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Review

Adaptation Strategies and Approaches for Managing Fire in a Changing Climate

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Abstract: As the effects of climate change accumulate and intensify, resource managers juggle existing goals and new mandates to operationalize adaptation. Fire managers contend with the direct effects of climate change on resources in addition to climate-induced disruptions to fire regimes and subsequent ecosystem effects. In systems stressed by warming and drying, increased fire activity amplifies the pace of change and scale of severe disturbance events, heightening the urgency for management action. Fire managers are asked to integrate information on climate impacts with their professional expertise to determine how to achieve management objectives in a changing climate with altered fire regimes. This is a difficult task, and managers need support as they incorporate climate adaptation into planning and operations. We present a list of adaptation strategies and approaches specific to fire and climate based on co-produced knowledge from a science–management partnership and pilot-tested in a two-day workshop with natural resource managers and regional stakeholders. This "menu" is a flexible and useful tool for fire managers who need to connect the dots between fire ecology, climate science, adaptation intent, and management implementation. It was created and tested as part of an adaptation framework used widely across the United States and should be applicable and useful in many fire-prone forest ecosystems.

Keywords: climate adaptation; wildfire; prescribed fire; fuel treatments; adaptive management; restoration; resistance; resilience; transition

1. Introduction

1.1. Climate Change, Fire, and Management Challenges

Climate and wildfire are inextricably connected [1–4], and broad trends in large or uncharacteristic wildfires driven by extreme weather and shifting ecosystem processes highlight a need to bolster adaptation to climate–fire interactions. Changing fire regimes (i.e., the set of characteristics and patterns of fire over time [5,6]) are consistently cited as a major ecological consequence of global climate change [7–9]. Climate change has direct and indirect effects on factors contributing to wildfire activity, such as weather conditions, fuel

availability, and ignition sources [10]. In concert with other anthropogenic influences on fire regimes (e.g., fire suppression), climate change is driving an increase in and intensification of fire activity globally [11], a trend that has been observed over decades [12]. Further, the disturbance of larger and more frequent fires that burn at higher severities may hasten the pace of underlying ecosystem transformation caused by changes in climate alone [13,14].

Interactions among climate, disturbance, and vegetation are complex [15], and there are multiple ways climate change may impact fire regimes [16]. Climate-induced changes to fire regimes often upset basic ecosystem characteristics and services in ways deemed undesirable by human communities [17,18]. Though observed and modeled shifts in fire regimes vary at regional and finer scales [19,20], there are clear signals that climate-altered fire regimes pose a serious threat to the integrity and resilience of ecosystems [9,10,21]. In the western United States (U.S.), general climate trends of warming and drying have direct implications for key fire regime characteristics, including frequency, severity, size, behavior, timing (seasonality), and spatial pattern of fires [7,16]. Models predict that warmer and drier conditions will lead to higher fire danger, increased fire activity, higher severity, and larger annual area burned, as well as longer fire season length [15,22–25]; empirical studies have already documented these changes [2,10,26–29].

Climate-induced changes to fire regimes have cascading effects on ecosystem characteristics [30]. Ecosystems experiencing fire regime change are subject to demographic shifts in plant populations, often including increased mortality and limited regeneration success [31–35]. Changes to fire regime characteristics can also have effects on vegetation species composition, structure, and fuel availability [3,36–38]. Where systems are already experiencing high levels of baseline stress due to climate change and other anthropogenic disturbances, disruptions to fire regimes may prove to be resilience "tipping points"—thresholds where even small changes can lead to large, abrupt alterations in the ecosystem state [39,40]. Additionally, reciprocal relationships between variables and positive feedbacks can amplify ecosystem effects [9,30,41,42]. Evidence from western forested ecosystems in the U.S. suggests that interactions between climate and fire will have lasting effects that alter the ecosystem services and values historically provisioned by these landscapes [18,26,28,43].

Resource managers are faced with considering these complex relationships and determining how climate change is expected to influence local fire regimes, including how ecosystem characteristics and operational capabilities may respond to such changes [44]. Their roles further include identifying opportunities to implement climate adaptation strategies using the best available science and traditional knowledge. Management strategies aim to address the threats to ecosystems and human values posed by altered fire regimes in ways that are robust to the uncertainty of future scenarios. When planning strategies and operational activities to respond to social and ecological needs (e.g., safety from catastrophic fire, sustained ecosystem services, etc.), fire managers and planners are further challenged with balancing social and environmental constraints (e.g., health hazards from smoke, hydrological considerations, competing and mutually exclusive ecological goals) that can complicate planning and preclude the implementation of certain strategies. Thus, understanding the full suite of management options can help managers design and implement adaptation actions that are holistic and acceptable given local and regional needs and constraints [45].

We refer to adaptation using the definition articulated by Swanston and others [46]: "the adjustment of systems in response to climate change". This simple definition is consistent with much more complex and detailed definitions, which are useful for exploring and applying the nuances of adaptation (e.g., [47]). A growing body of literature seeks to support managers in making adaptation decisions by producing results directly relevant to their challenges, spatial and temporal scales, and responsibilities (e.g., [48]). In the southwestern U.S., recent work generated through science–management partnerships has provided the management community with actionable information on climate–fire–ecosystem dynamics [35,49,50], including the perspective to offer a new term to address

the intersection of changing fire regimes and social values: "unacceptable fire". We define unacceptable fires as often departing from historic regimes and with effects that conflict with public safety, public health, and/or natural resource and ecological management objectives.

1.2. Menu-Based Framework for Climate Adaptation

In this paper, we present a tool to assist fire managers with climate adaptation using a vetted framework. The Climate Change Response Framework (CCRF) Adaptation Workbook outlines a process for identifying actionable adaptation strategies [46,51,52]. Other frameworks and typologies, such as the Adaptation for Conservation Targets Framework [53] or the Resist-Accept-Direct Framework [54], also provide useful approaches to climate adaptation conceptualization and planning. The CCRF is one of the most developed, supported, and widely used frameworks applied in natural resource management in the U.S. and was chosen as a good fit for this community of land managers. The Adaptation Workbook functions as a decision support tool, empowering managers to systematically consider their goals and objectives through the lens of climate change threats and opportunities and to identify feasible adaptation actions (Figure 1). The process incorporates considerations that are unique to different management organizations and geographic areas. The Adaptation Workbook relies on a "menu" of adaptation strategies, with nested approaches and example tactics, to assist with the exploration and selection of adaptation actions.
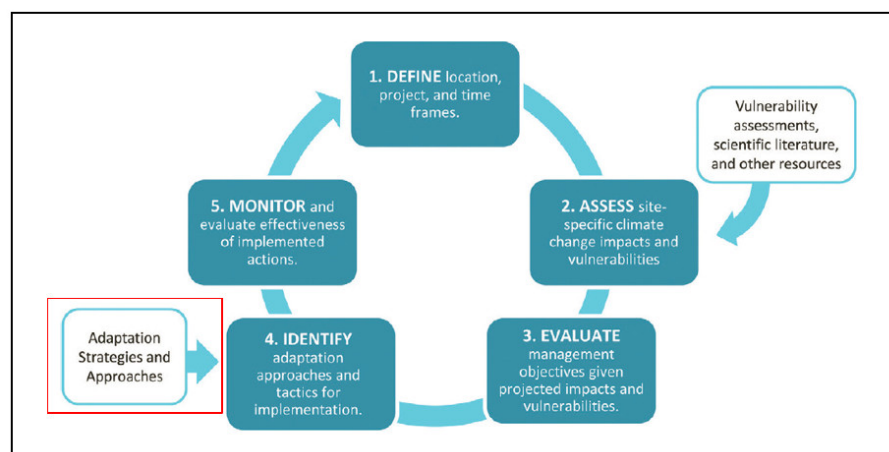
Figure 1. The Climate Change Response Framework Adaptation Workbook process. "Menus" of adaptation strategies and approaches are an input in Step 4. Adapted from Swanston et al. 2016 [46].

