruitment, herbaceous recruitment, and overall plant cover (Turner et al. 1994). With high tree mortality, the distance to the edge of a patch can greatly limit regeneration and recolonization after high-severity fire (Falk 2013). Bonnet et al. (2005) found little tree regeneration past 100 m from unburned forest following a high severity fire, with the farthest seedling at 180 m. Haire and McGarigal (2010) found low tree seedling densities postfire at all distances greater than 200 m. Beyond plant growth, soils and watershed effects are dependent on the intensity of a fire and by the amount of a watershed affected (Agee 1993). Large high severity patches can lead to runoff and soil erosion. Social values and viewsheds are also greatly affected by high severity patch size.

Soil burn severity: Soil burn severity refers to the degree of fire impacts on the physical, chemical, and biological properties of soil. Soil burn severity has long-term implications for ecosystem continuity because so much biological capital is tied up in soils—and can potentially be lost in fire events that severely alter belowground ecosystems. Both measures of fire severity, high severity patch size and soil burn severity, have profound social implications, which makes them metrics of concern for managers. Fire impacts on soils are dependent on fire temperature, intensity, duration, frequency, season, and topographical location (Wohlgemuth et al. 2018) and can vary spatially across a fire. Physical changes include changes in soil aggregation and thus soil bulk density, which affects soil porosity and water infiltration (Wohlgemuth et al. 2018). Chemical changes resulting from exposure to fire include nutrient volatilization, increased mineral mobility from ash, and changes in soil microflora. Biological changes happen with selective mortality of soil biota and changes in mycorrhizal relationships (Wohlgemuth et al. 2018). All these factors can affect erosion, plant growth, and recovery and hydrologic responses.

Ecosystem Components

Ecosystems respond to the interactive effects of climate and wildfire and, in turn, influence wildfire outcomes. A major challenge in the development of the FireCLIME VA tool centered on this circularity. For instance, fire severity is clearly an important fire regime characteristic but is also a good measure of ecosystem response. To represent ecosystem response, we include five components (table 2; see Appendix 1 for definitions). As with the fire regime components, we considered the relevance of each indicator to management, the availability of information on a given component, whether the component was likely to be impacted by changes in climate and fire regimes, and whether changes in the ecosystem component were likely to impact fuels and, consequently, feedback into fire regime response.

Species survivorship and species recruitment: These are two primary mechanisms that drive changes in biotic ecosystem characteristics—including species composition and stand structure. Species survivorship refers to local vegetation 1-year postfire, a time period that was chosen to distinguish this measure from the fire severity component. Species survivorship and species recruitment are strongly influenced by climate and fire. Low survivorship is a central concern with altered fire regimes (Abella and Fornwalt 2015; Shive et al. 2013) and drought in the Southwest (Allen and Breshears 1998). Species recruitment is also highly dependent on fire characteristics and climate variability (Brown and Wu 2005; Shive et al. 2013).

Erosion and debris flows: These are key abiotic ecosystem components that influence ecosystem responses to fire. Erosion and debris flows are a major concern for managers as they threaten human lives and property. They are also capable of degrading soils, which require long recovery times and may alter ecosystem conditions and function for decades or longer (Neary et al. 2005). Postfire debris flow risk increases due to vegetation loss and soil exposure, and is generally triggered by surface erosion caused by rainfall runoff or land sliding caused by rainfall seeping into the ground (USGS 2018). Consumption of trees, shrubs, forbs, grasses, and forest litter by fire changes the susceptibility of the underlying soil to erosion during postfire summer convective thunderstorms (MacDonald and Robichaud 2008). Furthermore, fire severity is expected to increase in response to higher temperatures associated with climate change (Dillon et al. 2011), likely increasing rates of erosion and debris flows (Pelletier and Orem 2014).

Species composition and stand structure: These are important biological characteristics of forest ecosystems that can be altered by both climate and fire, and subsequently alter fuel properties and future fire regime characteristics. Species composition and stand structure are often the focus of management interventions and are well-studied in the fire impact literature. For example, the restoration of Southwestern ponderosa pine ecosystems often focuses on the creation of low-density forest structure that approximates pre-settlement conditions and promotes fire resilience (Reynolds et al. 2013; Swetnam et al. 1999). Compositional change can be a major concern in the absence of fire as species with life history traits adapted to longer fire intervals invade an ecosystem (Cocke et al. 2005) or following high severity fire when persistent shrub species may become established and impede the reestablishment of trees (Guiterman et al. 2018).

Fuel Components

Fuel components integrate climate, ecosystems, and fire behavior processes. Fuel components are important for assessing ecosystem vulnerability to climate-fire interactions because their characteristics along with weather (climate) and topography determine fire behavior and, thereby, influence ecological fire effects. For the purpose of quantifying landscape effects of climate-fire interactions, we include fuel response (closer to or further from desired conditions) to climate and fire regime change. Horizontal continuity, fuel loading, and vertical arrangement (see Appendix 1 for definitions) are important considerations in most management plans. Including fuel responses within the FireCLIME VA facilitates our capacity to identify effective treatments.

Horizontal continuity: Horizontal fuel continuity relates to fuels that are close to or in contact with each other, providing a continuous path for fire spread where fire is not halted by or does not have to spread around discontinuities. Generally, patchy fuels will decrease the spread rate and fire intensity and be more resistant to fire ignitions and spread compared to a continuous fuel arrangement.

Fuel loading: The higher the fuel loading (fuel mass per unit area), the more energy that is potentially available for the combustion process. However, a higher fuel loading may decrease the rate of spread as the pre-heating of larger fuel sizes to ignition temperature will take longer, creating a bigger heat sink (van Wagtendonk 2018). Higher fuel loads in forest systems can create more heat and can increase the flame lengths, making it easier to pre-heat canopy fuels and allow the transition to crown fire.

Vertical arrangement refers to the upward distribution of fuels in a vertical dimension. Any fuel situated above a burning fuel is subject to strong convective heating as well as to radiant heating. Vertical fuel arrangement can increase airflow to the flame as well as increase exposure to wind. Finally, ladder fuels, a term that describes material on or near the ground (e.g. flammable shrubs, dead surface wood, branches, dead foliage, conifer limbs touching or close to the ground, and dead lower branches with foliage attached), may facilitate the spread of fire to the canopy.

Design and Structure

Once the underlying indicators of ecosystem vulnerability to climate-fire impacts were established, we engaged in an iterative process to develop a method to describe potential outcomes of climate, wildfire, and ecosystem processes and interactions within the context of a VA framework. For a given VA, each step in the assessment process quantifies system response to a disturbance in order to infer something about the magnitude of negative impact. Therefore, a critical first step in the development of a VA process is to clearly define what is considered a negative impact from that disturbance. Since this tool is meant to be used by managers to inform decision-making, negative impacts are identified in context of desired future conditions. Desired future conditions (DFC) are defined by a manager and based on their specific objectives for the ecosystem. Desired future conditions can be defined using planning documents or through scenario planning or other exercises (see Section II. Instructions), and are specified for each fire regime characteristics and each ecosystem and fuel component.

Vulnerability is defined as the susceptibility of a system to negative impacts from a disturbance. Definitions of vulnerability can vary among applications; we have aligned ourselves with those identified by the IPCC (2007) and modified the vulnerability equation to account for the dynamic interactions between climate-fire-ecosystem interactions. Another feature important to the FireCLIME VA is the ability to gauge the potential for management actions to mitigate vulnerability. Therefore, we distinguish between intrinsic and externally (management actions) driven sources of adaptive capacity or resilience within the system (fig. 4). The FireCLIME VA is based upon the following defined parameters:

- **Exposure** considers climate impacts on fire regime (change or no change) and the trajectory of fire regime components with respect to DFC (departed or not).
- **Intrinsic sensitivity** describes current conditions within the ecosystem that are likely to increase the negative response of the ecosystem to change in climate or fire regime.
- **Response sensitivity** occurs when an ecosystem or fuel component is expected to experience departure from DFC as a result of expected changes and trajectories of fire disturbance.
- **Intrinsic adaptive** capacity (resilience) occurs when an ecosystem or fuel component is expected to benefit or move toward DFC as a result of expected changes and trajectories of fire disturbance.
- **Extrinsic adaptive** capacity relates to the potential for management action to reduce vulnerability.

