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Perspective

A fire-use decision model to improve the United States' wildfire management and support climate change adaptation

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SUMMARY

The US faces multiple challenges in facilitating the safe, effective, and proactive use of fire as a landscape management tool. This intentional fire use exposes deeply ingrained communication challenges and distinct but overlapping strategies of prescribed fire, cultural burning, and managed wildfire. We argue for a new conceptual model that is organized around ecological conditions, capacity to act, and motivation to use fire and can integrate and expand intentional fire use as a tool. This result emerges from more considered collaboration and communication of values and needs to address the negative consequences of contemporary fire use. When applied as a communication and translation tool, there is potential to lower barriers to faster and more successful collaboration among stakeholders. Such improvements are a vital part of strategies to address climate adaptation, wildfire mitigation, and the well-being of ecosystems.

INTRODUCTION

Climate change is driving contemporary increases in the area burned by wildfires and the magnitude of impacts in the US each year, with significant consequences across a range of social-ecological systems.[1,2] Simultaneously, land-management choices, including fire suppression, exclusion of cultural burning, forest harvest and planting, and an expanding built environment and agricultural footprint, are reducing fire activity in places where it occurred historically. This fire deficit, representing a relative decrease in fire activity,[3–5] is interacting with climatic fire drivers, resulting in conditions conducive to unusually extensive and severe wildfire. Extreme wildfires pose catastrophic hazards to people,[6] and the emergence of novel fire regimes can lead to irreversible ecological transformations[7] that degrade ecosystem functions and services.

Many US forests and grasslands benefit from fire or are inevitably fire prone. Given that eliminating fire from these systems is neither desirable nor realistic, the intentional use of fire may be the most powerful tool available to natural resource managers to minimize negative consequences of contemporary fire activity and maximize socio-ecological benefits. Sometimes labeled as "good fire" to differentiate it from destructive wildfires and other negative outcomes,[8] we define *intentional fire use* as a decision to purposefully apply fire in the management and modification of landscapes. This includes methods like prescribed fire, managed wildfire, and Indigenous-led cultural burning, which all share a recognition of fire's benefits for ecosystems and communities (Figure 1). Intentional fire use supports a cycle of reciprocal benefits between people and ecosystems. Here, we elaborate on the space between broad intentions and decision implementation, which we characterize as a *decision space*. In their work on drought decision-making, Cravens et al.[9] define decision space as "configurations of people, institutions, and ideas that guide or constrain how actors think about and negotiate... decisions." Similarly, Peterson[10] defines it as "the space between decision and action, wherein constraints are recognized, strategies shift, and compromises develop." To explore decision-making around intentional fire use, we introduce a new decision model structured around components that can

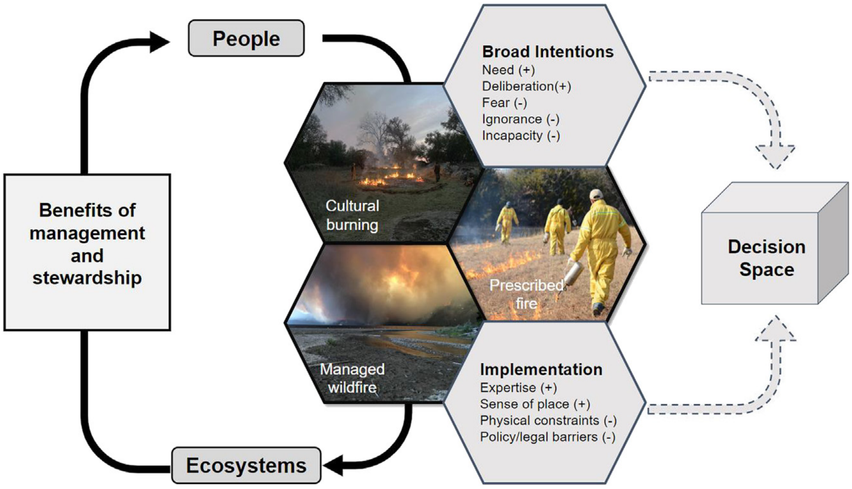


Figure 1. Cycle of benefits from ecosystems and related intentional fire applications

Methods for intentional fire use and relation to a cycle of producing and maintaining ecosystem benefits are highlighted. These include prescribed burns, managed wildfires, and cultural burning by Indigenous communities. (Photo credit: prescribed fire: Oklahoma State NREM; wildfire: Rick Trembath; cultural burn: Nina Fontana).

translate across fire-use and stakeholder types, thereby simplifying and unpacking components within the decision space.

ADDRESSING THE WILDFIRE CRISIS CALLS FOR PROACTIVE ACTION

In 2022, the US Forest Service produced a series of reports that identify an ongoing wildfire crisis as well as a 10-year strategy to address it.[11] While numerous voices, including diverse communities and rights holders, call for a reevaluation of fire management that emphasizes the urgency of the crisis,[12–14] there remains a pressing need to foster inclusivity and equity that considers diverse fire-use methods and stewardship goals. Siloed knowledge, institutional culture, and policy inertia remain barriers to innovation and action in landscape management in addition to political drivers that may moderate more proactive approaches.[15] Ultimately, defining the current wildfire situation as a crisis may lead to continued emphasis on suppression by decision-makers. Alternatively, fire is also a component of efforts to restore and maintain the benefits from and the health of natural systems (Figure 1). These two related emphases may result in a bind in how fire is framed within management discourses.

Finding ways to use fire safely, effectively, and intentionally represents a critical frontier in natural resource management despite significant social-ecological barriers.[12,16] A key federal management goal is to reduce biomass in high-risk areas and promote low-severity fires that increase public safety and help meet long-term goals of ecological restoration and climate adaptation.[17] In practice, fire management activities often concentrate on immediate fire risk mitigation at the expense of addressing the urgency and long-term magnitude of climate change impacts.[18] Such policies can overlook socio-cultural consequences faced by affected communities due to their limited strategic foresight. Moratoriums following disasters or seasonal bans on prescribed and cultural burning, triggered by resource capacity constraints, accidental fire escapes, or public concern, can further delay the implementation of restoration and climate adaptation goals.

INTENTIONAL FIRE-USE CONTEXTS

While key comprehensive strategy documents like the National Cohesive Wildland Fire Strategy (NWFCS)[19] and the 10-year strategy for confronting the wildfire crisis[11] outline pathways for improved management, they alone cannot guarantee implementation. The efficacy of current practices by federal agencies alone, which incurred expenses exceeding five billion dollars between 2009 and 2018,[20] also remains unclear. The feasibility of intentional fire-use (i.e., good fire) actions while wildfire risk remains severe depends on lowering barriers to more collaboration between often siloed management and stewardship contexts. In what follows, we provide background on each of the intentional fire-use types and then propose a new model for characterization and translation of decision-making components across their siloed contexts.