Adaptation menus provide lists of non-prescriptive, dynamic choices to natural resource managers facing complex climate challenges. Rather than guidelines or recommendations, these choices are presented in a menu format to provide a wide range of possible options that can fit users' circumstances. Selections will necessarily be different depending on vulnerabilities, assets, values, risk tolerance, and other factors [46]. Additionally, menus can be viewed as dynamic, long-term resources that can be revisited and improved over time. Menus have been created through multiple initiatives and various approaches to serve specific disciplinary, regional, and community-based interests [55–60].

The Adaptation Workbook is well-suited to support fire managers in identifying adaptation actions that can meet their objectives. We sought to enhance the functionality of the Adaptation Workbook for fire management by using an existing science–management partnership to create a menu of adaptation strategies specific to the effects of climate-induced fire regime change (hereafter referred to as the "Fire Menu"). The Fire Menu provides a broad range of science-based adaptation choices for managers to consider and can be used independently or as part of the Adaptation Workbook process (Step 4, Figure 1). In the following sections, we describe the co-production process used to develop the Fire Menu, present the Fire Menu, including descriptions for each adaptation strategy

and approach, and demonstrate its application through a case study applied to a real-world project.

2. Menu Development

2.1. Co-Production Model

The Fire Menu is a product of Southwest FireCLIME, a regional initiative that applied the principles of science–management partnership and the co-production of knowledge [48,50,61–63] to identify information needs related to climate–fire–ecosystem dynamics within the management community and enhance the relevance of research results. The FireCLIME team included 17 scientists and managers from universities, U.S. federal agencies, and non-governmental organizations (NGOs) in Arizona and New Mexico with expertise in fire ecology, climate science, and land management [50]. The team's integrated research and management perspectives lent a critical foundation for developing focused and targeted adaptation resources for managers. The Fire Menu directly builds upon the previous work of FireCLIME, including a synthesis of published literature addressing climate–fire–ecosystem interactions [64], a vulnerability assessment (VA) tool [49], and modeling work [65]. Though the Fire Menu was created in and initially targeted to the southwestern U.S., it is applicable to the rest of the western U.S., and likely beyond, at least as a starting point for using the Adaptation Workbook to help incorporate climate considerations into policies, planning, and operational strategies that guide fire and fuels management.

2.2. Input and Organization

An adaptation menu aggregates climate science and expertise in a particular focal area (in this case, fire) within the context of management institutions, their options, needs, strengths, and challenges. Drawing upon the collective science and management expertise of the Southwest FireCLIME collaborator group, we generated a list of fire-related adaptation priorities based on an extensive literature review [49,64], modeling [35], and decades of combined professional management experience. We also identified fire-focused strategies previously articulated in climate adaptation initiatives that have emerged from the western U.S., including the U.S. Forest Service report on Climate Change Vulnerability and Adaptation in the Intermountain Region [66,67] and the Climate Change Adaptation Library for the Western United States [68].

We used the original Menu of Adaptation Strategies and Approaches for forested ecosystems as a template to inform the design of the Fire Menu [46]. Likewise, we use the terms strategy, approach, and tactic as defined by the CCRF Adaptation Workbook and earlier menus [46,55,57,59,69]. Briefly, strategies are defined as "broad adaptation responses that consider ecological conditions and overarching management goals". Within each strategy are nested approaches, "more detailed adaptation responses with consideration of site conditions and management objectives". Under each approach, there is a short list of example tactics, "prescriptive actions designed for specific site conditions and management objectives" [46]. We organized and condensed information and priorities from Southwest FireCLIME as well as material from other adaptation sources into an initial tiered list of 10 strategies and nested approaches. This initial version was shared with the Southwest FireCLIME community, other potential users, and the CCRF community of climate science and adaptation experts for reaction and feedback. We iteratively incorporated feedback into a revised set of strategies and approaches, and ultimately vetted the final set through the FireCLIME collaborator group as a crucial component of the co-production model.

2.3. Pilot Test

We conducted a pilot test of the Fire Menu during a CCRF Adaptation Planning and Practices workshop [70] in which resource managers from the Kaibab National Forest (NF) and other regional stakeholders used the Menu in a real-world planning application (see Adaptation Demonstration below for a detailed description). During the two-day

workshop, participants worked through the steps of the Adaptation Workbook, including identifying the intent of specific adaptation actions by linking them to strategies presented in the Fire Menu. Though most of the workshop was dedicated to adaptation planning for the Kaibab NF, the final task asked participants to provide feedback about the practical application of using the Fire Menu to identify and link actionable adaptation options to real-world projects. In addition to group discussion, we used a brief survey to solicit recommended revisions to the Menu (Figure S1). We incorporated participant suggestions, finalized descriptions for strategies and approaches, and generated example tactics before submitting the iteration for final review to our expert group of scientists and managers. The product of this process was the Fire Menu presented in the next section, which is rooted in the scientific literature as well as decades of management and research experience.

3. Adaptation Menu for Fire Management (Fire Menu)

The Fire Menu is designed to reflect an array of conservation values and climate adaptation actions in the context of available opportunities. It provides managers with a wide suite of practical strategies, approaches, and tactics that may fit their individual circumstances, regardless of uncertainty in predictions of future scenarios. Not every strategy will make sense for a given situation or organization, and some may even seem contradictory. The ten strategies and 27 approaches that comprise the Fire Menu (Table 1) include actions currently employed in numerous fire management plans as well as activities not yet common in fire management planning or operations.

Strategies and their underlying approaches and tactics are designed to align with one or more of three key adaptation concepts, or "options": resistance, resilience, and transition (Table 1) [46,71]. We adopt the specific wording of Swanston et al. [46] to define resistance actions as those that "improve the defenses of an ecosystem against anticipated changes or directly defend the ecosystem against disturbance in order to maintain relatively unchanged conditions"; whereas "resilience actions accommodate some degree of change, but encourage a return to near-prior conditions after a disturbance, either naturally or through management"; and "transition actions intentionally anticipate and accommodate change to help ecosystems to adapt to changing and new conditions". This tiered alignment from adaptation option to tactic assists managers in identifying the adaptation intent of a given tactic, or conversely, identifying a tactic to meet a specified intent.

Strategy 1: Sustain Fire as a Fundamental Ecological Process

Wildfire is a critical ecological process in ecosystems throughout the world [72–75]. Fire shapes and maintains the diversity, structure, and function of vegetation communities, even in areas where it has historically occurred infrequently [72,76]. The characteristics of many fire regimes have been influenced by unprecedented anthropogenic disturbances over the past few centuries [10,15,76]. These disturbances include over a century of fire suppression that has effectively removed the regulating force of wildfire [77]. Subsequent changes in fuel characteristics have increased the risk of uncharacteristically large and intense wildfires in many areas [15,78]. As a result, recent management efforts have begun to emphasize fire regime restoration through prescribed burning and managed wildfires [79]. Returning fire to landscapes and cultures where it has been artificially excluded has been shown to have a variety of ecological and social benefits, including the reduction in future wildfire activity that is more likely to occur at undesired spatial scale or severity [80–82]. Despite uncertainties and challenges, fire may still have an important role to play in future forests altered by climate change [83].

Table 1. Strategies and approaches for climate and fire adaptation. Strategies are "tagged" with applicable adaptation concepts (resistance, resilience, and/or transition) in italics underneath the title. Example tactics for each approach are listed in Appendix A.