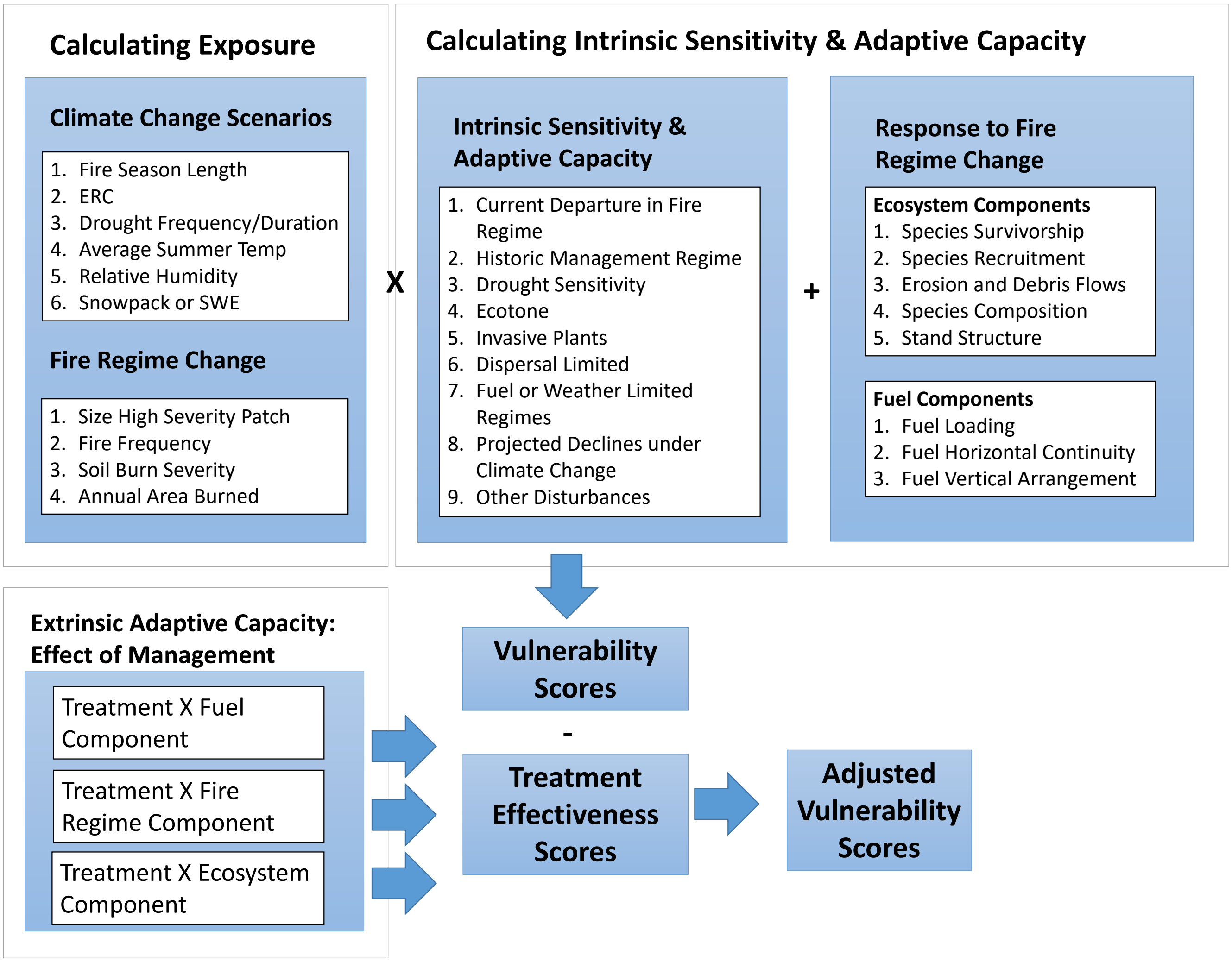

Figure 4—Diagram showing underlying inputs for each element of the FireCLIME framework and major outputs. Vulnerability scores may be used on their own to infer something about ecosystem vulnerability. One to three treatments can also be considered and will result in adjusted vulnerability scores. Pre- and post-treatments scores are then compared to assess treatment effectiveness.

The FireCLIME VA bases its estimate of exposure on the expected relationship between climate and fire regime change and whether a particular fire regime change leads to a departure from DFC. There are no assumptions regarding the nature of fire-climate interactions and exposure scores can reflect a number of outcomes (Appendix 2). For the purpose of calculating vulnerability, only those scenarios that result in a condition likely to negatively impact ecosystems are carried forward in the tool calculations as exposure values. For instance, climate must result in a change in a fire regime component that shifts it away from desired future conditions in order to be considered part of exposure. If climate is not expected to change the fire regime but the state of the fire regime is still considered to be moving away from desired future conditions, then exposure still exists. However, if the fire regime is determined to be neither changing nor moving away from desired conditions, then that fire regime component will not contribute to the final vulnerability score. In effect, the final results will show no impact from static or desirable fire regime elements.

Intrinsic sensitivity and adaptive capacity are calculated from the expected response of ecosystem components to fire regime change (Appendix 2). Because impacts of fire regime change will not always be negative, the FireCLIME VA allows both positive (move toward DFC) and negative (further departure from DFC) ecosystem response to fire regime change. In turn, these responses are scored in such a way that further departure contributes to increased vulnerability and reduced departure results in less vulnerability. This, in effect, is treating the response variables as measures of sensitivity (negative response expected) and adaptive capacity (positive response expected). In most vulnerability assessments, sensitivity is not necessarily the inverse of adaptive capacity.

To reduce redundancy in an assessment, it is advisable to attribute the presence or absence of some measure to either sensitivity or adaptive capacity. We avoid potential duplication by assigning each response component a value of -1, 0, or +1, where -1 is a positive response (closer to DFC) and +1 is a negative response (further departure) (see Appendix 2 for more detail). Each response can be assigned only one score and that score either decreases or increases the final vulnerability score. If multiple components are expected to respond positively to fire regime change, the collective ecosystem component score will be more negative, whereas a majority of components scoring as further departed will result in a larger score indicating greater vulnerability.

In addition to response scores, the FireCLIME VA considers intrinsic characteristics of the study ecosystem that may lend it greater sensitivity to disturbance (fig. 4). Unlike the response scores, which deal with individual components within the ecosystem, intrinsic measures of sensitivity typically describe conditions that affect the entire ecosystem or landscape. For instance, the presence of invasive species or other disturbances like insect outbreaks may predispose forests to decline or depart from DFC under changing climate and fire regimes. Intrinsic measures of sensitivity are tallied and added to the response scores, resulting in a baseline vulnerability score. Because current departure in fire regime influences a given ecosystem's potential resilience to further disturbance, current departure in fire regime contributes to ecosystem sensitivity scores (fig. 4).

Finally, we include a method for considering how externally driven actions (e.g., fuel treatments) influence landscape vulnerability (fig. 4). To estimate extrinsic adaptive capacity, FireCLIME VA calculates management impact for fire regime, ecosystem, and fuel components in context of DFC. Where management actions bring a component closer to DFC, extrinsic adaptive capacity is increased and vulnerability is decreased. A primary outcome of FireCLIME VA is this estimate of how well a treatment is able to reduce vulnerability. Where treatment results in a reduced vulnerability, extrinsic adaptive capacity (and potential success of management) is higher. Importantly, FireCLIME VA only considers potential positive impacts of management actions (Appendix 2) and is not an appropriate tool to use where the goal is to weigh the pros and cons of a particular treatment (Box 2).

Box 2—What the FireCLIME VA is … and is not

FireCLIME VA provides a flexible and rapid assessment method for exploring ecosystem response to climate-fire interactions and to potential management interventions.

FireCLIME VA *can* describe outcomes from dynamic climate-fire-vegetation interactions and from management approaches designed to reduce undesirable outcomes.

FireCLIME VA *can* help users understand complex interactions of plants-fire-climate by highlighting key components.

FireCLIME VA *can* assess vulnerability at landscape levels.

FireCLIME VA *can* estimate the impact of climate-related changes in wildfire on a wide range of ecosystems.

FireCLIME VA *can* produce quantitative estimates of relative vulnerability. Values can be used to compare vulnerability between ecosystems or scenarios.

FireCLIME VA outputs *cannot* provide predictions of future ecosystem outcomes (e.g., percent loss of suitable habitat).

FireCLIME VA *cannot* inform project level decisions for fire regime components not addressed in this tool.

FireCLIME VA *cannot* quantify expected changes in ecosystem or fuel properties within a landscape.

FireCLIME VA *cannot* model or produce projections of expected future conditions or fire regimes.

FireCLIME VA *cannot* identify desired future conditions.

II. INSTRUCTIONS

FireCLIME VA is available as a macro-enabled Excel file. Within this file are worksheets containing pre-work exercises and modules for collecting responses on expected changes and impacts within the ecosystem of interest. Individual modules focus on estimates for exposure, intrinsic sensitivity, and adaptive capacity and treatments (fig. 5). Users can rank the importance of fire regime, ecosystem, and fuel components (table 2) to customize outputs given management goals and/or mechanisms driving climate-fire-vegetation response (see Appendix 2 for more details). Results are presented in the form of graphs and tables and several sheets are dedicated to displaying the input responses so that users can quickly review their work. The following sections are organized by the worksheets in the Excel file. Within each section, we describe what type of information should be used and important considerations for the tool application. This document is meant to complement the instructions already provided in the tool itself. We suggest that you refer to the following instructions while exploring the referenced sections in the tool.