WILDFIRE

Unplanned ignitions and escaped fires from planned ignitions, known as wildland fires or wildfires, pose challenges and opportunities for natural resource managers and entail complex decision spaces. Wildfires often burn in undeveloped forests and grasslands, where fuel is abundant and hazards to people and infrastructure are low, but they can also burn through the wildland urban interface (WUI) and into developed areas. While 98% of wildfires are quickly controlled,[21] extreme fire weather can make containment of wildfires difficult or even impossible.[21–23] Despite the risks they bring, wildfires are inevitable in seasonally dry landscapes,[24] create landscape heterogeneity that confers resilience to future disturbances, maintain ecological function of fire-adapted systems,[25] and provide valuable ecosystem services to communities.[26]

The history of wildfire management in the US provides important context for understanding contemporary decision spaces. In the late 19th and early 20th centuries, large fires in the upper Midwest and northern Rockies played a significant role in the establishment of a national forest service, tasked with protecting timber resources by suppressing fires.[27,28] By 1935, the "10 a.m." policy, emblematic of federal agency fire management norms, mandated that all ignitions be extinguished within a few hours of discovery. The creation of National Forests and National Parks[29] also contributed to the dispossession of Indigenous lands, which limited the capacity for Indigenous people to conduct burns. While federal managers gained a better understanding of fire ecology as the 20th century progressed, Indigenous knowledge of fire was largely overlooked.[30] In 1968, the National Park Service relaxed its universal suppression policy, allowing fires to burn when they did not threaten people or infrastructure; the US Forest Service (USFS) adopted a similar policy in 1974.[31] Events like the 1988 Yellowstone fires[32] tested federal agencies' risk tolerance and their ability to communicate fire's beneficial ecological functions to the public. During the 1980s and 1990s, some fires, mainly in wilderness areas, were designated under "wildland fire use" and managed with tactics other than full suppression, but that nomenclature was abandoned in 2009.[33] While USFS's evolving approach has provided managers with some flexibility, it has also hindered comparison of different management strategies. Specific examples offer insights into how and why wildland fire use has been and could be employed to meet resource management and risk reduction goals (case example 1).

PRESCRIBED FIRE

Prescribed fires are intentional ignitions with specific goals and open containment plans that rely on natural or constructed barriers. They are deliberate, controlled ignitions that follow predetermined burn plans developed through collaboration between ecologists, natural resource managers, emergency services, and stakeholders. Though they are an application of western scientific and management ideals, they may rely idealistically on localized ecological knowledge.[34] They encompass a wide range of practices, from individuals setting small fires on private lands to well-organized operations with extensive documentation and specific containment objectives.[16] Prescribed burning practices make up a substantial component of strategy directives like the National Cohesive Strategy and US Geological Survey (USGS) Fire Science Strategy[35] and account for a large portion of intentional fire acreage nationwide.[36]

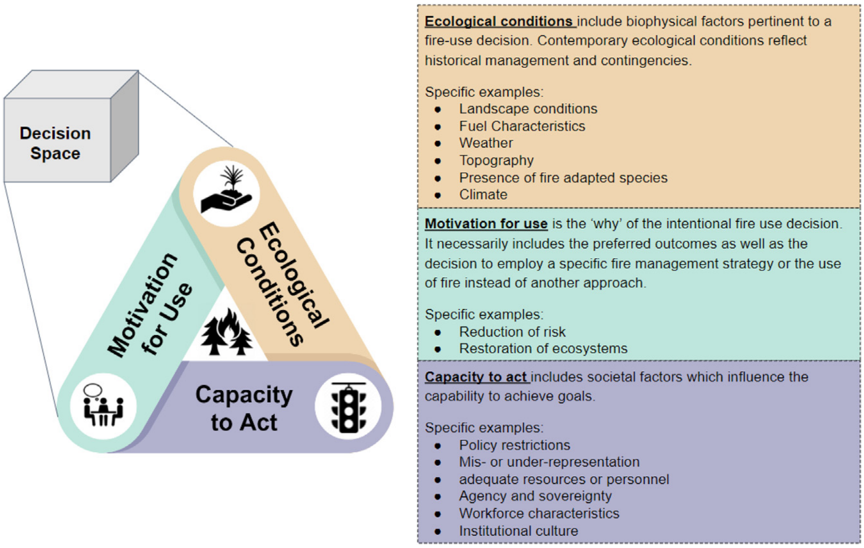
Burn plans are the primary documents guiding prescribed burn decisions. Burn plans establish the optimal conditions for vegetation to burn and achieve desired outcomes.[37] They consider multiple ecological factors, including, but not limited to, temperature, wind, humidity, vegetation moisture, smoke, and public safety. Each burn plan is unique, tailored to specific burn units and prevailing weather conditions, and reflects distinct goals and execution details. Prior to initiating burns, prescribed fire managers, or "burn bosses," assess ground conditions against the prescription outlined in the burn plans to make informed decisions for the day's burn activities.[38] Burn plans not only provide valuable insights for prescribed fire operations but also offer valuable ecological and sociological information that can inform decision-making in other fire-use cases. Recognizing similarities between different fire-use methods allows for knowledge transfer and effective decision-making across contexts.

CULTURAL BURNING

Indigenous peoples around the world, including in North America, have practiced the intentional use of fire for generations to maintain landscapes, promote ecosystem health, and nurture cultural resources for countless generations.[39,40] Some Indigenous communities are fire-dependent, and cultural burn practices uphold cultural traditions related to basketry, language, story, food, and medicine, among many others.[41] Cultural burn practitioners use mixed severity, controlled fire to actively steward species, habitats, and landscapes for numerous cultural reasons. Such practices are commonly known as Indigenous burning or cultural burning.