Strategy	Approach
1: Sustain fire as a fundamental ecological process *Resistance—Resilience—Transition*	1.1: Restore or maintain fire in fire-adapted ecosystems
	1.2: Develop fire use strategies in altered or novel ecosystems where fire can play a beneficial role
2: Reduce biotic and abiotic stressors affecting fire regimes *Resistance—Resilience*	2.1: Remove and prevent establishment of non-native invasive species
	2.2: Maintain or improve the ability of forests to resist pests and pathogens that may alter fuel regimes
	2.3: Limit, selectively apply, and monitor land uses that increase fire risk or threaten fire resilience
3: Reduce the risk of unacceptable fire *Resistance—Resilience*	3.1: Protect fire-sensitive and vulnerable ecosystems from fire
	3.2: Alter forest structure and composition to reduce the risk and spread of unacceptably severe fire
	3.3: Establish or maintain fuel breaks to stop the spread of unacceptable fire
4: Limit the effects of unacceptable fire and promote post-fire recovery *Resistance—Resilience*	4.1: Promote habitat connectivity and increase ecosystem redundancy
	4.2: Maintain or create fire refugia
	4.3: Stabilize and enhance the physical fire footprint
	4.4: Promote recovery of native vegetation and habitat
5: Maintain and enhance structural, community, and species diversity using fire and fuels treatments *Resilience*	5.1: Maintain or increase structural diversity from stand to landscape scale
	5.2: Promote diversity within and among communities to enhance fire resilience
6: Identify, promote, and conserve fire- and climate change-adapted species and genotypes *Resilience*	6.1: Promote native species and genotypes that are better adapted to future climate and fire regimes, disfavor species that are distinctly maladapted
	6.2: Use plant materials from regional areas that have current climate and fire regimes similar to anticipated future conditions
7: Facilitate ecosystem adaptation to expected future climate and fire regimes *Resilience—Transition*	7.1: Facilitate the movement of species that are expected to be adapted to future climate and fire regimes
	7.2: Use fire as a tool to align existing vegetation communities with changing climate and fire regimes
8: Use fire events as opportunities for ecosystem realignment *Transition*	8.1: Revegetate burned areas using fire-tolerant and drought-adapted species and genotypes
	8.2: Allow for areas of natural regeneration to test for future-adapted species
	8.3: Maintain ecosystems that have undergone post-fire type conversion or realignment
9: Promote organizational and operational flexibility *Resilience—Transition*	9.1: Develop adaptive staffing and budgeting strategies
	9.2: Explicitly consider changing climate and fire regimes during the planning process and adaptive management cycle
	9.3: Engage and incorporate values of Indigenous communities in fire management decisions
10: Promote fire-adapted human communities *Resilience—Transition*	10.1: Increase fuel reduction treatments in the wildland–urban interface (WUI)
	10.2: Actively promote broad social awareness and increase education about anticipated effects of climate change on fire regimes

Approach 1.1: Restore or Maintain Fire in Fire-Adapted Ecosystems

Fire has been suppressed in many fire-adapted ecosystems over the past few centuries to the detriment of native ecological and human communities [77,84]. Exclusion of fire from fire-dependent ecosystems has resulted in broad and cascading impacts across ecological scales. These impacts include accumulated hazardous fuel loads, which have led to fire intensity, size, severity, or seasonality that increasingly fall outside the historic range of variation [85]. Managed wildfires and prescribed burns (often preceded by mechanical fuel reduction treatments) are used to restore structure and function that provide ecosystem services [80,86,87]. Additionally, there is evidence that in fire-dependent ecosystems, process-based restoration of fire regimes may increase resilience to climate change [88–91].

Approach 1.2: Develop Fire Use Strategies in Altered or Novel Ecosystems Where Fire Can Play a Beneficial Role

In locations where the historic fire regime has been disrupted and an ecosystem displays significantly altered or novel characteristics, fire may remain (or become) a beneficial process [92]. For example, leveraging fire frequency may be a desirable way to achieve restoration or conservation management objectives. Such objectives may include reducing or eliminating populations of fire-sensitive non-native species [93], reducing fuel loading, changing soil moisture patterns, biota, and chemistry [94–96], diversifying forest composition and physical structure [97–99], or enhancing wildlife habitat [100]. Even in systems where fire regimes are expected to dramatically change (e.g., [43]), fire may remain important and desirable, albeit in a new context [35].

Strategy 2: Reduce Biotic and Abiotic Stressors Affecting Fire Regimes

Climate change and other environmental effects of human activity are projected to increasingly result in unprecedented stresses on ecosystems throughout the current century [101]. When biotic or abiotic stressors alter fuel regimes and fire risk, fire regimes can undergo drastic changes over short periods of time [102]. Biotic stressors with ties to fire regimes include non-native plant species [103–105] and pests and pathogens (both native and non-native) [65,106]. Abiotic stressors include human ignitions [107], industry (e.g., logging operations, grazing) [108], infrastructure (e.g., powerlines, roads, railroads) [109–111], land-use change [112], as well as changing climate-weather conditions (e.g., warmer and drier) [23,113,114]. While many extractive land uses alter fuel regimes in ways that increase the potential for unacceptable fire, and some, such as grazing, may reduce fuel loading and fire activity [115,116].

Approach 2.1: Remove and Prevent Establishment of Non-Native Invasive Species That Alter Fuel Regimes

Non-native invasive plants can have significant effects on fire regimes [117]. Some of the most well-documented examples of non-native invasive species significantly altering fire regimes occur in the arid desert and shrubland ecosystems of the southwestern U.S. where non-native annual grasses have proliferated [118]. Non-native grasses have increased fine fuel availability and fuel connectivity, which has in turn increased the frequency and intensity of wildfire [42,119]. Fire mitigation treatments and post-fire management activities are also potential vectors for the introduction, establishment, and spread of non-native species [36].

Approach 2.2: Maintain or Improve the Ability of Forests to Resist Pests and Pathogens That May Alter Fuel Regimes

Infestations of pests and pathogens can result in decreased health and resilience of forests and woodlands and increased mortality rates [106,120]. In the western U.S., changing climatic conditions have contributed to an increase in pests and pathogens, including bark beetles [121], spruce beetle [122,123], and spruce budworm [124]. Weakened and dead trees and understory vegetation change fuel dynamics, which can alter fire regimes and increase fire danger [125,126]. Decreasing density through mechanical thinning or managed

fire may improve the physiological capacity of trees to resist pests and pathogens [127], while fire suppression may exacerbate future outbreaks [122].

Approach 2.3: Limit, Selectively Apply, and Monitor Land Uses That Increase Fire Risk or Threaten Fire Resilience

The scale and intensity of human modifications to the environment have increased dramatically over the past few centuries [128]. In combination with a warmer and drier climate, industrial land uses (logging, mining, drilling, large-scale grazing, and agriculture), infrastructure development (forest roads, housing developments, agricultural infrastructure), and other activities (recreational camping, driving, target shooting) have the capacity to alter fuel regimes and increase ignitions [111,129–134]. In areas facing unacceptable levels of climate-induced fire activity, these land uses and activities could be reviewed, focused in low-risk areas, carefully applied at the smallest feasible scale, and monitored for compliance.

Strategy 3: Reduce the Risk of Unacceptable Fire

Terms such as "uncharacteristic" and "undesirable" have been used to describe fires that conflict with either ecological or social expectations and values [135–137]. Unacceptable fires may be ecologically uncharacteristic, socially undesirable, or both. Unacceptability often reflects a departure from historic regimes and includes effects that conflict with public safety, public health, and/or natural resource and ecological management objectives. Fire acceptability reflects human values, whether it is a desire for ecosystems to function as they have at a given time in the past, as they are expected to function in the future, or the need to protect human communities, infrastructure, or ecosystem services. Generally, management actions taken to reduce the risk of unacceptable fire will be preventative as opposed to reactive.

Approach 3.1: Protect Fire-Sensitive and Vulnerable Ecosystems from Fire

Fire regime disruptions are not limited to fire-adapted ecosystems. In fire-sensitive systems, locations where human values conflict with fire (e.g., WUI, forests managed for timber production, recreation areas), or where shifts in fire regime have rendered ecosystems vulnerable, there may be a very low tolerance for even low-intensity fires. Vegetation communities that are not fire-adapted may experience increased threats from altered fire regimes due to anthropogenic influences such as the profusion of invasive non-native grasses [42,104,138] and increased ignition potential from human activity [139]. For example, in desert ecosystems of the western U.S., native perennial vegetation is extremely slow to regenerate after fire, and recovery is complicated by non-native species and additional direct effects of climate change [31,32]. In these areas, proactive measures for fire prevention and suppression may be appropriate.