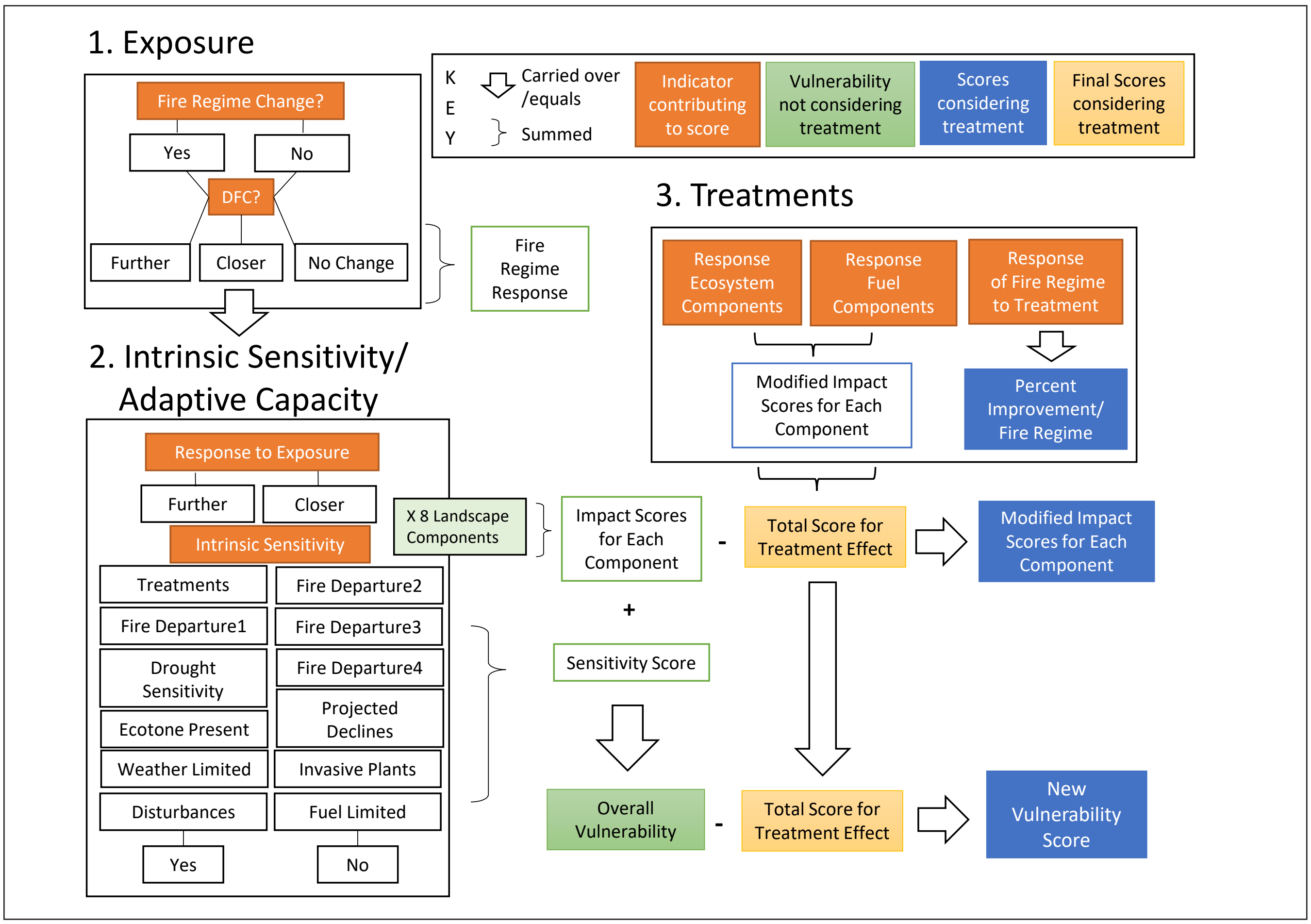

Figure 5—Diagram outlining workflow for FireCLIME VA. Users estimate exposure by considering climate impacts to four fire regime characteristics and the implications of potential changes with respect to desired future conditions (1. Exposure). This gives an exposure score that is then carried over and multiplied by scores created from user input regarding ecosystem condition and expected response to fire regime change (2. Intrinsic Sensitivity/Adaptive Capacity). The resulting Overall Vulnerability score can be used in a stand-alone fashion as a baseline assessment of ecosystem vulnerability. Treatment impacts are quantified as impacts to individual fire, ecosystem and fuel components (3. Treatments). Impacts of treatments on fire regimes are reported as separate percent improvement values. Individual and summed treatment effect scores are subtracted from component impact and overall vulnerability scores, respectively, to generate modified scores for ecosystem and fuel components and overall ecosystem vulnerability.

Pre-Work Worksheet

Worksheet 1. Prework

The FireCLIME VA can be implemented using a combination of expert opinion, literature review, or field data. Table 1 presents the major classes of data required to run the tool. Though the tool is amendable to a variety of data inputs and sources, we make recommendations for sources for each type of information in the next few sections. For the most part, these recommendations regard specific instances where manager input is required. The FireCLIME VA is most easily implemented when the basis upon which vulnerability is to be measured is explicitly outlined. Specifically, users need to have a clear understanding of their desired future conditions for fire regimes and ecosystems and must identify desired outcomes or goals of management treatments. Vaguely phrased goals or DFC will lead to ambiguity in potential responses within FireCLIME and reduce user capacity to distinguish differences in vulnerability.

Climate Scenarios

The first step in the vulnerability assessment is to outline a future climate trajectory for your landscape/ecosystem. A climate scenario can be described in many ways depending upon the need or question (e.g., contemporary, RCP 4.5, RCP 8.5, warmer-drier, warmer-wetter, and so on) (Santoso et al. 2008). Santoso et al. (2008) and Charron (2014) provide guidelines for scenario preparation. For the FireCLIME VA tool, the scenario description can be generalized but should include trends for the following six climate variables: fire season length; mean (peak) Energy Release Component (ERC); mean annual summer temperature; relative humidity; drought frequency and/or duration; and snowpack or snow water equivalent (SWE). The relevance of these climate variables for the FireCLIME VA tool are discussed within the Development section of this manual. Valid future climate scenarios may be informally based on hypothetical scenarios or rely on modeled output reported through a variety of sources. Among the suggestions presented within Santoso et al. (2008) and Charron (2014), perhaps the most relevant for this tool is that the climate information used to make a scenario should match the level of expertise of the decisionmakers. Additionally, whatever the form of the scenario, it is important to remember that decisions will be most robust if they are developed based on a range of future conditions (Charron 2014). Therefore, we recommend considering multiple scenarios before drawing conclusions about ecosystem vulnerability. A few useful sources for climate scenarios include:

- The Intergovernmental Panel on Climate Change (IPCC) reports (narratives and graphs by region)
- Climate Wizard (specific climate variables)
- Prism High-Resolution spatial climate data for the United States (specific climate variables)
- The Global Climate Change Viewer (USGS)
- NorthWest Future Climate Scenarios (for year 2100 based on RCP 8.5 and 4.5)

In addition to the specific variables used in this analysis, other conditions—for instance, extreme events—may be included in the scenario.

Landscape Characteristics, Desired Future Conditions, and Management Scenarios

The FireCLIME VA tool works best when the user outlines specific desired future conditions and the purpose for assessing vulnerability (e.g., compare ecosystem vulnerability, assess vulnerability under different climate futures, or compare ability for treatments to reduce vulnerability). On the Pre-Work worksheet, modules prompt the user to describe the study landscape and specify their environmental conditions and management goals (desired future conditions) for the landscape (table 3). Vulnerability is calculated based on the difference between desired conditions and current and future expected departure from those conditions. Treatment effectiveness is determined by considering how well the treatment brings a fire or landscape component closer to desired conditions. Desired future conditions (DFC) may relate to a variety of management goals over a wide range of geographic and temporal scales. The more precise the goals outlined for a landscape, the more informative the vulnerability score. For instance, generating a scenario 30 years in the future with vague definitions of desired conditions will produce an equally vague vulnerability score.

Table 3—Types of information used to describe Desired Future Conditions (DFC) and management goals. This information can come from environmental impact statements, planning documents, local manager input, or a hypothetical situation.

