

Research

Perceived changes in social-ecological resilience in fire-prone ecosystems in Colorado

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ABSTRACT. Assessing resilience of wildfire-prone social-ecological systems (SES) can provide a baseline for decision makers and inform future management actions. In this study, we measure stakeholder perceptions of how SES resilience was influenced by historic 2020-wildfire events in northern Colorado and what actions they think are needed to enhance future resilience to wildfire. We developed a contextualized set of resilience principles and indicators based on the literature and expert opinion that included ecological, ecosystem service, and social categories. We conducted 15 stakeholder interviews and 37 surveys to characterize subjective measures of SES resilience. Stakeholders perceived that the resilience of ecological indicators pre- and post-wildfires remained mostly unchanged, but that ecosystem service indicators were negatively affected and social indicators positively affected. Related to future resilience, stakeholders underscored a need for more strategic fuel treatments, especially prescribed fire, and more collaboration and engagement across landowner types. Our findings highlight that wildfire events can have negative and positive effects on components of SES resilience, underscoring the need to disaggregate resilience components. Additionally, we find that stakeholder perceptions of resilience are in line with the literature on objective measures of post-wildfire resilience, suggesting that expert opinion can be used as a reliable method to measure resilience indicators in some contexts.

Key Words: *forest resilience; social-ecological systems; wildfire management; wildfire mitigation; watershed resilience*

INTRODUCTION

Climate change and its effects on temperature and rainfall, combined with past wildfire suppression policies, are driving more severe and intense wildland fires (van Mantgem et al. 2013, Abatzoglou and Williams 2016, Parks et al. 2018, Parks and Abatzoglou, 2020). The subsequent impact of these changing fire regimes on human communities are felt in the places they occur, through impacts to ecosystem services such as water regulation and provision (Robinne et al. 2020), and remotely, through harmful wildfire smoke (Eisenman and Galway 2022). Wildfire-prone ecosystems, such as densely forested watersheds under wildfire suppression regimes, are a classic example of a social-ecological system (SES), or a system in which the social and natural elements interact (Walker et al. 2004, Walker and Salt 2006). Resilience is a key part of SES and refers to the maintained and adaptive capabilities of the ecological, social, and social-ecological interactive variables of the system to return to a specific state, structure, or function (Waltz et al. 2014, Johnstone et al. 2016, Sterk et al. 2017). As new wildfire regimes emerge globally, there is increasing recognition that human communities need to move beyond basic resilience that allows ecosystems and communities to recover from fire, to incorporate adaptive and transformative resilience approaches, which allow communities to modify and transform their systems in response to a changing climate (McWethy et al. 2019).

Although the western U.S. has historically experienced fire and has a variety of wildfire-adapted ecosystems, the frequency and severity of large-scale fires is increasing (Brown et al. 1999, Keane et al. 2008). High-severity fire can decrease ecological resilience through abrupt changes to the ecosystem's post-fire structure or function (Johnstone et al. 2016). However, in some cases, a wildfire, particularly frequent, low severity fires, can mitigate risk

and reduce harmful impacts, thereby bolstering SES resilience (Stevens-Rumann and Morgan 2016, McWethy et al. 2019). Wildfires influence the provision of many ecosystem services, or the benefits people value from ecological functions and processes, from forested watersheds (Writer et al. 2014, Kinoshita et al. 2016). Post-fire water quality, flooding, and debris flow influence water provisioning, regulation, and quality (Bladon et al. 2014, Kinoshita et al. 2016, Robinne et al. 2020, Wohl et al. 2022). In the western U.S., this problem is of particular concern because forested landscapes supply water to as much as 70% of the population (Reneau et al. 2007, Robinne et al. 2020, Badik et al. 2022). Other ecosystem services, including recreation and other cultural ecosystem services, are also often negatively affected by wildfire events (Jones et al. 2022).

Wildfire events also influence the social dimensions of SES. Although in the short-term wildfires often negatively influence community and economic resilience, these events can lead to learning and understanding about complex systems and ultimately enhance social capital (Carmen et al. 2022). In some western U.S. communities, wildfires have catalyzed the development of new collaborative watershed groups (Blount and Kroepsch 2019) that implement forest restoration treatments across jurisdictional boundaries as an adaptive strategy (Morgan et al. 2023).