Approach 3.2: Alter Forest Structure and Composition to Reduce the Risk and Spread of Unacceptable Fire

Forest structure can play a large role in burn severity outcomes across a landscape [98,140]. Legacies from the past few centuries of forest and fire management in the U.S. have often resulted in critical changes to fuel loading, increasing the likelihood of wildfires that burn outside of the range of acceptability [141–144]. In response, managers have begun to implement a variety of treatments to alter forest structure and composition, most notably mechanical thinning [145–147], prescribed burning [98,148,149], and containing and managing (as opposed to suppressing) acceptable wildfires for resource benefit [150–152]. These techniques have been effective in reducing fuel loads and, subsequently, mitigating fire risk, severity, and intensity [81,86,91,153–156]. In addition to limiting the likelihood of unacceptable fire, decreasing stand density can help to reduce competition and buffer against mortality due to climatic stressors [157,158].

Approach 3.3: Establish or Maintain Fuel Breaks to Stop the Spread of Unacceptable Fire

In the western U.S., an increase in the occurrence and size of large fires is an observed trend linked to climate change that is expected to continue [10,24]. Independently or in combination with fuel reduction treatments, fuel breaks can be successful for managing fire size in appropriate systems [159,160]. Fuel breaks are intended to break the continuity of fuels and hinder fire spread but can also facilitate rapid access to fire suppression resources [159,161]. Fuel breaks can be pre-established natural or human features (e.g., bodies of water, areas devoid of fuels such as rock, or roads) [162], but they can also be created proactively during or prior to fire events for the specific role of breaking fuel continuity [163]. Spatially arranging proactive fuel breaks on landscapes in concert with other existing breaks, such as water bodies, can maximize the potential to limit wildfire size [164]. However, concerns exist about the efficacy of fuel breaks in certain circumstances, including their potential to encourage the establishment and spread of invasive species [165].

Strategy 4: Limit the Effects of Unacceptable Fire and Promote Post-Fire Recovery

Fire regimes altered by climate change are more likely to result in fires that are considered unacceptable due to size, severity, fire behavior, or location of occurrence, and will necessitate greater sophistication in fire mitigation and recovery strategies [20,166,167]. For example, patches that are large and/or burned at very high intensities associated with extreme fire behavior often create high severity effects such as soil and hydrologic challenges in addition to the slow or non-existent regeneration of key plant species [168–170]. As the climate continues to change, vegetation regeneration may be limited after large, severe wildfires [33,171,172]. Thus, preventative treatment (pre-fire) and/or active restoration (post-fire) will be important considerations necessary for mitigating ecosystem effects and enhancing recovery [20,38,166]. Many of the below approaches relate to post-fire actions, though preventative treatments implemented to reduce the risk that a fire is unacceptable (see Strategy 3 above) are also expected to increase survivorship and regeneration [173].

Approach 4.1: Promote Habitat Connectivity and Increase Ecosystem Redundancy

Increasing habitat connectivity and ecosystem redundancy have the potential to facilitate recovery through revegetation and repopulation [71,174,175] and are preventative measures that can buffer against the effects of unacceptable fire. Proximity to source populations and corridors provide pathways for vegetation regeneration and wildlife repopulation [176–178]. Promoting the replication of specific ecotypes at the landscape or regional scale and over a range of abiotically diverse locations also hedges against the loss of a species or community type in a single fire event [179,180].

Approach 4.2: Maintain or Create Fire Refugia

Fire refugia are locations that have not been adversely affected during previous fires [181]. They harbor species that have survived past fires, providing habitat and a source for the recovery of surrounding areas affected more heavily by fire [181,182]. A robust network of refugia provides important continuity of ecological function, habitat, source populations, and other resources to allow the return of ecosystem structure and function following disturbance [183,184]. As the changing climate puts more stress on ecosystems and constrains post-fire regeneration opportunities, refugia reduce the risk of forest type conversion and provide some protection against the negative impacts of large, high-severity wildfire [181].

Approach 4.3: Stabilize and Enhance the Physical Fire Footprint

High-severity fire can change both biotic and abiotic ecosystem characteristics, which in turn affect ecological processes and associated ecosystem services. For example, the post-fire alteration of hydrologic function has had significant impacts on aquatic ecosystems [185] and high-severity fire can reduce carbon storage [186]. Extreme flooding and erosion events following stand-replacing fire have been tied to historic periods with warm and dry climates [187]. Exposed mineral soil is the primary factor controlling post-fire hillslope erosion, and dry mulches can be highly effective in reducing post-fire runoff and erosion [188]. Treatments can also partially and gradually reverse incising channels

to conserve riparian areas [189]. Equally valuable could be avoiding post-fire practices that may be inconsistent with efforts to restore ecosystem functions, such as seeding exotic species, livestock grazing, ground-based logging, removal of large trees, and road construction [190,191].

Approach 4.4: Promote Recovery of Native Vegetation and Habitat

Fire-adapted native plant species and communities may confer resilience to future climate or fire disturbance, even in novel assemblages [192]. Activities that promote the recovery of such native vegetation and habitat can occur before or after a fire event. For example, in some cases, preventative fuel-reduction treatments have been shown to promote native tree regeneration following high-severity fire [193,194]. Following fires, active planting or seeding of native species can enhance the rate of regeneration and/or boost competition with disturbance-adapted invasive species [195,196]. Post-fire revegetation throughout an entire burned area can be unnecessary, unrealistic, or not practical. In these cases, focusing on smaller target areas with higher risk and/or higher probability of revegetation success may be a strategic approach [197].

Strategy 5: Maintain and Enhance Structural, Community, and Species Diversity Using Fire and Fuels Treatments

Landscapes with higher structural, community, and species diversity may benefit from enhanced resilience to the anticipated effects of climate and fire regime changes [198–200]. For example, in southwestern mixed conifer forests, the heterogeneous application of fire enhances structural and compositional diversity, which may increase resilience to future change [170]. Projections of climate and fire regime change are more uncertain at smaller scales [201,202], and the potential effects and outcomes for individual jurisdictions or projects are unpredictable. Promoting diversity and heterogeneity from the stand to landscape scale will increase the likelihood that some subset of species and vegetation communities will persist in the uncertain future [203–206].

Approach 5.1: Maintain or Increase Structural Diversity from Stand to Landscape Scales

Structural diversity is a direct result of species and age class diversity because vegetation structure relates to functional types and growth patterns. Trees and other key plant species have different vulnerabilities at different ages. Diverse age classes dilute the threats posed by individual disturbance events, potentially increasing resilience [207]. Structural complexity is also associated with higher levels of biodiversity than more uniform stand structures [208,209]. The structural modification of forest vegetation, such as through enhancing structural diversity and vertical and horizontal gap space, also alters fire behavior by reducing fuel continuity [210,211]. Thus, a more structurally homogenous forest may be more susceptible to unacceptable fire [212]. In a feedback effect, forests that experience large and/or high-severity fire effects may regenerate with a more homogeneous structure [98,213,214].

Approach 5.2: Promote Diversity within and among Communities to Enhance Fire Resilience

Diverse communities are generally better at resisting stressors such as climate change and have shown enhanced resilience to disturbance. They include a range of plant growth forms, functional types, and traits that together contain a broader suite of adaptations to changing environmental conditions [215,216]. Functional diversity of the pre-fire vegetation community may be an important factor in ecosystem recovery or reorganization following mortality and recruitment failure, which can be especially important in landscapes that have undergone large fires [217]. Landscape-level diversity can provide a similar buffer to disturbance and offer pathways to recovery on broader spatial scales [66,218,219].