Landscape description	Management scenarios
Basis of DFC: reference (historical) conditions, climate adapted, management goals, etc.	Treatment strategy: single large or multiple smaller application?
Ideal/desired fire regime	Seasonality: growing/dormant?
Ideal/desired seral stage, species composition, stand structure	Annual area treated?
Ideal/desired fuel structure, composition, and loading	Percent of total area treated?
Outcome date: mid-century, 10 years, etc.[a]	Type: first entry or multiple burns?
	Time period: how many applications?
	Duration of treatment: how many years?

[a]Outcome date refers to the time period for which this assessment is being conducted and also relates to management goals. Outcome date is included within the landscape description so that users are directed to consider an end point of the assessment even in the absence of considering treatment alternatives.

Tool Worksheet

NOTE: Reference to sections, figures, and tables in the FireCLIME VA tool are italicized below to distinguish them from similarly referenced items within this document.

Worksheet 2. Tool

This receives the bulk of the information used to estimate impact and vulnerability scores, which are reported on *Worksheet 3. Results*. To calculate impact and vulnerability, the user must complete the series of tables and forms by selecting responses using either check boxes or from a prepopulated list. Inputs on the Tool worksheet are organized within three sections: (1) Fire Regime Response (*tables 1.1-1.3*); (2) Ecosystem and Fuel Response (*table 2.1; Modules 2.1 and 2.2*); and (3) Response to Treatments (*Modules 3.1-3.3,* optional). Section 4 contains the weighting schemes and is optional. Additionally, three worksheets in this file, *Notes.PreWork*, *Notes.Response*, and *Notes.TreatmentResponse*, automatically copy user inputs to provide a quick method for concisely reviewing entries.

Section 1. Fire Regime Response

Section 1 consists of three tables that ask for information on current fire regime characteristics, expected changes due to climate, and the impact of those changes relative to DFC. For each response, users should indicate confidence using a numerical score where "1" indicates low confidence, "2" indicates moderate confidence, and "3" indicates high confidence. Additionally, here and throughout the tool, space for comments has been provided. It is strongly suggested that the user take advantage of these spaces to record information on assumptions and reasoning for response decisions, especially where multiple iterations of the tool are being conducted.

Table 1.1 asks the user to indicate the current status of each of the four fire regime components: mean high severity patch size, fire frequency, soil burn severity, and annual area burned. Users should consider whether each fire regime component currently falls within the range of desired conditions (reference, adapted landscape, etc.). This information will contribute to the sensitivity score for the ecosystem such that ecosystems with already departed fire regimes will receive higher sensitivity scores. The next two tables are used to calculate exposure using the expected change of each fire regime component to climate change and the implications of that change with respect to DFC. Here, the user should indicate responses by checking the appropriate boxes and then rating confidence in the blue boxes. *Table 1.2* asks the user to indicate whether the collective impact of climate changes (completed during pre-work exercises) will increase, decrease, or result in no change in each fire component. Over time, fire regimes may experience both increases and decreases as a result of climate changes. Often, these conflicts will be most apparent if the assessment period covers a long span of time. To reduce potential ambiguity in trends, users should focus on the designated assessment outcome date (recorded during pre-work) and focus on the types of changes that are most likely by that point in time. In addition, various climate changes may have conflicting impacts on a fire regime. In these situations, the most appropriate action is to select the trend that is most common or likely. Alternatively, the user may run additional iterations of the tool using alternative scenarios (e.g., assuming fire frequency increases and then assuming fire frequency decreases).

Table 1.3 asks the user to identify whether the trends indicated in *table 1.2* will lead fire regimes further away from or closer to DFC. Again, trends in fire regime responses may not always be clear and the user should balance responses to reflect the most likely outcome with respect to desired conditions and the identified end point or outcome date of the vulnerability assessment.

Section 2. Ecosystem and Fuel Response

In this section, we gather information that is used to measure ecosystem sensitivity and adaptive capacity to fire disturbances and to climate-related changes in fire regimes.

Table 2.1 considers various characteristics of the ecosystem that might lend it greater sensitivity to disturbances. Users may only indicate a yes or no response for each question. Not checking a response will have the same effect as checking no; no sensitivity will be indicated for that indicator.

Modules 2.1 and *2.2* record individual ecosystem and fuel components responses (further departure from DFC, closer to DFC, or no change) to expected changes in fire regimes that may reflect sensitivity or adaptive capacity. For these and other modules, confidence is indicated by selecting low, mod (moderate), and high. *Module 2.1* considers the influence of fire regime change on five ecosystem (species survivorship, species recruitment, erosion and debris flows, species composition and stand structure) components. *Module 2.2* considers the influence of fire regime change for three fuel components: fuel loading, fuel horizontal continuity, and fuel vertical arrangement. Here, users indicate whether fire regime change will drive components further or closer to DFC. Where responses are not known or mixed, users should select "no change" and indicate low confidence.

Section 3. Response to Treatments (Optional)

Section 3 consists of three modules relating to potential management effects for fuel components (*Module 3.1*), fire regime components (*Module 3.2*) and ecosystem components (*Module 3.3*). All three modules are similarly organized. Each asks the user to rate on a scale from poor through excellent (corresponding to a score of 1 to 5) how well the treatment was able to bring each component closer to DFC. If a treatment has a negative impact (moves a component further from DFC), a response should not be provided. The FireCLIME VA tool does not incorporate potential negative impacts into its estimates of treatment effectiveness. However, leaving the selection blank will ensure that the treatment does not show at least some improvement (i.e., poor rating gives a score of 1 not 0, see Appendix 2).

Module 3.1 considers the effect of treatments on fuel components. For each component, the user indicates how well treatment is able to improve fuel conditions (i.e., bring them closer to DFC). Unlike previous modules, this form is not asking the user to consider the response of fuel components with respect to fire regime change. Instead, it simply considers the impact of treatment on each fuel component with respect to desired future conditions.

Module 3.2 considers treatment impacts for fire regimes. This module provides the user with the original responses for fire regimes under climate change. The response should be selected that best describes the degree to which the treatment was able to bring the fire regime closer to desired conditions.

Module 3.3 considers the effect of treatment on ecosystem components. Unlike previous modules, this form is not asking you to consider the response of ecosystem components with respect to fire regime change. Simply consider the impact of treatment on each ecosystem component with respect to desired future conditions.

Section 4. Ranking Variables (Optional)

By default, fire, ecosystem, and fuel components are assigned equal weights and each component contributes equally to the total score (Appendix 2). Within the tool, each component is given an initial rank of 1 indicating it is contributing equally to the impact score within its category (fire, ecosystem, fuel). However, you may want to adjust these ranks under certain conditions. Ranks for individual components should be changed if one of the following criteria apply: you believe that some components will be more strongly influenced by climate changes than others, OR you believe that certain components have a stronger influence on desired future conditions, OR your management focus is on a certain component (e.g., to reduce fire frequency or increase species composition).

Ranking will affect scores by giving greater weight to components given a high ranking and assigning less weight to a component with low ranks. To change ranks, give the most important characteristics a score of 1, the next most important a score of 2, the next a score of 3 and so on. If some are equally important, give them the same number. For example, if you consider fire frequency and soil burn severity more important than other fire regime components, assign each a score of 1 and assign the remaining components a score of 2 (see Appendix 2 for more examples). Any combination is possible as long as you do not skip a value.

III. INTERPRETATION

Worksheet 3. Results contains three sections: Summary: Your Responses, Summary: Results, and Summary: Management Scenarios.

Summary: Your Responses

This section contains a review of your responses that describe the study area and change to climate and fire regimes. It also contains a summary of confidence scores for fire regime change. Each fire regime component can receive a score of 1, 2, or 3 indicating low, moderate, and high confidence, respectively.

Summary: Results

This section contains calculated responses for Exposure, Sensitivity, Impact, and Overall Vulnerability. With the exception of Overall Vulnerability, values reported in *table 2.1* are scaled to a range of -10 to +10, with higher scores associated with greater negative impact (contributing to greater vulnerability). Scores lower than 0 indicate that the net effect of expected climate changes will bring the fire regime or ecosystem closer to DFC. Overall Vulnerability values are presented on a scale of -7 to +10 (see Appendix 2). Scores reported in *tables 2.2 and 2.3* are also scaled -10 to +10, again with higher scores indicating a more negative impact.

Relative scores for Ecosystem, Fuel, and Fire components are presented in *figures 1-4.* Ecosystem and Fuel component scores are scaled -10 to +10 and reflect the response across all four Fire Regime components (*figs. 1 and 2*). Fire regime impact scores (*fig. 3*) are calculated as the total of all Ecosystem and Fuel component scores for each fire regime component. In other words, the score for high severity patch size is calculated by adding up all scores for ecosystem and fuel components' response to change in high severity patch size. *Figure 4* presents each Fire Regime x Ecosystem/Fuel response score. For unweighted schemes, each element has a possible score of -1, 0, or +1. In weighted schemes, the maximum score is 1.6 and minimum is 0.4.