The legacy of colonization in the US records widespread disruptions to Indigenous practices, including forced removals and relocations of Indigenous peoples by government agencies.[42–44] These disruptions have created significant changes in ecosystems dependent on active fire regimes, particularly cultural fire regimes.[45,46] Traditional livelihoods dependent on those same ecosystems have also suffered.[47] Furthermore, many tribes highlight that without ability to follow traditional burning practices, Native American cultural identities are also at risk.[41,48] Addressing this harm and ongoing risk calls for the revitalization of Indigenous traditional ecological knowledge (ITEK) related to cultural burning across ancestral lands and territories throughout the country. The lands of federally recognized tribes are predominantly managed as Indian trust assets by the federal government and administered by the Bureau of Indian Affairs.[49] This "trust responsibility" to manage tribal lands for the benefit of tribes can create unique barriers to self-determination in the use of fire. Whether ignited by lightning or by Native Americans, fire once shaped many North American ecosystems. Euro-American settlement and 20th-century fire suppression practices drastically altered historic fire regimes, leading to excessive fuel accumulation and uncharacteristically severe wildfires in some areas and diminished flammability resulting from shifts to more fire-sensitive forest species in others. Prescribed fire is a valuable tool for fuel management and ecosystem restoration, but the practice is fraught with controversy and uncertainty. Here, we summarize fire use in the forests and woodlands of North America and the current state of the practice and explore challenges associated with the use of prescribed fire. Although new scientific knowledge has reduced barriers to prescribed burning, societal aversion to risk often trumps known, long-term ecological benefits. Broader implementation of prescribed burning and strategic management of wildfires in fire-dependent ecosystems will require improved integration of science, policy, and management and greater societal acceptance through education and public involvement in land-management issues.[50] These include necessary certifications and training. Many Indigenous land stewardship practices are affected by systems of state or federal laws and rulemaking requiring navigation of the complex political and legal landscape.[43]

Historically, federal and state agencies tended to implement active fire suppression using a command-and-control approach to natural resource management.[51,52] However, efforts to restore fire to ecosystems began in the 1930s in southeastern forests and gained traction in the 1960s with the reintroduction of wildfires and prescribed fires in western national parks and wilderness areas.[53] Concurrently, many American Indian tribes have persistently advocated for the reintroduction of fire to assert their sovereignty through self-governance and



Ecological conditions include biophysical factors pertinent to a fire-use decision. Contemporary ecological conditions reflect historical management and contingencies.

Specific examples:
- Landscape conditions
- Fuel Characteristics
- Weather
- Topography
- Presence of fire adapted species
- Climate

Motivation for use is the 'why' of the intentional fire use decision. It necessarily includes the preferred outcomes as well as the decision to employ a specific fire management strategy or the use of fire instead of another approach.

Specific examples:
- Reduction of risk
- Restoration of ecosystems

Capacity to act includes societal factors which influence the capability to achieve goals.

Specific examples:
- Policy restrictions
- Mis- or under-representation
- adequate resources or personnel
- Agency and sovereignty
- Workforce characteristics
- Institutional culture

Figure 2. The social-ecological decision space for intentional fire use

Left, the sides of the triangle correspond with decision-making components related to motivation, ecological conditions, and capacity to act. Decisions at a focal scale are constrained by processes at broader and finer scales, which range from single events all the way to region-scale processes impacting fire regimes.[56]

stewardship of tribal lands and ancestral territories.[41,50,53] Native communities hold a wealth of ITEK related to fire use and cultural burning.[41] This knowledge is highly valued within and beyond Indigenous communities; its significance was officially recognized by the US Federal Government in December 2022, when the White House Office of Science and Technology Policy (OSTP) and Council of Environmental Quality (CEQ) issued a memorandum that acknowledged ITEK's contribution to scientific, technical, social, and economic advancements. The memorandum centers the importance of ITEK, elevating its role in federal decision-making, including scientific and policy processes.[54]

THE FIRE-USE DECISION SPACE

Ultimately, effective fire management and utilization require a deep understanding not just of biophysical dimensions but also the constraints, historical contexts, and decision-making processes that natural resource managers face. That is, people are part of both the problem and the solution.[55] Those who intentionally use fire, the ways they employ it, their motivations, and their capacity to act need to be incorporated into knowledge frameworks describing the overarching problem and the role of fire use in solving it. By incorporating these considerations into one framework, we propose a new socio-ecological fire-use triangle (Figure 2) to conceptualize and translate decision spaces around intentional fire use.

Early fire triangle concepts summarize the physical characteristics of fire at multiple scales.[57,58] Recent adaptations incorporate social considerations, including the arena where planning decisions are made and the governance dimensions of coupled human-natural systems in fire management.[27] We adapt the decision-space concept by breaking it into three components reflective of biophysical and socio-cultural elements: motivation for the intended burn, ecological conditions, and capacity to act. These components reflect a combination of factors, including land ownership, local physical environment and weather conditions, place-specific knowledge about fire behavior, and a standardized set of tools, technologies, and practices. Fire use also extends across cultural contexts and geographical regions; therefore, understanding decisions where these processes occur is important in aligning future efforts to achieve maximum benefits. Failure to do so risks undesirable outcomes, including negative perceptions, conflicts, and misallocation or inefficient allocation of resources.

ECOLOGICAL CONDITIONS

Ecological conditions for fire-use decision-making may vary considerably across regions and at different times of the year. Despite that, important considerations are often common between different fire-use types. These include prevailing weather and fuel conditions, landscape characteristics like slope and soil types, and the presence of valued or protected species. Decision spaces necessarily must include the dynamics and variability present in these systems as well as the human element. Severe wildfires that disrupt historically fire-adaptive species traits, like individual fire resistance or the development of serotinous cones, can have undesirable impacts on ecosystems and adjacent communities.[59] In ecosystems where high biomass and infrequent, severe fires were historically present, the widespread suppression of fires has created landscape-scale vegetation homogeneity. This promotes larger and more intense fires, with extensive high-severity patches within them.[60] Such situations may also set the stage for short-interval, high-severity reburns.[61–63] Forests are experiencing significant restructuring and composition changes, often transitioning to non-forested states.[64] Other ecosystem types, such as grass and shrublands, are also facing increased frequency and severity of fires, largely driven by extreme fire weather.[65,66]

Like fire management in forests, fire frequency and severity in grasslands can be influenced by prescribed fire, grazing, or a combination of the two, such as patch-burn grazing.[67–69] Suitable meteorological conditions for prescribed burns, or "burn windows," play a crucial role in determining the feasibility of conducting prescribed burns. Climate change affects these burn windows, which in turn have subsequent effects for other decision-making aspects. For instance, in previously fire-dependent ecosystems, prescribed fire is increasingly difficult to use due to increasing occurrence of extreme weather patterns associated with climate change in addition to an overabundance of fuel.

Similarly, areas in the southeast US that have not been burned for a decade or longer may require alternative treatments before burning becomes viable.

Historically, burn windows have been established based on weather conditions and fuel characteristics[70,71]; however, climate change is causing burn windows to shorten during summer seasons.[72] In a continuously changing climate, the definitions of burn windows in their current form may become increasingly irrelevant as burn windows become infrequent and historical burn seasons are curtailed. These issues highlight the growing difficulty of meeting existing burn criteria and emphasize the need for adaptive management strategies to prepare for future changes.[72] Since the effects of climate change are likely to be heterogeneous across different parts in the US, further research may be necessary to identify which ecological parameters should be considered for amendment under different weather and climate conditions to continue to meet prescribed burn objectives.