Strategy 6: Identify, Promote, and Conserve Fire- and Climate Change-Adapted Species and Genotypes

The effects of climate change have already begun to exert selective pressure on plant species [220–224]. We can begin to identify species and genotypes that may be best suited to

future conditions, as well as those that are not, by observing and documenting species and individuals that are currently persisting and adapting to altered climate and fire regimes. Conserving and promoting climate- and fire-resilient species and genotypes that are already present in a given area may allow a similar vegetation community to persist further into the future [225,226]. Species can be identified based on the observed response to current changes or functional traits expected to confer resilience [227]. Efforts can then be made to locate and protect wild populations and propagate plant materials for use in revegetation.

Approach 6.1: Promote Native Species and Genotypes That Are Better Adapted to Future Climate and Fire Regimes, Disfavor Species That Are Distinctly Maladapted

Using climate- and fire-adapted species and genotypes for planting and seeding has the potential to increase the persistence of populations, communities, and entire ecotypes [228,229]. There may also be opportunities to determine which species and genotypes appear to be adapting poorly to fire disturbance and recovery and, consequently, make management decisions to discontinue investing in their persistence [230–232]. Disfavoring maladapted species or genotypes could include a range of tactics, from cessation of their use in planting and seeding to active removal to reduce competition.

Approach 6.2: Use Plant Materials from Regional Areas That Have Current Climate and Fire Regimes Similar to Anticipated Future Conditions

Modeling shows that many ecoregions are expected to experience future climatic conditions similar to current conditions at different elevations and latitudes [233–236]. Across these latitudinal and elevational ranges, individual plant species are often present as various unique ecotypes, depending on local conditions [237]. The migration of ecotypes from a constricting range to one that is expanding may conserve genetic diversity and specific traits adapted to future conditions. However, the success of natural migrations like this is likely to be challenged by the pace of climate change, discontinuity in species ranges, or barriers to migration [238]. Assisting the introduction of genetic material from populations that are already adapted to probable future climate and fire conditions may help a subset of a site's current suite of species to persist longer into the future [239–241]. Where there is uncertainty in future climate and fire regimes, diversifying the sources of plant materials to include a range of possible future conditions may help hedge bets [242,243]. This approach may require expanding the acceptable geographic range of plant materials used in revegetation [244]. Note that this approach addresses the movement of ecotypes/genotypes within a species, whereas Approach 7.1 addresses assisted migration of novel species.

Strategy 7: Facilitate Ecosystem Adaptation to Expected Future Climate and Fire Regimes

Promoting species adapted to future conditions increases the likelihood that forests and other fire-adapted ecosystems will persist through or recover from increased fire disturbances and novel fire regimes [67,245]. The ability to persist or recover will reduce the likelihood of undesirable vegetation type conversion (e.g., from forest to non-forest conditions, such as shrublands and grasslands) [246,247]. In some cases, though, traditional management may not be effective in preventing significant changes [35,248]. The active facilitation of ecosystem adaptation provides the opportunity to align vegetation communities with new fire regimes, reducing the likelihood of undesirable fire behavior and ecosystem response [45,249,250]. Effective implementation of this strategy may require management actions that are unconventional and outside of current agency or organizational guidelines, compelling cycles of rapid learning and adjustment. These rapid learning cycles may be best achieved through an adaptive management framework, with actions based on the best science, carried out with caution and explicit intention, documented and effectively monitored to assess outcomes, and adjusted according to robust monitoring feedbacks.

Approach 7.1: Facilitate the Movement of Species That Are Expected to Be Adapted to Future Climate and Fire Regimes

Current species may not be able to persist under future climate and fire regimes [44,246,251]. Consequently, new species must establish and disperse across sites where they are not currently present. Especially in areas that are on the southern or low-elevation edge of an ecoregion, the current suite of species is expected to shift on decadal time scales [252]. Proactively preparing for such shifts may include facilitating the movement of species whose current habitat, possibly from lower elevations or latitudes, is similar to a potential future habitat at the site. Natural species migrations may require too much time to keep up with the rate of change. Additionally, there is evidence that there may be prolonged delays between species arrival and species expansion at a site [253], and planting can help shorten these delays [254].

Approach 7.2: Use Fire as a Tool to Align Existing Vegetation Communities with Changing Climate and Fire Regimes

There is an opportunity to proactively begin increasing the frequency of prescribed fire and managed wildfire in areas where fire return intervals are expected to decrease based on climate projections [45]. Especially in locations experiencing mild fire years, fire can be used to regulate future fire intensity and increase resilience to future fires [91,255]. Anticipating projected changes has the benefit of empowering managers to guide climate- and fire-induced transformation of existing vegetation communities. Active and early management that acknowledges likely future fire regimes may enable more successful transitions and preserve key structural elements, functions, species, and ecosystem services [35,256,257]. These actions can decrease the likelihood of unacceptable fire and unacceptable fire effects.

Strategy 8: Use Fire Events as Opportunities for Ecosystem Realignment

The immediate aftermath of a disturbance provides a very practical window for realigning successional trajectories to expected future conditions instead of historical references [71]. Facing altered climate and fire regimes, some forest types and vegetation communities will be unlikely to recover from large-scale or high-severity wildfires [35]. Traditional revegetation efforts in these forests may result in species ill-suited to the sites they occupy or dominance of other undesirable (e.g., invasive non-native) species, potentially resulting in maladapted ecosystem trajectories [247,258]. In such areas where vegetation type change is likely to occur following fire, despite management attempts to resist change, realignment may be a preferred option [238]. An alternative management approach would be to guide ecosystem realignment calibrated to emerging climate and fire regime realities, acknowledging changing fire regimes and planning for re-burns.

Approach 8.1: Revegetate Burned Areas Using Fire-Tolerant and Drought-Adapted Species and Genotypes

Traditional post-fire revegetation efforts generally seek to restore a burned area to a pre-fire vegetation community [190]. Especially in the dry forests of the southwestern U.S. and other ecosystems at the southern edge of their ranges, these efforts are not always meeting their targets [195]. Revegetation using climate- and fire-adapted species and genotypes from a broader geographic range could result in a plant community that is better adapted to future conditions [228,238,249]. Using seedlings that have been conditioned for drought and higher temperatures may also confer adaptation in post-fire plantings [259]. This approach involves intentional management to establish or maintain valued services by realigning ecosystems to changing fire regimes.

Approach 8.2: Allow for Areas of Natural Regeneration to Test for Future-Adapted Species

Though revegetation is an important approach, there is also an opportunity after fire events to allow for areas of unassisted, "passive" recovery or autonomous adaptation [71]. Observing and documenting patterns of natural regeneration may provide insight into species, and even genotypes, that are able to establish and grow under increasing climate

and fire stressors (e.g., [260–262]). Knowledge gained from such experimentation could prove very useful in determining appropriate references and expectations for ecosystem recovery under changing climate and fire regimes. Plant materials could also be gathered to be used for active revegetation in similar sites. This approach allows for autonomous realignment, without active management intervention, and does not establish a desired condition, but it may seek to learn and benefit from emerging ecosystems.

Approach 8.3: Maintain Ecosystems That Have Undergone Post-Fire Type Conversion or Realignment

Increased fire frequency or severity may exceed the resilience of some ecosystems, pushing them into a new state and resulting in a type conversion of the vegetation [246,263,264]. This realignment, or autonomous adaptation, may shift key functions or services provisioned by the original plant community, but restoration to pre-fire conditions may be unrealistic [238]. Specifically, revegetation with species that are no longer able to survive at a site presents a high-risk investment and may not be ecologically practicable. It is likely that many type-converted systems such as grasslands and persistent shrublands will prove to be relatively well adapted to future fire and climate conditions [265,266]. In a resource-limited management environment, it may be beneficial to acknowledge that some type-converted areas may have fewer costs and more benefits when managed in their new state [267]. This approach acknowledges that realignment has already happened and is better adapted to the altered fire regime and seeks to maintain beneficial aspects of the emergent post-fire ecosystem.