Summed confidence scores are presented in *figures 5-7*. Each measure of Intrinsic Sensitivity (*fig. 5*) can receive a score of 1, 2, or 3 indicating low, moderate, and high confidence, respectively. Total confidence is presented for Ecosystem and Fuel (*fig. 6*) and Fire regime components (*fig. 7*). Ecosystem and Fuel response (*fig. 6*) confidence is tallied from each Fire Regime question and summed to result in a score with a minimum possible value of 4 (low confidence in response across all four fire regime components) and maximum value of 12 (high confidence in response across all four fire regime components). For example, a total confidence score for Survivorship sums all the confidence scores given for Survivorship to each of the four fire regime components. Fire-Ecosystem Response confidence (*fig. 7*) is tallied across all ecosystem and fuel components with a minimum possible value of 8 (low confidence across all eight components) and a maximum score of 24.

Summary: Management Scenarios

This section presents a table with the original and modified vulnerability scores as well as charts depicting impacts of treatments for each fire, ecosystem, and fuel component. Original vulnerability scores are presented on a scale of -7 to +10, with higher scores indicating greater vulnerability and modified values representing the magnitude change in vulnerability arising from treatment effects on component scores. Graphically displayed changes in vulnerability derive from the calculated difference between scaled values for each ecosystem, fuel, and fire regime component impact score. Therefore, a minimum score of -17 (original score of -7 indicating no or low vulnerability and maximal effectiveness of treatments to draw components toward DFC) and a maximum score of 8 is possible (maximum vulnerability score and poor treatment effect). If a treatment effect has not been recorded for a particular landscape component (because it has no or a negative impact on DFC), the tool outputs a default value of -25 and any components with this score should not be considered in the comparison. Summed confidence scores are presented in charts and are represented as described earlier.

Example

Several outputs are displayed on the *3. Results* sheet to help interpret results of vulnerability assessment. Figures 6-9 describe each type of output in greater detail.

Table 2.1. Scores	reported on scale of -10 to +10
Overall Vulnerability *	4.8
Overall Exposure	7.5
Instrinsic Sensitivity	8.5
Average Response Score	3.4
Average Impact	3.4

*Overall vulnerability scale is -7.04 to +10

Table 2.2. Scores-Components	reported on scale of -10 to +10
Survivorship	2.5
Recruitment	7.5
Erosion and Debris Flows	2.5
Composition	5.0
Structure	0.0
Fuel Loading	2.3
Fuel Horizontal Continuity	6.8
Fuel Vertical Arrangement	0.0

Table 2.3. Average scores for Components across each fire regime element	reported on scale of -10 to +10
Size of High Severity Patch	9.0
Fire Frequency	2.0
Soil Burn Severity	2.7
Annual Area Burned	0.0

Figure 6—Resulting scores for an example assessment. Overall, this system is vulnerable to future expected changes (score +4.8 out of a max of +10). Exposure and Intrinsic Sensitivity received the highest scores and thus drive vulnerability (*table 2.1*) and indicating this system is expected to be negatively impacted by changes in fire regime and it has a high number of characteristics associated with increased sensitivity. Average response and impact scores were positive but relatively lower than the maximum value of +10 reflecting varying (both positive and negative) responses at the scale of ecosystem and fuel components (*table 2.2*). *Table 2.2* presents the average score for each component across all four fire regime elements and *table 2.3* presents the average of ecosystem and fuel component scores by each fire regime. So, the score of "2.5" for Survivorship (*table 2.2*) represents the average scores for Survivorship across all fire regimes components and the score of "9" for the Size of High Severity Patch (*table 2.3*) represents the average response of all eight landscape components for that fire regime component. Note that within both *table 2.2* and *table 2.3*, some components received a score of 0 indicating a net 0 effect.

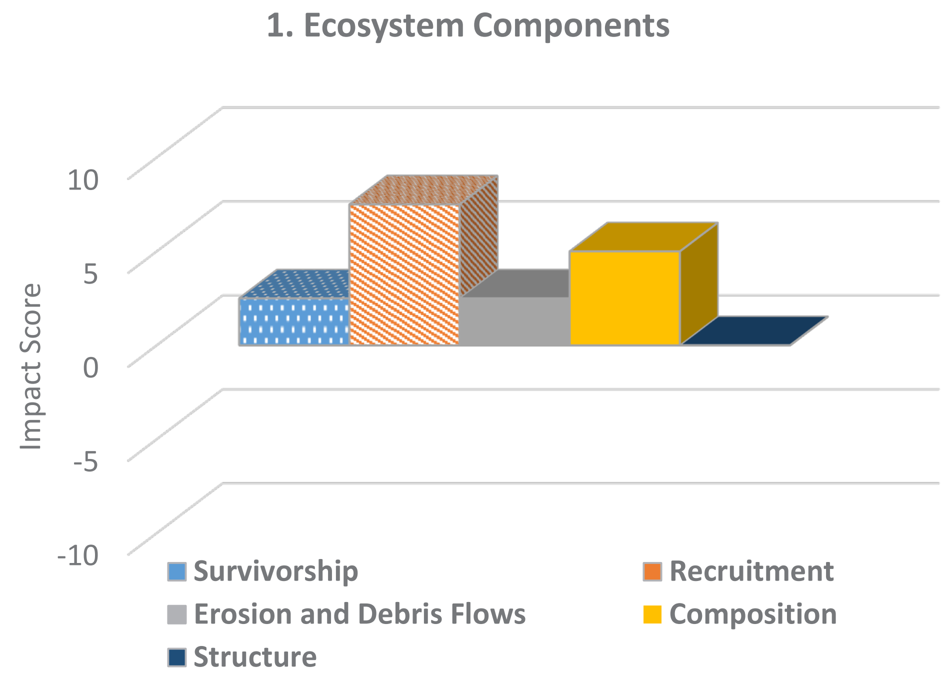

Figure 7—Ecosystem impact scores show that recruitment is likely to be most negatively impacted by changes to climate and fire regimes. Stand structure appears least likely to be negatively impacted as indicated by its very low (negative) score result. These results correspond to values presented in *table 2.2* of figure 6.

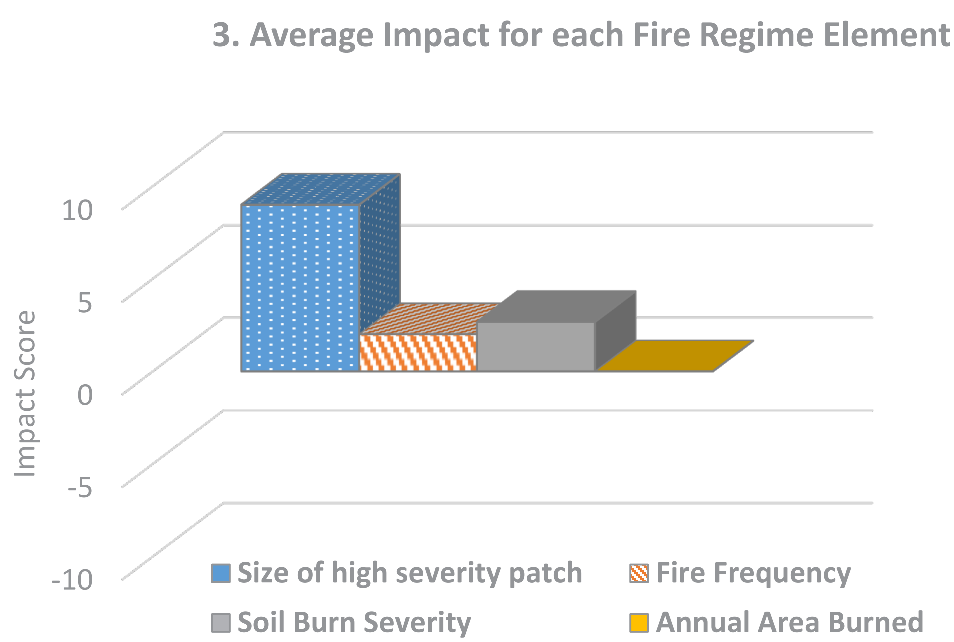

Figure 8—Impact scores for fire regime components show that fire frequency is likely to be most negatively impacted (experience greatest or most consistent departure from DFC) and annual area burned is least likely to experience change from DFC due to climate. These results are also presented in table 2.3 from figure 6.