Cultural burns are subject to the same ecological parameters as prescribed burns, such as burn windows and fuel characteristics. However, seasonal restrictions and resource allocation in the fire management system, such as the availability of fire personnel during high fire seasons, can constrain optimal timing for cultural burning. In addition to considering the typical factors for prescribed burns, cultural burn practitioners assess ecological indicators through a community lens to determine safety and effectiveness. These indicators, identified by tribal practitioners and elders, encompass aspects like fuel loading, tree density/canopy cover, and response of resources to broader climate or habitat influences.[41] These factors are often specific to the local environment and are used to evaluate the condition and quality of the site.

MOTIVATION

The goals motivating intentional fires use are often broadly categorized as risk reduction, safety/hazard related, or ecological.[73] Managers recognize the vital role of intentional fire use as an essential tool to maintain desirable ecosystem states that are compatible with future climate conditions.[17,74] As climate-driven ecological transformations emerge,[7] natural resource management paradigms are evolving to address novel, complex decisions under dynamic ecosystems.[75] Wildfire use is one approach that is complementary with other intentional fire and non-fire management strategies. Because wildfires are inevitable in many ecosystems, finding ways to minimize negative outcomes and derive benefits is a strong motivation for this use type. Wildfire use is consistent with federal management goals to align ecosystems with future climate conditions,[17,19] and natural resource agencies have embraced wildfire use for decades due to its potential to restore or maintain fire-dependent ecosystem processes.[31]

Wildfire use increases the efficacy of mechanical fuel treatments, which aim to reduce the likelihood or severity of future fire events by manipulating aboveground biomass.[76] However, their effectiveness is enhanced when combined with prescribed burning, cultural burning, or wildfire use, as mechanical treatments leave behind fine fuels when they are not followed by fire, and fires alter vertical fuel structure differently than fuel treatments.[77,78] Moreover, fuel treatments are temporary and require regular reapplication to remain effective. Their implementation footprint is small relative to the extent of fire-prone areas, and robust evidence for their effectiveness at the landscape scale remains limited.[79] While fuel treatments are crucial for reducing fire risk, they currently do not and may never match the pace and scale needed to address widespread fire deficits[80] and adapt ecosystems to future climate conditions.

Suppressing wildfires poses inherent risks, but the strategic use of wildfires can help mitigate these risks to personnel. Wildfires often occur in remote areas with limited access and evacuation options. These areas are characterized by steep terrain and hazardous vegetation structures, such as standing dead snags, which impede movement and increase the difficulty of firefighting operations. Additionally, predicting fire behavior at the flaming front is challenging. Incorporating wildfire use into pre-fire planning can assist fire managers in making informed decisions to avoid suppression when dangerous fire situations are likely. Unlike fuel treatments, wildfires have unique effects on vegetation. Previous fires can alter the vegetation composition, which can contribute to more efficient suppression of subsequent fires.[81] By considering wildfire use in planning efforts, fire managers can enhance their ability to respond effectively and safely to fire incidents.

In circumstances where more active management is possible, prescribed burning is one of the most cost-effective tools for achieving goals.[16] Using prescribed fire as a method of reducing the volume of fuel material for wildfire is a primary application. Prescribed fires are also used to maintain agricultural and rangelands and reduce the spread of invasive species. For example, prescribed fires in the plains are used for combating woody plant encroachment into valuable grasslands.[82] Although prescribed fire operations often call for regular re-burning, a long-term cost commitment for agencies, the benefits of implementation can be significant. In areas where private landholding is predominant, prescribed fires are often facilitated through prescribed burn associations (PBAs) or other organizations, which, in addition to education on writing burn plans and conducting fires safely, promote adaptation, co-management, cross-border networking, and collaboration among institutions.[83–85] PBAs can disperse innovative approaches to management and fire education and provide essential equipment.

Prescribed burning has its origins in Indigenous knowledge and practice; however, there are important differences in decision components. Notably, "...the most overarching difference between cultural burning and prescribed burning is that cultural burning is situated in a culture that is deeply rooted to the land which is being burned."[86] This fundamental distinction gives rise to the significant and nuanced differences in the components of the fire decision space. Motivations for cultural burning are centered in intergenerational stewardship. Cultural burning practices aid in the stewardship of medicinal species, materials for basketry, traditional foods, and wildlife habitats, including riparian areas. Additionally, cultural burning improves and maintains water access, hunting grounds, and various management goals related to crops, pest control, range management, fireproofing, and trail maintenance/creation.[87] Many of the objectives of prescribed burns, such as fuels reduction, risk mitigation, and ecosystem maintenance, are natural outcomes of cultural burning motivations often related to individual communities' unique place-specific practices. Sites are intentionally burned for cultural purposes and are regularly monitored and visited on a seasonal basis, creating a form of community-based monitoring. For example, community members may come back to place to evaluate the growth rate, strength, and straightness of a basketry material (willow, sourberry, and redbud) after a burn.

The decision-space framework for cultural fire use incorporates distinct characteristics from other uses. These characteristics include frequency, seasonality, specificity, responsibility, and reciprocity. Cultural burns are aligned with the phenology of culturally important species often requiring more frequent ignitions. Particularized resources and cultural or community needs also contribute to frequency. More so than for prescribed burns, cultural burning could involve specific species or landscapes for finely targeted management and conservation efforts. Additionally, responsiveness to factors like fuel loading, weather conditions, topography, resource quality, and cultural objectives[41,88,89] ensures that fire practices are carried out in a way that harmonizes cultural goals with ecological considerations, aligning them as inherently interconnected. Most importantly, cultural burning is deeply rooted in generational systems of knowledge where language, stories, and practice are passed from elders to youth. This practice is intricately connected to spiritual practices.[88] This spiritual dimension guides and informs these practices, highlighting the significance of language preservation and intergenerational learning.

Cultural burning practitioners start with a community-oriented lens based on connection to place when evaluating the success of a burn. Their focus is on long-term, active stewardship and the ongoing propagation of culturally significant species and landscapes. Success is measured through the lens of place-based ecological, social, and spiritual outcomes. For example, success may look like community connection, building and healing, or reemergence of a dormant native species after a burn, among others. These outcomes are guided by the wisdom and knowledge of community elders and directly linked to cultural practices and traditions. For cultural burning practitioners, success goes beyond immediate ecological changes and encompasses the sustained vitality of the land and its resources. The continuous propagation of culturally important species and landscapes is the central aspect of success, as it ensures the cultural integrity and resilience of community members.