Individual and collective responses to wildfire risk and events can, in turn, influence future SES resilience in wildfire-prone ecosystems. The adaptive or transformative ability of the SES depends on both the social and ecological context (McWethy et al. 2019). Research suggests that systems with greater institutional diversity in governance structures can enhance SES resilience (Jones et al. 2013). Additionally, well-developed social networks

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between stakeholders can improve wildfire management by fostering information sharing and improving planning (Fischer et al. 2016). Wildfire mitigation actions, like fuels reduction treatments in mixed conifer systems, can increase forest resilience as defined by similar structure and function in the face of a wildfire event (Waltz et al. 2014, Timberlake et al. 2021). Indigenous cultural burning as a mitigation strategy uniquely offers myriad benefits to ecological and cultural resilience (Smith et al. 2021, Vázquez-Varela et al. 2022). Many post-wildfire mitigation actions, like mulching and stream restoration projects, aim to stabilize soils and protect water supplies after fire to maintain basic resilience (McWethy et al. 2019).

Resilience assessments aim to understand resilience of a given system at a specific point in time to inform future resilience planning (Walker and Salt 2006). Various methods and indicators have been used to measure resilience across disciplines and SES contexts (Quinlan et al. 2016, González-Quintero and Avila-Foucat 2019). One difference across approaches is the use of objective versus subjective indicators to measure resilience. Objective indicators rely on field-based empirical information (Higuera et al. 2019). For example, measures of post-fire tree regeneration following wildfire events have been used to measure changes in forest resilience linked to climate change (Stevens-Rumann et al. 2018). Subjective indicators are derived from stakeholder perceptions through social science methods, and stakeholders often participate in the development and vetting of contextualized resilience indicators (Feldmeyer et al. 2019, Keenan and Maxwell 2022). Incorporating subjective measures into existing bodies of objective assessments has been suggested by conservation social scientists to enhance the relevance and applicability of objective assessments (Bennett et al. 2017).

In subjective assessments, resilience principles, or the characteristics of the system needed to maximize resilience, have been translated into resilience indicators and expert opinion is used to assess the resilience indicators or changes in resilience indicators over time (Walker and Salt 2006, Biggs et al. 2012, Nemec et al. 2013, Allen et al. 2018, Salomon et al. 2019). Often these studies address the question of “the resilience of what, to what?” (Cosens and Fremier 2014). For example, Salomon et al. (2019) used stakeholder knowledge to understand how the resilience of the Pacific herring fishery in Canada shifted under indigenous-led and colonial governance regimes.

Our research builds on existing subjective resilience assessments to develop indicators of SES resilience for wildfire-prone ecosystems. This case study assesses expert opinion on the resilience of wildfire-prone watersheds to the wildfire events that are becoming increasingly more frequent and severe in the western U.S. Specifically, we (1) develop a set of SES resilience indicators relevant to wildfire-prone watersheds in the western U.S.; and (2) use these SES indicators to elicit expert opinion on the current condition and perceived changes to resilience of two watersheds in northern Colorado before and after historic 2020-wildfire events. The primary research questions of this study are: (1) What are experts’ perceptions of SES resilience pre- and post-2020 wildfire events? (2) What is the perceived influence of the 2020-wildfire events on changes to SES resilience? (3) What is needed to adapt and transform future SES resilience of these wildfire-prone systems? Answering these research questions provides

insights into the way experts perceive changes to different components of SES resilience due to wildfire events—addressing the question of “resilience of what to what”—and sheds light on actions stakeholders prioritize to adapt and transform resilience in wildfire-prone watersheds in the western U.S. in the face of climate change.

METHODS

Study area

Our study area included the Poudre and Big Thompson River watersheds of northern Colorado (Fig. 1). Both watersheds contain a mix of private and public lands, serve as source water systems for local populations, and were impacted by large wildfire events in 2012 and 2020. In 2012, the High Park Fire burned 87,284 acres. In 2020, the Cameron Peak Fire became the largest fire in the state’s history and burned 208,913 acres in both watersheds. Concurrently, the East Troublesome Fire burned 193,812 acres and ignited on the west side of the Continental Divide before moving east into the Big Thompson watershed. These wildfire events impacted the quality of water supply and other ecosystem services of the area (Writer et al. 2014, Heath and Thorp 2022).