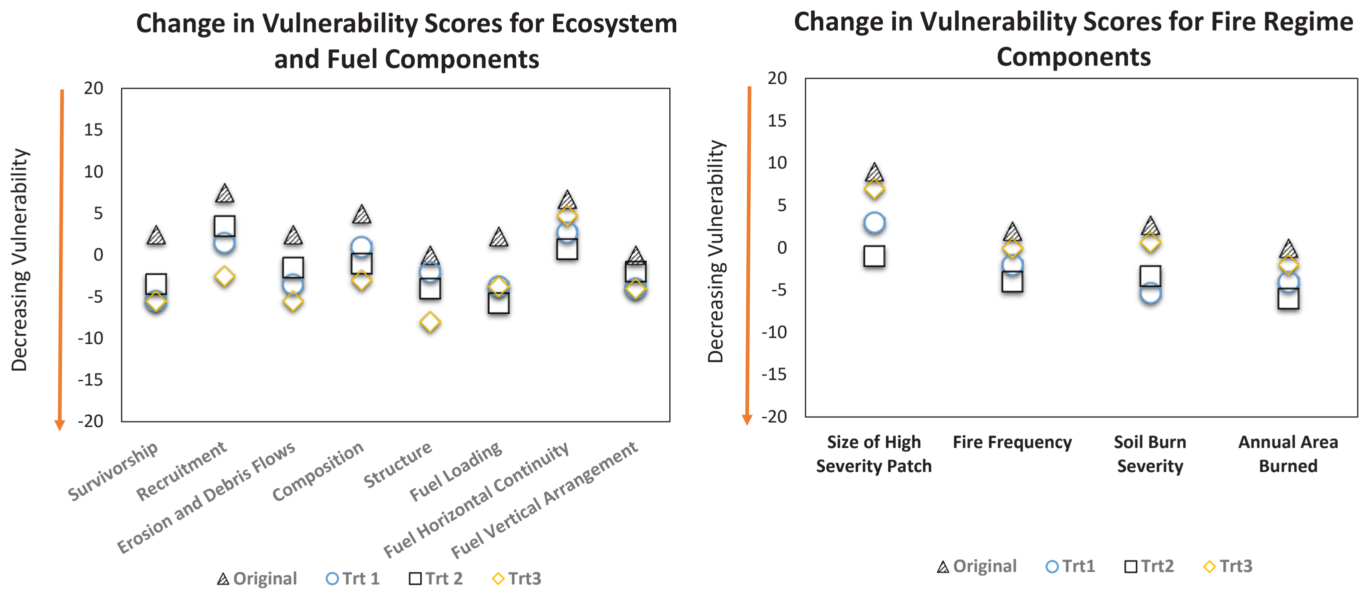

Figure 9—Results of treatments for ecosystem, fuel, and fire regime components. New scores are generated by subtracting treatment response scores (scaled 1-10) from each ecosystem, fuel, and fire regime component response score (scale -7.04 to +10). Treatments can only reduce original vulnerability scores. In this example, treatments 1-3 appear able to reduce ecosystem and fuel component impacts to a small extent (left panel). Treatment 3 appears to be most consistently able to reduce vulnerability among ecosystem components. Treatment 2 appears slightly more effective at reducing impacts for fuel components than other treatments. Since vulnerability and treatment impacts are described in terms of DFC, we could also interpret these results as demonstrating that Treatment 2 appears best able to bring fuel components closer to DFC. Treatment 2 also appears to be most effective for bringing Fire Regime components near DFC (right panel). Variation does exist, however. Treatment 1 appears to be the most effective method for bringing the soil burn severity closer to DFC (right panel).

IV. USING THE "FireCLIME VA Tool": TIPS AND TROUBLESHOOTING

Troubleshooting Excel Workbook

- Open only one instance of Excel at a time.
- Save document often. If an issue arises, data entered will be saved and can be viewed with the **Recall Last** button.
- Check to make sure responses have been saved by reopening the forms and hitting the **Recall Last** button, especially when reopening a document. You can also check this in the *Notes* tabs.
- If buttons or warning boxes stop responding, hit ESC and then click on the **Close** box.
- To clear data from a form, open the form (module) and hit *Submit without recalling past responses.* **Submit** will save current selections, and if none are selected, it will effectively clear the form of responses.
- If running an assessment for a new landscape, consider opening a fresh copy of the tool. Too many iterations based on the same file can cause issues.
- If you get a warning that content is blocked, close the workbook and change the file properties in Windows File Explorer. To do this, right-click on the file name, choose Properties, and click "unblock" at the bottom of the General tab.

Tips for Completing an Assessment

- Outline the scale of your study landscape, (i.e., landscape scale or site-specific scale).
- Outline goals, assumptions, and desired future conditions as specifically as possible.
- Outline treatment alternatives as specifically as possible. Avoid treatment alternatives that are orders of magnitude different only (i.e., avoid comparing treating 100 acres with treating 1,000 acres). Results of such a comparison will not be particularly meaningful.
- Run several iterations to work through potentially ambiguous responses (e.g., both positive and negative effects possible).
- Similarly, once completed, resist tweaking to conform to preconceptions. Instead complete a second assessment to use as a comparison.
- The tool does not need to be completed in order. Continue to the next section if you get stuck and return later.
- Go with your instinct. If you get stuck, move on. Uncertainties can be recorded as confidence scores or in comment boxes.
- Consider adding a fire ecologist or fire management specialist to your assessment team. Consultation with individuals who are already familiar with fire regime characteristics can help streamline the assessment process.

V. SUMMARY

We have developed a framework for assessing the vulnerability of landscape components to changes in fuels and fire regimes that can be used to identify at-risk resources and guide management actions. The FireCLIME VA tool helps resource managers and researchers identify critical vulnerabilities and potential intervention points under various climate conditions. As climate projections are improved and as climate-fire-ecosystem interactions are better understood, this tool can be updated to reflect the best available science.

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APPENDIX 1–DEFINITIONS

Fire Regime Components

Annual Area Burned: annual (typically calendar or water year) total mapped extent of wildfire within a specified area.

Fire Frequency: recurrence of fire in a given area over time, in units of number of fires per unit area.

Fire Regime: characteristic fire traits occurring in ecosystems over an extended period of time, including temporal, spatial, and magnitude attributes. Fire regimes are defined in terms of fire frequency, seasonality, size, spatial complexity, intensity, severity, and type.

Fire Return Interval (FRI): inverse of fire frequency, measured in units of average number of years between fires, typically expressed as a mean and with variance. Fire frequency and fire interval are both scale dependent; that is, estimates depend on the area over which the statistic is estimated.

Fire Rotation: length of time (years, decades, or centuries) for an area equal in size to a defined area to burn once.

Mean High Severity Patch: average size of a contiguous area of tree mortality.

Soil Burn Severity: impacts of fire-induced changes on the physical, chemical, and biological soil properties that affect hydrological and biological soil functions. The degree of soil burn severity is dependent on the peak temperatures and duration of temperatures within the soil.

Ecosystem Components

Composition: biodiversity of an ecological system, including the variety of genes, species, communities, and ecosystems. This includes abundance, distribution, and interactions, as well as the number and relative abundance of species. Forest composition refers to all plant species found in a stand or landscape, including trees, shrubs, forbs, and grasses.

Debris Flow: moving mass of unsorted sediment, sand, soils, and rock, which has been saturated with water and surges downslope in response to gravity, generally triggered by surface erosion caused by rainfall runoff or landsliding caused by rainfall seeping into the ground.

Erosion: movement and transport of soil by various agents, particularly water, wind, and mass movement.

Recruitment: process by which new individuals (plants) establish a population or are added to an existing population. Although recruitment may refer to clonal offspring, seedling recruitment—including the processes of seed germination, seedling survivorship, and seedling growth—is the most common example of recruitment.

Stand Structure: the horizontal and vertical distribution of components of a stand, classified by the age distribution, height, diameter, crown layers and stems of trees, shrubs, herbaceous understory, snags, and down woody debris.

Survivorship: the ability of vegetation to survive post-fire.

Fuel Components

Horizontal Continuity: arrangement of fuels in the horizontal plane or the degree or extent of continuous or uninterrupted distribution of fuel particles (live or dead) in a fuel bed.

Fuel Loading: amount of fuel present, expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel (consumable fuel) or total fuel, and is usually dry weight.

Vertical Arrangement: Fuels above ground and their vertical continuity, which influences fire reaching various levels or vegetation strata. The progression of vertical fuel arrangement can be described in three categories: ground fuels, surface fuels, and canopy fuels.

For additional fire terms and definitions not included here, see the National Wildfire Coordinating Group (NWCG 2006) Glossary of Wild and Fire at https://www.nwcg.gov/glossary/a-z

APPENDIX 2–CALCULATIONS

The FireCLIME VA tool quantifies vulnerability and associated scores based on the following formula:

Vulnerability = (Exposure + Sensitivity)/Adaptive Capacity

such that vulnerability increases with increasing exposure or sensitivity and decreases with increasing adaptive capacity. The collective effect of Exposure and Sensitivity represents the impact to the system, which is reduced by the system's Adaptive Capacity. This formula was modified to reflect characteristics of climate-fire-vegetation interactions and to incorporate both intrinsic (inherent to the system) and extrinsic (management actions) drivers of vulnerability.