CAPACITY TO ACT

The capacity for intentional use of fire by natural resource managers in the US depends on policy and existing legislation, unstated norms and incentives, and available resources. In 2009, the USFS, the country's largest fire management agency, revised its guidance to no longer assign a single designation to fire events.[90] This shift acknowledges that objectives and tactics can change as fire events progress and conditions evolve, allowing for adaptive decision-making. While this theoretically supports wildfire use, for instance, it has posed challenges in quantifying the extent of area burned under non-suppression tactics and communicating about those activities within and beyond federal agencies.[31] Despite these changes, the ecological importance of wildfire has been repeatedly recognized and codified in federal documents, including the National Cohesive Strategy[19] and the Confronting the Wildfire Crisis report.[91] However, the implementation of tactics beyond full suppression faces obstacles due to concerns over liability and professional accountability concerns among fire management officers.[90]

Efforts are underway to enhance pre-fire planning and risk assessment, identify opportunities for wildfire use, and provide information to guide manager decision-making.[92,93] For example, the "potential operational delineations" (PODs) framework, developed by the USFS, formalizes managers' understanding of landscape conditions, risks to valuable resources and assets, potential fire control locations, and appropriate response strategies. Congress has allocated significant support for these initiatives in high-priority firesheds.[11] The PODs planning processes also recognize and document situations where wildfire use is not appropriate because of high risks to people, infrastructure, or ecosystem services. These innovations, although not yet widely applied, suggest that efforts to improve capacity through greater recognition of the complexity of fire options on a landscape are already under way.

Prescribed burning is carried out by practitioners from public agencies at federal, state, and local levels and private entities, including individual landholders, corporations, and NGOs. The capacity for a given organization to act depends on stakeholder priorities, which often manifest in the form of agency and private burn practitioners prioritizing different areas to burn based on different rationales or objectives. The southern and eastern regions of the US have the largest land area in the WUI,[94,95] resulting in greater complexity of interactions between stakeholders and practitioners. Time since a previous burn and ecosystem maintenance or restoration have emerged as key criteria used by practitioners to prioritize sites.[94–96] Alternatively, Costanza and Moody[96] found that the most important constraint for all respondents was the presence of development near proposed burn areas.

Agency practitioners focus on fuel buildup in the WUI as a primary rationale, as it increases the risk of fast-moving and intense wildfires, which pose the most threat to people.[14] By contrast, private practitioners often prioritize managing smoke impacts near the WUI. Furthermore, their results suggest that practitioners from private companies tend to place greater importance on immediate outcomes from burning in the WUI rather than considering the long-term potential for wildfire after fuel accumulation due to not burning, a phenomenon known as "mental discounting" in risk analysis.[97] This can be attributed to the higher liability burden faced by private forestry companies, who often operate on 1–2 year contracts,[98] leading to a focus on short-term, non-ecological consequences.

Liability is also recognized as a significant challenge among private and public fire practitioners.[99] However, the liability burden tends to be lower for agency practitioners. Public agencies, responsible for long-term ecosystem maintenance and bearing the cost of wildfire suppression, prioritize long-term fuel reduction and ecosystem management. Limited budget and staffing are cited as major institutional impediments to prescribed burning for agency practitioners. Additionally, Kupfer et al.[72] found differences in prioritizing ecological and non-ecological outcomes, with the presence of threatened and endangered species receiving higher priority on public lands compared with private lands, while fuel reduction was prioritized more on private lands than public lands. Concern for risk does sometimes overwhelm management objectives on public lands. The USFS enacted a national pause on burning for several months in 2021 to undertake a systematic review of procedures following escaped prescribed burns in New Mexico.[100] While the risk of a prescribed fire escaping is objectively low,[101] the perception of risk in communities varies, as do their priorities for utilizing available funds and other resources for fire mitigation.[97,101,102]

Given the diversity of ownership, practitioner, and vegetation types within the US, consideration for more burning outside of the presently tightening burn criteria may be needed. Constraints to prescribed fire in the WUI are unlikely to become more lenient over time, and the impacts of climate change will further reduce the available time windows to resolve management priorities.[72] Even managers who reported relatively frequent burn returns of 4 years or less acknowledged that they are not burning as often as necessary to achieve their goals.[103] As ecological conditions continue to change, the capacity of managers to agilely respond will be affected. It is crucial to document knowledge gained through implementation to facilitate its application to other regions of the country, each with its own unique approaches to fire management.

For Indigenous cultural burn practitioners, the capacity to act is often constrained by the ability to navigate the dominant governance structures of fire management. This contrasts with decentralized Indigenous fire governance that operates within specific firesheds (firesheds, in this context, refers to a geographic area where cultural burning is carried out by Indigenous communities as part of their traditional land stewardship and management practices, acknowledging both the ecological and cultural dimensions of fire management within a specific geographic area). This difference in governance structures creates constraints and tensions in addition to those related to ecological needs or risk reduction.[34,104] Such constraints often have a legal basis and are determined by often-limited communication scenarios, jurisdiction, sovereignty, and liability.

In the complex landscape of fire management, cultural burning implementation faces a multitude of challenges that hinder consistent implementation and, ultimately, the capacity to act. For example, National Environmental Protection Act (NEPA) mandates and wildlife laws restrict and specifically define when and how action can be taken,[105] and the reliance on seasonal employees by federal agencies can create obstacles to the consistent implementation of cultural burning.[106,107] Liability concerns, air quality permitting, certification authority, agency personnel turnover, inadequate engagement between tribes and agencies all impact the capacity to act. On the practical side, the availability of training opportunities, funding, and grant cycles affect the ability to implement. In this intricate context, collaborative solutions encompassing innovative agreements, training, and policy adjustments are pivotal for empowering cultural burning communities and achieving broader fire management goals.

SYNTHESIS ACROSS DECISION SPACES

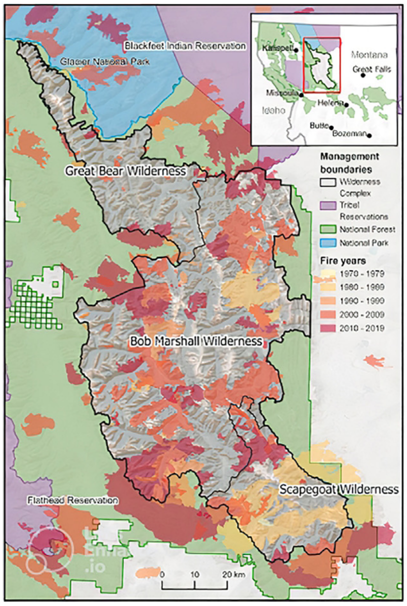
Our framework for intentional fire-use decision-making lets various end users align priorities and expertise by translating decision space. It highlights pathways for improving current practices by expressing commonalities and variations in decision components across multiple scales and gaps within existing management systems (Figure 2). We represent decision spaces as the dynamic interplay of motivations, ecological conditions, and capacity factors.