Strategy 9: Promote Organizational and Operational Flexibility

Spatial and temporal variabilities in climate change impacts pose challenges for managers working at the scale of individual jurisdictions or project boundaries. Planning and budgeting time and other resources in the face of this uncertainty will greatly benefit from institutional flexibility and organizational learning [71,268,269]. Management organizations that are able to respond adaptively and creatively to changing fire regimes may be able to increase efficiency and successful outcomes of management actions [270]. Organizational flexibility will require explicit acknowledgment that increased wildfire activity can no longer be considered anomalous, and traditional institutional practices may not be sufficient to respond to changing conditions [271].

Approach 9.1: Develop Adaptive Staffing and Budgeting Strategies

Agencies responsible for fire prevention, response, and recovery are generally operating with limited personnel and financial resources [272]. Internal policies and regulations as well as public views about fire management can restrict the options for reallocating resources in an actionable timeframe [273–275]. At the administrative level, embedded and longstanding policies are often inflexible, but innovative solutions may be possible within these constraints [276,277]. Looking to creative options at the operational level and partnerships with boundary organizations may increase capacity and flexibility within fire-prone regions [66,278,279].

Approach 9.2: Explicitly Consider Changing Climate and Fire Regimes during the Planning Process and Adaptive Management Cycle

Expected changes to future climate and fire regimes may necessitate a shift in framing management goals and objectives in planning cycles [28,280]. There are obvious challenges and some opportunities that stem from these changes, many of which managers are already experiencing [101]. Ensuring that the realities of climate-induced changes to fire behavior and effects are explicitly discussed early in the planning process and frequently revisiting goals and objectives will ensure that managers are making decisions using the best available science and having weighed various options [281].

Approach 9.3: Engage and Incorporate Values of Indigenous Communities in Fire Management Decisions

Members of the fire science and management community are working to incorporate traditional knowledge and values of Indigenous peoples in fire management decisions, emphasizing responsible collaboration from planning through implementation [82,282]. Including perspectives from both western science and Indigenous knowledge systems adds value to management and can increase successful outcomes of climate and fire adaptation actions [283,284]. Opportunities exist to respond and adapt fire management operations with cross-cultural partnerships and programs that support traditional fire practitioners, an Indigenous fire ethic, and cultural burning [60,87]. Cultural burning practices can provide new ways of thinking for non-Native fire managers that allow for increased learning about locally adapted fire management solutions. To successfully adapt to changing fire regimes under climate change requires collaboration and partnerships that share knowledge through respectful consultation and trust [82].

Strategy 10: Promote Fire-Adapted Human Communities

Changing climate and the related effects on fire regimes and ecosystems do not exist independently of human communities. Viewing these changes in the context of an integrated socio-ecological system provides an opportunity to consider the important role of people in adaptation efforts [285]. Changing fire regimes affect not only the natural environment but also challenge human communities in new ways [18,286]. Human societies and the environments we inhabit are equally being pushed to the limits of our capacities to adapt and react by the rapid pace of global environmental change [287–289]. Individuals and communities have essential responsibilities within a climate adaptation framework, both in modifications to the physical environment and our collective understanding of challenges and solutions.

Approach 10.1: Increase Fuel Reduction Treatments in the Wildland–Urban Interface (WUI)

Many people live in communities located in areas that are susceptible to wildfire [290]. Especially in the western U.S., there are abundant low-density rural areas, small communities, rapidly growing suburban developments, and expanding metropolitan areas that are adjacent to forests that have historically burned, and where fuels and climate conditions have combined to increase future fire risk [28,271,291]. These wildland–urban interface areas are an excellent example of locations where an unacceptable fire might be defined by any occurrence of fire at all [292–294]. Taking decisive action to prevent or reduce the likelihood that inevitable future fires will negatively impact human communities is inherent in socio-ecological adaptation to climate and fire futures [20,166,167].

Approach 10.2: Actively Promote Broad Social Awareness and Increase Education about Anticipated Effects of Climate Change on Fire Regimes

Adaptation to future climate and fire regimes will require changes to "business-as-usual" resource management [166,272]. Enacting change can be intimidating and practically challenging, but the risks of inaction also present grave challenges [295]. Climate science and fire ecology are complex and nuanced fields, but both have benefitted from concerted efforts to advance science communication to the public [70,296–298]. Continuing to support and improve awareness and education about the impacts of climate change on fire regimes and ecosystems through programs and planning frameworks, such as FireWise USA, Community Wildfire Protection Plans, and Fire Adapted Communities, can only serve to reduce barriers to implementing adaptation management action [299–301].

4. Adaptation Demonstration Project

Investigators from Southwest FireCLIME and the Northern Institute of Applied Climate Science tested the ability of the Fire Menu to inform decision making in the context of a real-world management project by convening a hands-on workshop centered on a fire-focused restoration project in the Kaibab National Forest (KNF) in northern Arizona.

The workshop brought together 31 participants, including regional scientists and land managers from the KNF and neighboring jurisdictions, to discuss the North Kaibab Ranger District's Kaibab Plateau Ecosystem Restoration Project (KPERP). The workshop took place over three days in February 2020 and followed the general Adaptation Workbook-based format of the Adaptation Planning and Practices workshops [70]. During the workshop, participants worked through the steps of the Adaptation Workbook: they reviewed the effects of climate change on fire in forested ecosystems; identified challenges and opportunities for fire managers; and developed actionable steps to adapt forests to changing fire regimes (see Figure S2 for complete workshop agenda).

4.1. DEFINE Location and Project (Step 1)

The first part of the workshop used a series of short presentations to set the stage for the project, describing local ecosystems and fire regimes and defining the scope and scale of the KPERP. The KPERP covers 518,000 acres that include multiple vegetation types, primarily ponderosa pine forests, mixed conifer forests, and pinyon–juniper woodlands. Throughout the project area, forest density is higher than desired historic reference conditions due to over a century of fire suppression. The overarching goal of the KPERP is to restore landscape-scale fire resilience. Using a phased process of mechanical thinning treatments and increased prescribed fire, KPERP partners intend to promote structural heterogeneity, reduce the risk of high-intensity wildfire, and protect the wildland–urban interface.

4.2. ASSESS Regional and Local Climate Impacts (Step 2)

A second set of short presentations established regional trends and projections in climate change as well as potential impacts on local ecosystems and fire regimes. The group then discussed the climate change impacts of highest concern for the project area: warmer annual and seasonal temperatures, increases in drought- and heat-induced tree mortality, more pest- and pathogen-induced tree mortality, higher vapor pressure deficit and lower relative humidity (RH), greater area burned at high severity, and longer fire season length.

4.3. EVALUATE Management Objectives Given Projected Impacts and Vulnerabilities (Step 3)

Participants were able to recognize both challenges and potential opportunities linked to climate change and fire. Many managers noted that hotter and drier conditions during the summer have the potential to move conditions out of the prescription for controlled burns, reducing windows of feasibility for implementing treatment. Similarly, variable burn windows could create conflicts with other forest uses such as recreation (e.g., hunting) and wildlife phenology (e.g., goshawk nesting). A few participants cited the risk to the mesic mixed conifer forest type, which occurs in the project area at the southern end of its range and could be lost due to proximate climate impacts before treatments are implemented. Participants also discussed human dimensions concerns, including challenges in matching the KNF workforce to treatment needs. On the other hand, participants recognized that shifts in seasonality may create new windows during the year (e.g., extended shoulder seasons) for implementing prescribed burns or mechanical treatments when weather conditions had once been constraints. Additionally, changing conditions may enable or even encourage managers to experiment with non-traditional burning techniques. Ultimately, management objectives were considered feasible with some adjustment to tactics.