This resulted in the following formula:

Vulnerability = (Exposure + [Sensitivity/Adaptive Capacity (Intrinsic)])/Adaptive Capacity (Extrinsic)

where **Exposure** is the impact of climate on fire regime (change or no change) and the trajectory of fire regime components with respect to DFC (closer or further) (fig. A1). **Sensitivity** tallies the number of characteristics of the ecosystem associated with increased negative impacts under changing climate/fire regimes and the potential increased departure of ecosystem or fuel components from DFC as a result of expected changes and trajectories of fire disturbance (fig. A2). **Intrinsic adaptive capacity (resilience)** tallies ecosystem or fuel components that benefit or move toward DFC as a result of expected changes and trajectories of fire disturbance. **Extrinsic adaptive capacity** accounts for the potential for management action to bring fire regime or ecosystem closer to desired conditions (fig. A3). Vulnerability can be quantified with or without extrinsic adaptive capacity in this system.

For each element of the formula (e.g., exposure, sensitivity, adaptive capacity), we identify relevant indicators or measures. These indicators form the basis of questions, and responses to those questions are converted to a dimensionless numerical value. Specifically, scores of +1 are given for factors that contribute to increased vulnerability, 0 is given where no influence is determined, and -1 is given where a positive effect is expected. These indicator values are then summed and sums are normalized to a scale of -10 and +10, where +10 indicates the highest vulnerability.

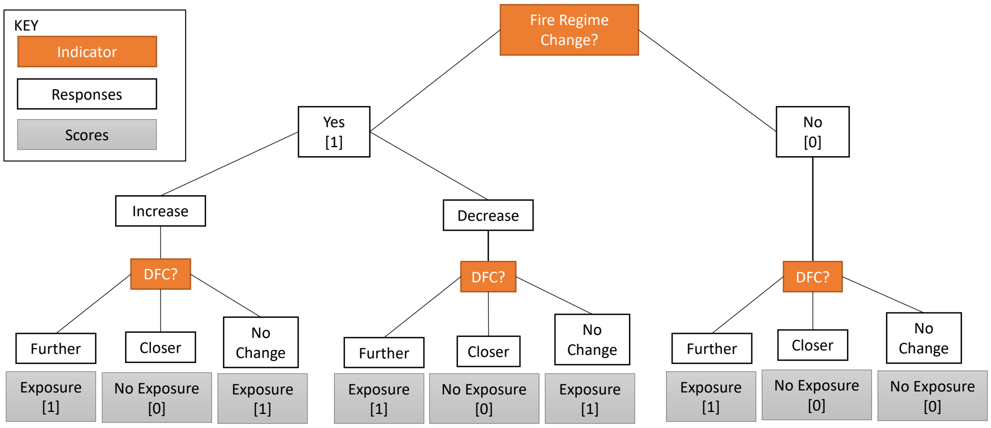

Figure A1—Flow diagram for calculating exposure. For each of four fire regime attributes, users indicate whether it is expected to change under climate change. Then, users indicate whether those changes lead to departure from DFC. Final resulting scores (1, 0) are shown in gray boxes. Exposure scores are treated as a multiplicative within the tool to ensure impact and vulnerability are calculated only when Exposure is greater than 1.

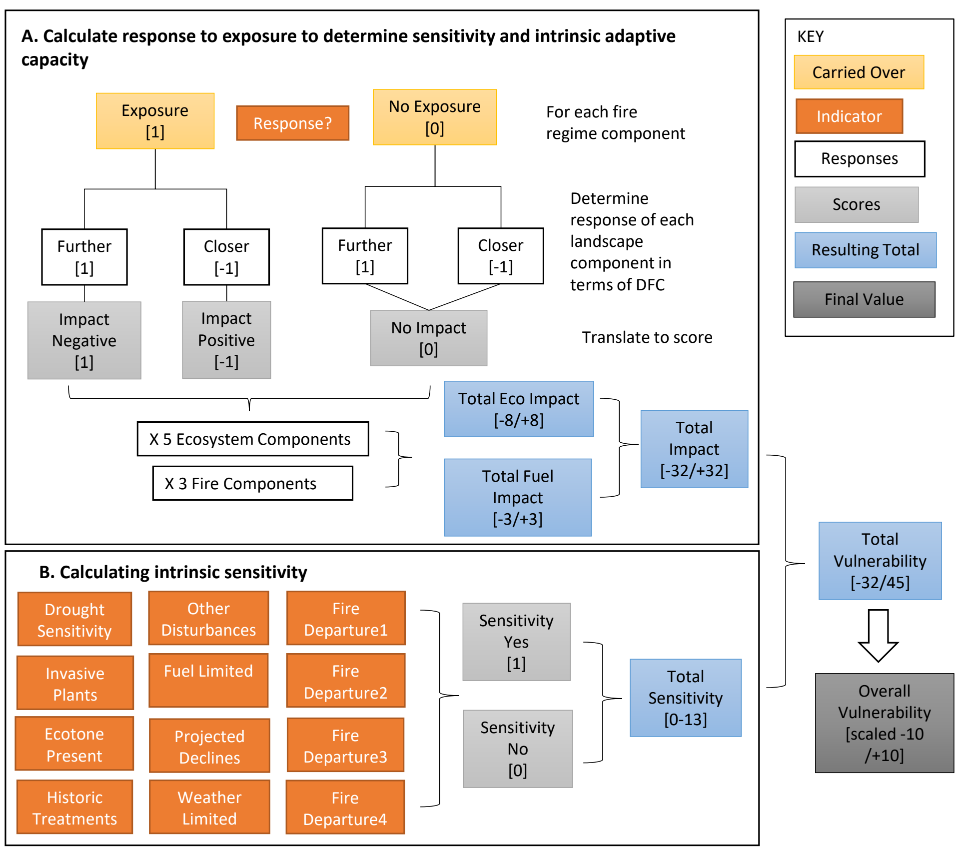

Figure A2—Flow diagram for calculating Vulnerability. Sensitivity is identified as "further" departure in response scores (A) and through the presence of intrinsic characteristics (B). Adaptive capacity is identified as less departure ("closer") in response scores. Total impact and sensitivity scores are added to generate a Vulnerability Score.

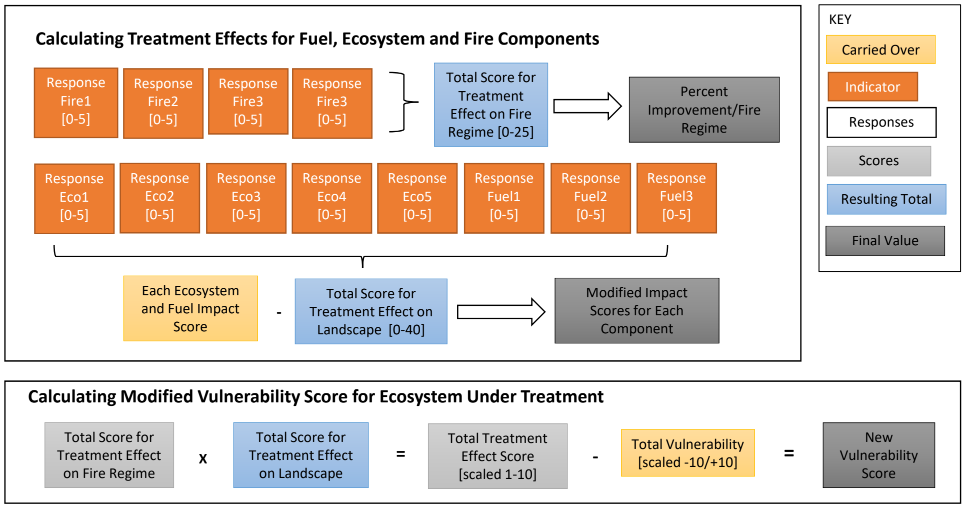

Figure A3—Flow diagram showing process for calculating adjusted impact and vulnerability scores based on treatment effectiveness. Users provide responses for each treatment and for each fire, ecosystem, and fuel components. These responses are translated into scores that are subtracted from the original scores. Effectiveness of treatment can consider the proportion of components that experience a positive effect (percent effectiveness) or degree to which vulnerability score is reduced.

Calculating Exposure

Exposure is determined through responses given in *tables 1.2* and *1.3,* which consider expected change to fire regime elements and whether that change results in further departure from DFC (fig. A1). During the development of the tool, we determined the target of this assessment was ecosystem vulnerability to negative climate-fire outcomes. Negative impacts are interpreted as those that lead to further departure in DFC. Therefore, exposure equates to any change in fire regime that leads to further departure in DFC.