Intentional fire-use methods may not be considered interchangeable by their communities of practice and are often siloed in terms of research; however, we view them as overlapping strategies for putting fire on the ground where it can be most beneficial. The ecological conditions across these contexts are the same in many situations where a combination of fire deficit and effects of climate change exist. Important differences include instances where, for example, prescribed fire is not possible due to topography or remoteness and wildfire use is more desirable. Similarly, the presence of culturally significant species may indicate the need for tribal collaboration. In highly heterogeneous geographies, there may be appropriate applications of all three methods, indicating that expending resources on communication and collaboration is important. We present three specific case examples demonstrating how the decision-space model simplifies and translates elements of fire use. Lastly, we synthesize several concluding thoughts.

CASE EXAMPLE 1: WILDFIRES IN THE BOB MARSHALL WILDERNESS

The Bob Marshall Wilderness Complex (“the Complex”) spans approximately 1.5 million acres and is renowned as a management unit that supports an active fire regime (Figure 3). It has a history of Indigenous stewardship, currently composed of three federally designated wilderness areas. Located at the convergence of three national forests, two tribal nations, a national park, and private lands, the Complex serves as a roadless core for the larger protected-area network. While suppression efforts are used to safeguard built infrastructure from wildfires, the past abundance of fire activity and a policy shift in 1983 illustrate the benefits derived from intentional wildfire use across jurisdictional boundaries.[3,108]

Intentional fires serve multiple purposes in the Complex: promoting ecological function,[109] reducing future risks to infrastructure inside and outside the Complex, enhancing the effectiveness of other management activities, and providing opportunities for observation and knowledge development.[110] Fires spanning a range of sizes and ecological effects are the key drivers of diversity in ecosystem structure, composition, age, and spatial pattern in the Rocky Mountains, exemplified in the Complex. This diversity supports biodiversity, ecosystem services, and resilience to future disturbances,[111] making it a desirable characteristic of landscapes across jurisdictions and levels of development. Beyond their ecological roles, the mosaic of wildfires in the Complex reduces the risk of destructive regional fire seasons by breaking up forest cover at broad scales and impeding the spread of fires to nearby communities. Extensive



Ecological Conditions
- Areas of landscape-scale vegetation homogeneity due to suppression of fire
- Shifting burn windows for prescribed fire due to climate change
- Complex mountainous topography

Motivation for Use
- Preservation of biodiversity, ecosystem services, and resilience
- Wildfire risk reduction
- Knowledge development
- Institution of more managed post-wildfire prescribed burning

Capacity to Act
- Various land-ownership and jurisdictional contexts including national forests, present and ancestral Tribal lands, and private landholdings
- Difficult access to some parts of the wilderness for highly technical fire operations

Figure 3. Application of the socio-ecological decision space to the Bob Marshall Wilderness case

Map on the left includes management boundaries and fire boundaries separated by decade. Scale bar, 20 km.

burning within the Complex created opportunities for large, prescribed fires in the early 2000s, further reducing risks associated with high-severity fire near communities. A large body of scientific research conducted in the Complex has revealed how fire shapes terrestrial and aquatic ecosystems, offering insights applicable beyond the area.[112]

CASE EXAMPLE 2: WARREN GROVE RANGE FIRE

Fire has been a part of the pine barrens ecosystem (New Jersey [NJ], USA) for thousands of years.[113–115] For over a century, fire suppression has changed the scale and frequency of wildfires in the pinelands and pine barrens ecosystems in current-day NJ. While the NJ Forest Fire Service has used prescribed burning as a tool to mitigate wildfire risk since 1928, WUI expansion in the state has led to several wildfire disasters over the years.[115]

The Warren Grove Range has been used by the NJ Air National Guard for nearly 60 years, having originally been developed as a World War II weapons research station. It is one of the most heavily utilized Air National Guard training ranges in the US. On May 15, 2007, a flare deployed from an aircraft ignited dry vegetation on the ground, sparking a wildfire. Originating in the eastern part of Bass River Township in Burlington County, the wildfire consumed more than 17,000 acres of woods before rain, and over a thousand firefighters were able to halt its spread. The fire triggered the evacuation of thousands of residents, destroyed four homes, and damaged dozens more (Figure 4). The Warren Grove training range was closed for over a year afterward.

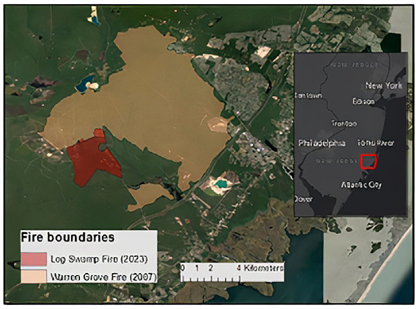
The 2007 fire defined the future focus for wildfire preparedness in NJ at different levels. The NJ Fire Safety Council was formed in 2015 to coordinate wildfire preparedness efforts statewide in cooperation with the NJ Forest Fire Service. The Council is a part of the Fire-Adapted Communities Learning Network, dedicated to reducing the risk of wildfire and creating fire-resilient communities. The US Department of Defense Readiness and Environmental Protection Integration Program (REPI) has also worked to establish buffer lands by acquiring thousands of acres of forest surrounding the range. The buffer lands are used to conduct prescribed fire management, protect surrounding residents from the constant threat of wildfire, and protect the viability of continued training missions. Finally, the Prescribed Burn Act was signed into law in NJ in 2018; it allows for the use of prescribed burns for ecological goals in addition to fire safety and offers greater liability protections to private landowners that look to use prescribed burns on their properties. The new law is expected to increase the opportunities to use fire as a management tool and improve the stewardship of pinelands forests.[116]

Prescribed burning season in NJ currently stretches from October 1 to March 31. On an annual basis, prescribed burns cover more than 8,000 hectares of land statewide. Through state and federal partnerships, prescribed fire is now used at a scale and frequency on the Warren Grove Range to dramatically reduce risks. In April 2023, a wildfire that struck Southern Ocean County burned through 1,607 acres and was contained the following day. Dubbed the “Log Swamp Fire,” it burned parts of Bass River State Forest, the Stafford Forge Wildlife Management Area, and the Warren Grove Bombing Range, according to the NJ Forest Fire Service. As expected, the prescribed burns that had been conducted in the area earlier in the year had successfully limited fuel loads, slowing further wildfire spread and facilitating containment.