4.4. IDENTIFY Adaptation Approaches and Tactics (Step 4)

Considering project objectives, challenges, and opportunities, participants then began to select adaptation strategies and approaches from the Fire Menu that best facilitated progress toward current management goals while addressing difficulties imposed by changing fire and climate regimes (Step 3). During the selection process, we encouraged participants to identify implementation tactics that bridge gaps between adaptation approaches and actions. Likewise, some managers already had tactics in mind, and they linked these to the Menu's approaches and strategies, clarifying the adaptation intent of

the chosen actions. Numerous adaptation tactics and approaches could apply at various points in time or in the landscape, but the strategies and approaches that received the most endorsement are presented in Table 2.

Table 2. Adaptation strategies and approaches selected during the KPERP workshop.

Strategy	Approach
1: Sustain fire as a fundamental ecological process	1.1: Restore or maintain fire in fire-adapted ecosystems
3: Reduce the risk of unacceptable fire	3.2: Alter forest structure and composition to reduce the risk and spread of unacceptably severe fire
5: Maintain and enhance structural, community, and species diversity using fire and fuels treatments	5.1: Maintain or increase structural diversity from stand to landscape scale
6: Identify, promote, and conserve fire- and climate change-adapted species and genotypes	6.1: Promote native species and genotypes that are better adapted to future climate and fire regimes, disfavor species that are distinctly maladapted
7: Facilitate ecosystem adaptation to expected future climate and fire regimes	7.1: Facilitate the movement of species that are expected to be adapted to future climate and fire regimes
	7.2: Use fire as a tool to align existing vegetation communities with changing climate and fire regimes
9: Promote organizational and operational flexibility	9.1: Develop adaptive staffing and budgeting strategies

4.5. MONITOR and Evaluate Effectiveness (Step 5)

Finally, the group discussed monitoring variables that could be used to measure progress toward meeting project adaptation goals. An important distinction made was that this was not "climate change monitoring," but monitoring the effectiveness or success of the actions chosen. Proposals included measuring the basal area pre- and post-treatment, conducting burn severity mapping to uncover trends, and the use of lidar to assess forest structure.

At the end of the workshop, participants provided feedback on the Fire Menu and Adaptation Workbook and articulated what had been most impactful about the experience (see Figure S1 for Menu feedback survey). Multiple KNF staff expressed appreciation for a menu format that included core resilience strategies common to Forest Service management, but they also provided clear and explicit approaches for facilitating climate adaptation through active transition. Though transition can be a controversial topic in resource management, participants expressed and demonstrated increased comfort with this option by the end of the workshop, especially when framed as a set of choices within a spectrum of adaptation strategies and approaches. For example, a suggestion was made that management choices typically centered in a historic or natural range of variability could also be usefully informed by "future range of variability." This would not preclude resilience strategies but would help clarify a conceptual framework for also considering transition strategies.

5. Concluding Remarks

Land and resource managers face new challenges in applying current climate science and fire ecology to operationalize adaptation in day-to-day practice. The Adaptation Menu for Fire Management presents users with a full spectrum of possibilities ranging across the concepts of resistance, resilience, and transition, and provides logical connections between concept and action. These were strengths highlighted by the workshop participants during reflection at the end of the workshop. The group also expressed interest in continuing future collaboration as part of a Kaibab Climate Workgroup to keep regional conversations, science, and management efforts around fire and climate adaptation moving forward in the future, including by sharing the Fire Menu and Adaptation Workbook process with other audiences. Ultimately, the Menu owes its strength to the co-production model and

the insights generated by genuine partnership between professionals with differing, but complementary, skillsets and perspectives. Though the Menu was created by and for a group focused on fire and climate in the southwestern U.S., the strategies and approaches it contains are applicable far beyond one region. Groups in other ecoregions may need to adjust the wording and develop unique tactics for implementation but will nonetheless likely find themselves working with applicable strategies and congruous ideas. Indeed, these strategies could be applicable not only within the U.S. but also within fire-prone ecoregions in many countries. In all these places, this Menu can be a component of broader educational efforts about the beneficial effects and uses of fire, presenting clear strategies for addressing uncharacteristic and unacceptable fire in an era of climate change. The Fire Menu is thus both a tool and a catalyst; we encourage others to use it directly, but also to view it as a foundation from which to explore all possibilities for adaptation to changing fire and climate regimes.

Appendix A Fire Menu with Example Tactics

Strategy 1: Sustain Fire as a Fundamental Ecological Process

Approach 1.1 Restore or Maintain Fire in Fire-Adapted Ecosystems

Example tactics:

- Restore fire resilience using prescribed fire and mechanical treatments to manipulate structure and fuels
- Promote fire- and drought-adapted species and communities
- Increase use of managed wildfires whenever possible

- Restore cultural fire practices

Approach 1.2 Develop Fire Use Strategies in Altered or Novel Ecosystems Where Fire Can Play a Beneficial Role

Example tactics:

- Manage forest restoration for future range of variability
- Consider using more prescribed fire, where supported by evidence
- Consider using prescribed fire in non-traditional ways (e.g., low-intensity controlled burning in mesic mixed conifer to reduce fuels and risk of high-severity fire)

Strategy 2: Reduce the Effects of Biotic and Abiotic Stressors Affecting Fire Regimes

Approach 2.1 Remove and Prevent Establishment of Non-Native Invasive Species That Alter Fuel Regimes

Example tactics:

- Increase inventory and monitoring of non-native invasive species, especially early detection
- Use mechanical or chemical methods to eradicate high priority populations of non-native invasive species
- Create and enforce regulations for internal staff, contractors, and the public to prevent accidental introduction of non-native invasive plant material

Approach 2.2 Maintain or Improve the Ability of Forests to Resist Pests and Pathogens That May Alter Fuel Regimes

Example tactics:

- Increase inventory and monitoring of pests and pathogens, focusing on high priority areas
- Anticipate the arrival of pests and pathogens and prioritize management actions
- Promote species, age class, and stand-structure diversity to reduce density of a host species
- Use chemical control in heavily infested areas
- Promote pest- and pathogen-resistant species or genotypes during thinning and planting
- Restrict harvest and transportation of logs in or near stands with known infestations

Approach 2.3 Limit, Selectively Apply, and Monitor Land Uses That Increase Fire Risk or Threaten Fire Resilience

Example tactics:

- Actively manage fire risk in areas of heavy recreational use
- Encourage recreational use in areas with low fire risk
- Limit increased WUI area resulting from development and urban expansion
- Monitor and enforce contractor/lease holder fire safety compliance

Strategy 3: Reduce the Risk of Unacceptable Fire

Approach 3.1 Protect Fire-Sensitive and Vulnerable Ecosystems from Fire

Example tactics:

- Suppress ignitions in areas sensitive to fire
- Control fire-adapted non-native invasive species in fire-sensitive native vegetation
- Implement and maintain fuel breaks in strategic locations
- Encourage acceptable fire in buffers surrounding fire-sensitive areas
- Full suppression of wildfires that threaten ecological consequences that conflict with management objectives

Approach 3.2 Alter Forest Structure and Composition to Reduce the Risk and Spread of Unacceptable Fire

Example tactics:

- Implement strategic fuel treatments/fuel breaks to reduce fire behavior
- Reduce tree density (total basal area) within stands (thinning, Rx burning), considering historic ranges of variation and anticipated future conditions
- Reduce ladder fuels and increase crown base height using mechanical or Rx burn treatments

Approach 3.3 Establish or Maintain Fuel Breaks to Stop the Spread of Unacceptable Fire

Example tactics:

- Create fuel breaks preventatively in strategic locations
- Create fuel breaks to protect infrastructure (WUI) and other non-negotiable resources

Strategy 4: Limit the Effects of Unacceptable Fire and Promote Post-Fire Recovery

Approach 4.1 Promote Habitat Connectivity and Increase Ecosystem Redundancy

Example tactics:

- Increase overall area, number of patches, and sites in various successional stages of each community type
- Locate and map habitat types, corridors, and patches at a landscape scale, identify priorities for protection and/or restoration
- Restore native species and vegetation structure in areas of low connectivity
- Work with partners to achieve connectivity goals at the landscape level

Approach 4.2 Maintain or Create Fire Refugia

Example tactics:

- Inventory and study existing fire refugia to identify processes and conditions that create fire refugia
- Add refugia to maps/lists of resources requiring special protection during fire suppression/management, communicate this information to fire managers
- Identify and protect focal areas for regeneration and recovery following a disturbance

Approach 4.3 Stabilize and Enhance the Physical Fire Footprint

Example tactics:

- Use contour felling, wood mulching, and other slope stabilization techniques to reduce soil loss and post-fire flooding
- Create suitable physical conditions for natural regeneration through site preparation after a burn to promote seed establishment
- Seed and re-plant with native species
- Avoid or limit disturbances such as grazing, logging operations, and road construction

Approach 4.4 Promote Recovery of Native Vegetation and Habitat

Example tactics:

- Experiment with seeding or planting native species to compete with invasive non-native species expected to colonize after fire
- Restore or increase a community type across a range of topographic positions and elevations
- Plant native species with an emphasis on those adapted to expected future conditions

Strategy 5: Maintain and Enhance Structural, Community, and Species Diversity Using Fire and Fuels Treatments

Approach 5.1 Maintain or Increase Structural Diversity from Stand to Landscape Scales

Example tactics:

- Employ techniques such as variable-density treatments or irregular fire return intervals to encourage the development of multiple age cohorts
- Promote age class and structural diversity through regeneration harvest, thinning, prescribed fire, and managed wildfire

- Implement a variety of management activities or silvicultural prescriptions across areas with similar starting conditions to diversify forest conditions and evaluate different management approaches
- Use prescribed burning to create openings or early successional habitat

Approach 5.2 Promote Diversity within and among Communities to Enhance Fire Resilience

Example tactics:

- Maintain up-to-date inventory of native understory plant species in management area, monitor health of populations
- Use silvicultural treatments to promote and enhance diverse regeneration of native species
- Plant desired native species to augment their populations in areas otherwise expected to regenerate naturally
- Identify keystone species and roles in fire-adapted systems, maintain or restore where possible
- Prioritize and maintain unique sites and sensitive or at-risk ecological communities

Strategy 6: Identify, Promote, and Conserve Fire- and Climate Change-Adapted Species and Genotypes

Approach 6.1 Promote Native Species and Genotypes That Are Better Adapted to Future Climate and Fire Regimes, Disfavor Species That Are Distinctly Maladapted

Example tactics:

- Plant stock from seeds collected from local trees that have survived past fire and other disturbances
- Monitor areas of natural regeneration to identify well-adapted phenotypes
- Protect existing species resilient to fire and other disturbances
- Promote species with shorter times to sexual maturity
- Promote species with wider ecological amplitude
- Promote species with specific fire-/drought-resilient traits
- Remove unhealthy individuals of a declining species to promote other species known or expected to be better adapted
- Do not continue to promote species that are known or expected to be maladapted to future fire regimes
- Increase seed banking to preserve fire resilient species and genotypes

Approach 6.2 Use Plant Materials from Regional Areas That Have Current Climate and Fire Regimes Similar to Anticipated Future Conditions

Example tactics:

- Use mapping programs to match seeds collected from a known origin to planting sites based on climate and fire regime data
- Plant seedlings germinated from seeds collected from various locations (i.e., different ecotypes) throughout a species' native range
- Plant stock from seeds of the same species, collected in warmer and drier locations in the region

Strategy 7: Facilitate Ecosystem Adaptation to Expected Future Climate and Fire Regimes

Approach 7.1 Facilitate the Movement of Species That Are Expected to Be Adapted to Future Climate and Fire Regimes

Example tactics:

- Plant disturbance and fire-adapted species on sites within the current range that have not been historically occupied by those species
- Consider planting species native to lower elevations, drier, and/or warmer geographic areas nearby, or areas with more frequent fire, based on projected range expansion

Approach 7.2 Use Fire as a Tool to Align Existing Vegetation Communities with Changing Climate and Fire Regimes

Example tactics:

- Shift prescribed burn seasons to align with projected climatic changes
- Consider using managed and/or prescribed fire to facilitate transition to new fire regimes
- Consider increasing acreage treated with prescribed fire in the short term in areas where current regeneration responses are desirable (and future regeneration trends are uncertain)

Strategy 8: Use Fire Events as Opportunities for Ecosystem Realignment

Approach 8.1 Revegetate Burned Areas Using Fire-Tolerant and Drought-Adapted Species and Genotypes

Example tactics:

- Integrate climate-sensitive revegetation planning into the Burned Area Emergency Response (BAER) and other post-fire activities
- Consider specific experiments such as common gardens to test performance of different species or genetically different populations
- Monitor and control invasive species
- Focus active revegetation efforts in areas where natural regeneration is slow or absent

Approach 8.2 Allow for Areas of Natural Regeneration to Test for Future-Adapted Species

Example tactics:

- Increase post-fire monitoring to collect information on mortality and regeneration at the species level
- Incorporate areas of natural regeneration or "passive realignment" into BAER and other post-fire management and monitor outcomes
- Consider traits such as drought tolerance, shade tolerance, and C3/C4 pathways in monitoring efforts

Approach 8.3 Maintain Ecosystems That Have Undergone Post-Fire Type Conversion or Realignment

Example tactics:

- Consider future range of variability in post-fire management
- Plant species expected to be better adapted to future conditions, especially where natural regeneration is slow or absent
- Create novel communities where the level of disturbance necessitates intensive remediation efforts to recover desired ecosystem services or characteristics (e.g., tree cover)
- Reduce or remove focus on eradication of non-native or aggressive native species where they may form part of a novel community that is preferable to a lack of vegetation

Strategy 9: Promote Organizational and Operational Flexibility

Approach 9.1 Develop Adaptive Staffing and Budgeting Strategies

Example tactics:

- Cross train staff to prepare for short time frame/high-effort projects
- Implement new agreements with partners to increase implementation capacity
- Consider establishing a dedicated staff person to navigate partnerships and agreements
- Strategically use single-year funds

Approach 9.2 Explicitly Consider Changing Climate and Fire Regimes during the Planning Process and Adaptive Management Cycle

Example tactics:

- Devise flexible management protocols to avoid rigid requirements to restore historic conditions
- Explicitly consider opportunities created by a longer prescribed burning season
- Build "if/then" statements before fire or other disturbance events to plan and prepare for multiple future management scenarios

Approach 9.3 Engage and Incorporate Values of Indigenous Communities in Fire Management Decisions

Example tactics:

- Understand the role of Indigenous fire stewardship and cultural burning practices in your geographic area
- Engage in dialogue with Indigenous nations, agencies, and stakeholders early in the planning process, while respecting their right to opt out of participation
- Increase Indigenous representation by supporting Native early career professionals in the fire science and management communities

Strategy 10: Promote Fire-Adapted Human Communities

Approach 10.1 Increase Fuel Reduction Treatments in the Wildland–Urban Interface (WUI)

Example tactics:

- Implement mechanical thinning in areas adjacent to developed areas and structures
- Develop spatial priorities for implementation of thinning or other fire mitigation efforts
- Consider the full spectrum of ecosystem services that may be compromised by unacceptable fire in the WUI (e.g., soil stabilization, flood control, water quality, wildlife habitat, recreation)

Approach 10.2 Actively Promote Broad Social Awareness and Increase Education about Anticipated Effect of Climate Change on Fire Regimes

Example tactics:

- Share climate adaptation plans and examples of implementation with the public
- Explicitly address climate adaptation in agency planning documents made available to the public
- Communicate examples of climate adaptation efforts that have social benefits to stakeholders and the public (e.g., increased opportunities for products such as fuelwood)

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