Potential outcomes of the exposure module include a score of 1 or 0 (fig. A1). Exposure scores are calculated based on two sets of questions. First, a score of 1 is given to regime components likely to change under climate change (fig. A1). Second, if the fire regime component is expected to experience further departure from DFC under climate change, it is given a score of 1; if it is expected to approach DFC, it is assigned a value of -1; and no change is assigned a score of 0 (fig. A1). These values are then reassigned a final score so that each fire regime component is given a score of 0 or 1 (table A.1).

Table A.1—Resulting final exposure score assignment given combination of potential responses to two questions.

Change?	Trend DFC?	Score
Yes	Further from DFC	1
Yes	Closer to DFC	0
Yes	No change from DFC	1
No	Further from DFC	1
No	Closer to DFC	0
No	No change from DFC	0

Qualitative responses from the assessment of exposure (e.g., increase fire frequency) are used as a point of reference for later modules measuring landscape response. Quantitative values (0, 1) are used to distinguish between changes that represent true exposure (disturbance that causes undesirable outcome) and those that do not. Response score values are multiplied by the quantitative exposure scores, resulting in a response score of 0 where exposure = 0. This effectively eliminates the potential that the tool would produce a vulnerability score for a fire regime component that is not expected to or is not currently departed from desired conditions.

Calculating Sensitivity and Adaptive Capacity Via Ecosystem and Fuel Response

Sensitivity and Adaptive Capacity are estimated based on expected responses of ecosystem and fuel components generated in *Modules 2.1* and *2.2.* Users indicated the likely response, in terms of departure from DFC, of each ecosystem component to each fire regime component (fig. A2a). Where departure is expected, a score of 1 is given to indicate sensitivity. Where less departure or return to DFC is indicated, a score of -1 is given. Neutral scores are also possible. Impact is calculated by multiplying the exposure score, carried over from the previous exercise, by each of the response scores. Where Exposure = 0, responses will also equal 0. Where Exposure = 1, response variables will retain their original value. Response values are then summed to create an overall impact score for ecosystems and fuels. Importantly, ecosystem and fuel component response scores are reported separately as values scaled to -10 to +10 but the combination score based on both is calculated based on the original summed totals (not scaled) that are first combined and then standardized to a scale of -10 to +10. Combining the unscaled totals reduces potential bias arising from the unequal distribution of indicators in these two categories. The final result of this process is a Total Impact score.

Higher positive Total Impact values are associated with greater potential for negative response (sensitivity) to changes in fire regime (exposure). Lower or negative values indicate potential benefit for the ecosystem. There are 32 potential scores (8 landscape x 4 fire components) in this section, leading to a combined total ranging from -32 to +32.

Calculating Intrinsic Sensitivity

Intrinsic Sensitivity, relating to questions in *table 1.1* and questions 1-9 of Section 2, considers the inherent condition of the ecosystem that may lead to a greater negative response to fire disturbance (fig. A2b). Each question is given a score of 0 (no sensitivity) or 1 (sensitive). These are then summed to create a total sensitivity score. Maximum raw score is +13, though this is scaled to a maximum of +10 for final reporting. A score of +10 indicates that the ecosystem has high sensitivity.

Calculating Vulnerability

Total Vulnerability is calculated by summing the Total Impact and Sensitivity scores (fig. A2). This results in a value ranging from -32 (lowest possible vulnerability with no intrinsic sensitivities and all positive responses) to +45 (highest possible vulnerability with all intrinsic sensitivities and all negative responses). The final score is rescaled by multiplying the raw value by 0.222, resulting in a potential range of scores from -7.04 to +10. The positive bias results because intrinsic sensitivity can contribute only positive values, whereas response variables consider both positive and negative effects. A score of +10 represents the highest possible vulnerability and -7.04 indicates the lowest vulnerability. Again, non-positive scores result when the net response to fire regime change is positive and may represent ecosystem resilience.

Calculating Treatment Impacts

Management treatments are evaluated in *Modules 3.1-3.3* in of the tool. For each set of components, Fire, Fuel, and Ecosystems, users are asked to indicate the degree to which a given treatment brings a component closer to DFC. Responses include Poor (score of 1), Fair (2), Good (3), Very Good (4), and Excellent (5). For most calculations, these values are converted to a 2-10 scale and subtracted from the similarly scaled impact and vulnerability scores calculated in previous exercises.

Treatments calculations are not made for every Fire x Ecosystem/Fuel component combination. Therefore, treatment impacts cannot be estimated for each individual Fire x Ecosystem/Fuel component. Instead, treatment impacts are reported as a percent improvement calculated as the total score received/total potential score for fire regimes and ecosystem and fuel components. Total treatment effects are summed across ecosystem and fuel components, scaled to 1-10, and the resulting value is subtracted from ecosystem and fuel impact scores to produce modified scores that demonstrate magnitude of improvement. Finally, the total score for treatment effects on fire regime are multiplied by the total score for treatment effects on landscape elements, scaled to 1 to 10, and subtracted from the original vulnerability score to create a new score representing treatment impacts (fig. A3). The FireCLIME VA tool does not consider potential negative impacts from management actions. Where negative or no impacts are apparent, users are directed to leave the question blank, which prevents the minimal score of 1 being assigned. In this situation, the tool will automatically assign a value of -25 to that particular component to distinguish it as an invalid comparison. Thus, the treatment scores is either -25 (not effective/no change in trend toward DFC/not able to reduce vulnerability/negative impact) or falls along a spectrum from 2 to 10 (corresponding to treatment capacity to move component toward DFC/reduce vulnerability), which is subtracted from the original impact or vulnerability score.

Ranks and Weighting

Ranks allow users to identify relative importance among fuel, ecosystem, or fire regime components. Ranking these components may be useful where users believe that some characteristics will be more strongly influenced by climate changes and/or fire regime than others, where certain characteristics have a stronger influence on desired future conditions, or in situations where the management focus is on a certain characteristic. Ranking individual components adjusts the proportional assignment of score totals among the component group (fire, ecosystem, or fuels). In other words, ranks adjust the weight of individual components by reapportioning each component's contribution to the total (0-1) (table A.2). Ranking adjusts the weights assigned to each component by effectively increasing the most important component's scores approximately 1.5 x 5 times and decreasing the remaining components in a proportional manner with the least important component adjusted to contribute approximately ½ a score to the total.

Table A.2—Example proportional contribution of variables across different ranking schemes. Ranking changes the proportion of contribution of any one variable to the total, which remains constant at 1. Different combinations of rankings are based the subsequent breakdown of ranks and their placement relative the fully ranked proportion scheme. For example, a fire regime component ranking combination of 1 2 2 3, would assign a weight of 0.4 to 1, 0.25 to each 2, and 0.1 to the 3. The single rank of 1 receives a corresponding proportion of 0.4, the two values of 2 will split the 2nd and 3rd place proportions among them (0.3+0.2=0.5/2) and the single 3 retains a value of 0.1. A rank of 1 2 3 3 would result in proportions of 0.4, 0.3, 0.15, 0.15.

Rank values		Fuel Components		Fire regime components		Ecosystem components	
No weighting	**Fully ranked**	**Prop. no weighting**	**Prop. full weighting**	**Prop. no weighting**	**Prop. full weighting**	**Prop. no weighting**	**Prop. full weighting**
1	1	0.3334	0.50	0.25	0.4	0.2	0.3
1	2	0.3334	0.3334	0.25	0.3	0.2	0.25
1	3	0.3334	0.2	0.25	0.2	0.2	0.2
1	4			0.25	0.1	0.2	0.15
1	5					0.2	0.1
Total		1.0	1.0	1.0	1.0	1.0	1.0

In practice, the actual value used as a weight depends upon the number of classes being ranked and the nature of those ranks (table A.2). For instance, in a 3-class system (e.g., fuel components), each component score is assigned a weight of 0.33 so that each contributes to 1/3 of the total score. However, when components are ranked 1, 2, and 3, the most important component score is assigned a weight of 0.5, the second a weight of 0.3, and the third a weight of 0.2. The effect of this is that the most important component contributes more to the final calculation of impact (0.5/0.33 = 1.5) and the least important component contributes less (0.2/0.33 = 0.6). The final weight assigned to a particular component also depends on the overall structure of ranks assigned to components (table A.2). For example, in a 4-class system (e.g., fire regime components), a rank set of 1, 2, 3, 4 would assign the most important component a weight of 0.4, but if the ranks were instead 1, 1, 2, 2, each of the higher-ranking components would be assigned a weight of 0.35 (table A.2).

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