CASE EXAMPLE 3: TERA

Tribal EcoRestoration Alliance (TERA) is a cross-cultural, multigenerational, and multi-organizational collaborative that centers Indigenous-led land stewardship to promote ecological, economic, and cultural revitalization in the northern Coast Ranges of California. It was formed in August 2019 in Lake County, as a response to escalating wildfire risk in an already vulnerable area with very active Indigenous communities. TERA was established to address the suppression of cultural burning in the region and reconcile historical injuries (Figure 5). The organization includes partners such as the Robinson Rancheria Pomo Indians of California, the Scotts Valley Band of Pomo Indians, and the Mendocino National Forest.

TERA is engaged in projects focused on cultural burning, prescribed fire, native seed collection, post fire restoration work,



Ecological Conditions
- Wildland Urban Interface expansion
- Robust evidence of thousands of years of fire use
- Abundance of fuels due to present suppression strategies

Motivation for Use
- Wildfire risk reduction to local communities
- Protect viability of military training operations

Capacity to Act
- limited due to proximity of nearby communities
- Perception of prescribed fire as risky
- Air quality concerns
- Varying jurisdictional and land-ownership contexts.

Figure 4. Application of the socio-ecological decision space to the Warren Grove case

Map on the left shows the boundaries of the Warren Grove Fire and Log Swamp Fire as well as nearby communities. Scale bar, 4 km.

and lake shore restoration. To enhance workforce capacity, TERA has implemented the Native Stewards Fellowship, a 140-h workforce development program that prioritizes ITEK and fosters ecological literacy, cultural knowledge, and vocational skills. TERA also hires a tribal hand crew (trained firefighters) that undertakes contracts on public, private, and tribal land. In terms of capacity to act, private landowners face fewer regulatory barriers in conducting prescribed burns on private land compared with tribal leaders who wish to burn on trust land. As a result, cultural and prescribed burning often occurs in collaboration with private landowners. An ongoing collaborative project on Cobb Mountain in northern California brings together the Big Valley Tribe with private landowners to restore watershed health and restore habitat for endangered Clearlake hitch fish species (*Lavinia exilicauda*). Through this collaborative stewardship, tribes are engaged in revitalization efforts on ancestral territories where they may not otherwise have access.

SHARED CHALLENGES AND GAPS

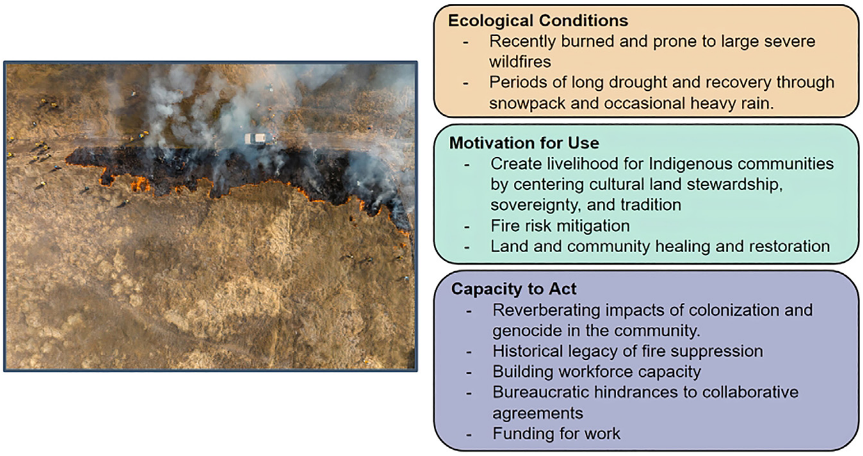
Motivating factors are an especially important aspect of decision spaces around fire use. For instance, in cultural burning, motivating elements are sometimes similar to prescribed fire but are informed by ITEK and the experience of community elders who evaluate ecological conditions differently than dominant fire governance structures/agencies. Prescribed burns, with their aims of reducing fuel loads, mitigating risks, and maintaining ecosystems, frequently align harmoniously with some of the intrinsic motivations driving cultural burns—motivations intricately woven into the distinct and site-specific traditions of individual communities. Prescribed fire motivations include producing specific management outcomes according to a plan with specific conditions and active control of the fire. For managed wildfires, goals may be similar, but the amount of control is more limited, so planning and preparation are essential. In determining capacity to act, each fire-use context involves questions related to liability determined by policies ranging from the local to national levels. Practitioners must weigh risks against benefits but must also navigate a hierarchical structure of decision-making authority and self-determination. This is especially limiting in decision spaces around cultural burning but can be exacerbated in all fire-use contexts by negative perceptions related to accidents like prescribed burn escapes or degraded air quality from wildfires.

The majority of empirical research development regarding fire is concentrated on understanding wildfire behavior and mitigation.[13] By contrast, prescribed fire has received less comprehensive exploration, and its practice frequently occurs under opposite ecological conditions.[16] Another major challenge in effective fire management is the limited availability of "science-based, regionally relevant information that is accessible to land managers and responders."[117] Uncertainty surrounding the comparative success and anticipated effects of naturally occurring fires compared with intentional fire use across various contexts complicates decisions. Simulation and experimentation by scientists and practitioners could accelerate the development of knowledge more rapidly than the body of observational studies.[90,118]

Funding cycles and extended rulemaking processes can pose challenges to nimble and successful intentional fire operations. Due to greater numbers of values at risk in fire-prone areas, there has been a significant increase in the number of forest service employees dedicated to fire suppression.[107] There is a need to rebuild skills and capacity within the workforce to effectively carry out fuels and forest health treatments and fully engage with communities at the necessary pace and scale. This can be achieved through initiatives like the Civilian Climate Corps and partnerships with other intermediary organizations like non-government organizations. The USFS manual defines success as "safely achieving reasonable objectives with the least firefighter exposure necessary while enhancing stakeholder support for our management efforts."[119] However, when it comes to fire management, these discrepancies around resources and goals can be exacerbated by temporal mismatches between the long-term dynamics of fuel accumulation and short-term risks associated with fire events. Decision-makers and scientists may not serve long enough in their roles to participate in fire-based activities from start to finish, and funding allocations are not indefinite or guaranteed.[107]

BLENDING APPROACHES FOR BETTER STRATEGIES

This model represents a way for managers from various intentional fire-use contexts to approach an understanding of each other's shared motivations, constraints, and resources. The three components of the model exist outside of the traditional fire management siloes, and we argue that they can be used as tools for organizing discussions of collaborative fire strategy. As a communications aid, this model can assist in recognizing when similar decision factors might exist under different names



Ecological Conditions
- Recently burned and prone to large severe wildfires
- Periods of long drought and recovery through snowpack and occasional heavy rain.

Motivation for Use
- Create livelihood for Indigenous communities by centering cultural land stewardship, sovereignty, and tradition
- Fire risk mitigation
- Land and community healing and restoration

Capacity to Act
- Reverberating impacts of colonization and genocide in the community.
- Historical legacy of fire suppression
- Building workforce capacity
- Bureaucratic hindrances to collaborative agreements
- Funding for work

Figure 5. Application of the socio-ecological decision space to the TERA case

Photo credit: Alex Roa (alex@topcollective.com). A bird's eye view of good fire spreading on a grassland. This low-intensity fire will help knock back invasive plants and support native grasses, forbes, and sedge, all important cultural species for tribes in Lake County. This burn is a culmination of efforts led by the Tribal EcoRestoration Alliance and a coalition of partners, including tribal leaders at Middletown Rancheria and Big Valley Rancheria, partners at the Watershed Research and Training Center, and private landowners.

or are nested within different policy structures. This is particularly useful in cross-boundary situations and between neighbors for whom decision space is often constrained by administrative territory.

During a single-burn event, enhanced communication among diverse stakeholders and rights holders could address multiple convergent motivations or shared capacity limitations. Organizations such as TERA (case example 3) or local PBAs can serve as valuable mediators in defining these factors and fostering interactions among different interests. Additionally, by defining and concentrating resources related to fire use, practitioners and planners can expand available options, especially amidst changing fire seasons and burn windows, thus increasing capacity across various use cases.

In many parts of the southern and western US, where optimal burn windows are contracting and fire seasons are becoming less predictable, efficient use of limited resources is critical. This might mean prioritizing wildfire safety, including using managed wildfires should the opportunity arise. Similarly, sharing fuels information widely among prescribed and cultural burn practitioners could allow them to make decisions that optimize safety and other desired outcomes. Specifically, vegetation management in anticipation of potential wildfires relies on factors such as workforce availability and the existence of cooperative or joint management agreements. Additionally, in some cases and places, vegetation management and prescribed fire needs to be applied regularly before cultural burning can be considered. Coordinated efforts between fire management communities offer collaborative opportunities to enhance their capacity to act through shared motivations and known ecological conditions.

When engaging with tribes, agencies could consider the climate and wildfire impacts on resources, habitats, and land that hold significant value for Indigenous communities in the region. This boundary-stepping approach combines ecological and cultural data to identify wildfire threats to habitats that are of special importance to tribes. These habitats may harbor numerous species that are not typically prioritized in western science-based approaches. By equitably incorporating Indigenous knowledge into prescriptions and operational strategies, government-to-government agreements between tribes and agencies can be established. Active involvement of heritage resource consultants and the protection of cultural resources are important components of this strategy. As our ecosystems become increasingly vulnerable due to climate change, a comprehensive approach to fire management becomes necessary. This approach includes working across multiple jurisdictions and forging diverse partnerships. Such an approach supports Indigenous-led initiatives, including cultural burning, within the ever-evolving landscape of fire management decision-making.

Finally, the role of fire on the landscape is liable to change over time due to a shift in underlying ecological conditions. For example, semi-arid regions, which transform to arid regions, may also undergo a complete transformation of fire regime. Consequently, intentional use of fire hinges on understanding these changes. An alternative to a reactive approach to fire management is to shift the decision space to center on a more proactive approach. This shift highlights the need for knowledge on how to effectively find proactive practices, including those that involve collaboration with active communities who engage with fire networks and Indigenous communities who use intentional fire or want to steward landscapes through cultural burning. To facilitate informed decision-making that encompasses the broader fire-use landscape and not just isolated emergency events, comprehensive data collection and effective dissemination are necessary. These efforts will contribute to more accurate projections of future fire patterns and decision-making in the context of climate change.

CONCLUSIONS

This synthesis presents a conceptual model for intentional fire-use decision-making, aimed at facilitating communication among various stakeholders and rights holders. Fire science and social science highlight the technical and specific nature of the contextual and geographic elements involved. To effectively address many of the issues and questions raised, it is crucial to implement collaborations that integrate multiple layers of planning, such as PODs and PBAs, and otherwise improve communication between decision-makers, planners, managers, and practitioners. Collaboration and communication are pivotal in aligning community values with landscape restoration, climate change considerations, and wildland fire research and management strategies, with a focus on heterogeneity and resilience considerations.

This exploration of intentional fire uses also raises several questions for decision-makers, including burn practitioners, who must make effective decisions quickly. The first and perhaps most actionable of these is to ask, as a burn practitioner, how can decision spaces incorporate a diversity of motivations or address capacity issues for individual events? Over longer timeframes, what types of fire-use motivations are limited by capacity to act, and what strategies might be implemented? At the scale of fire seasons, it is also important to continue to research how fire regimes and conditions for prescribed burns are changing. Finally, over the long term, we would ask how the role of fire is changing and how that will change what intentional fire use means. In particular, what does the future of fire management look like with increasing the capacity to act at various scales? Each of these questions represents avenues for research, synthesis, and discussion among the fire-use community.

While intentional fire use is an effective strategy in fire-adapted ecosystems, the application of fire lies on a spectrum of possible management practices. It may be limited in areas like Hawai'i, Puerto Rico, and other territories that are either not fire-adapted or represent novel contexts. Some locations, like Alaska's wildernesses, are geographically isolated and lack sufficient management resources, making the use of fire impractical; however, these factors may change in the future. Lastly, variable climate change impacts are expected to redefine the efficacy of fire use as a tool. No single context covers all possible approaches of intentional fire use, and different approaches should be considered based on seasonal variations, specific goals, and the prevailing physical and social conditions.

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AUTHOR CONTRIBUTIONS

A.R.: conceptualization, investigation, writing – original draft, writing – review & editing, visualization, and project administration. N.F.: conceptualization, investigation, writing – original draft, writing – review & editing, and visualization. T.H.: conceptualization, investigation, writing – original draft, writing – review & editing, and visualization. A.K.: conceptualization, investigation, writing – original draft, and writing – review & editing. R.M.: conceptualization, investigation, writing – original draft, writing – review & editing, and visualization. J.S.: conceptualization, investigation, writing – original draft, writing – review & editing, and visualization. A.M.Y.: conceptualization, investigation, and writing – original draft. A.E.C.: conceptualization, writing – review & editing, and supervision. C.G.: conceptualization, writing – review & editing, and supervision. K.H.: conceptualization, writing – review & editing, and supervision. J.L.: conceptualization, writing – review & editing, and supervision. A.T.: conceptualization, writing – review & editing, and supervision.

DECLARATION OF INTERESTS

The authors declare no competing interest.

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