Stakeholder database

This study elicited views from experts through interviews and an online survey. In this study, stakeholders were defined as professionals engaged in watershed protection through wildfire mitigation actions within the two watersheds, because water has been the focal ecosystem service driving collaboration and wildfire mitigation actions in the area (Writer et al. 2014, Gannon et al. 2019). We developed an initial database of all known stakeholders, organized by academic or research group, city or county government, coalition or non-government organization (NGO), federal or state government agency, private business, and water utility (Table 1). The initial database was created through web-based research and author knowledge. For interviews, key informants were selected to achieve a representative sample of organizational types and based on which organizations were most active in the study area. For surveys, we used our initial database and bolstered it by adding experts identified by interviewees. Informed consent was given by all research participants and all instruments went through Institutional Review (IRB: #3584).

Indicator development

We selected a set of eight resilience principles based on the works of Walker and Salt (2006) and Biggs et al. (2012) that reflected the ecological, ecosystem service, and social dimensions of our system. Next, we developed specific indicators through a literature review and expert knowledge that reflected our system of wildfire-prone watersheds of northern Colorado (Table 2). As a starting point we used two recently published papers that developed subjective indicators of SES resilience (Allen et al. 2018, Salomon et al. 2019) and refined their indicators based on wildfire-specific literature, expert knowledge, and discussions with practitioners (Appendix 1). The final set of resilience principles and indicators were employed in both the interview and survey instruments.

The grouping of principles and indicators into ecological, ecosystem service, and social dimensions (Table 2) explicitly recognizes the distinct ecological and social aspects of SES and their interactions through ecosystem services. Ecological

Fig. 1. Study area map illustrating the large wildfires in the area in 2012 and 2020. Boundaries of the Cache la Poudre River watershed and the Big Thompson River watershed in blue; the High Park Fire, the Cameron Peak Fire, and the East Troublesome Fire in red hash marks.



Table 1. Conducted interviews and completed surveys by organization type.

Organization type	Interviews conducted	Completed surveys
Academic or research group	3	2
City or county government	2	4
Coalition or NGO	4	8
Government agency	4	17
Private business	0	3
Water utility	2	3
Total	15	37

principles and indicators capture the ecological structure and functions of the upstream watershed, with a focus on forested ecosystems and watershed functions. Ecosystem service indicators capture the benefits that people value in these watersheds, informed by previous post-fire studies and stakeholder elicitation that point to water and recreation as most important (Writer et al. 2014, Gannon et al. 2019, Chamberlain and Jones 2024). Although ecosystem service indicators are theoretically related to ecological resilience, we treat them independently in this study. Social principles and indicators capture the governance and participation aspects known to influence resilience (Biggs et al. 2012) and are not directly connected to the ecological or ecosystem service indicators. Although we could have easily added more indicators under each principle, to be cognizant of stakeholders' time and to reduce complexity, we strove for the most efficient yet comprehensive list possible.

Qualitative data collection and analysis

Semi-structured interviews were used to gather details on how experts characterize resilience of their system, how it has changed over time because of wildfire events, and how future resilience could

be improved (Appendix 2). The set of resilience principles and indicators (Table 2) were sent to interviewees alongside the interview questions for reference during the interviews. We solicited interviews from 20 stakeholders in summer 2022 and conducted 15 interviews across all organizational types except private business, who were nonresponsive (Table 1).

Interview data provided a nuanced understanding of how changes to the system pre- and post-2020 were attributed to wildfire events. Qualitative data was coded using the analysis platform, Dedoose. We used thematic analysis, where data segments are coded thematically and grouped based on similarities (Braun and Clarke 2006, Thornberg and Charmaz 2014). As new codes on wildfire influence came to the surface, influence codes were separated into different parent codes of positive and negative influence and denoted as ecological, ecosystem service, or social to compare with quantitative findings. Codes with three or fewer assigned excerpts were deemed insufficiently supported to be incorporated into the final write up leading to a final codebook of 67 codes (Appendix 3). Although there was only one coder of the qualitative data, best practices were used to minimize error, including cross-referencing survey responses with interview responses to ensure validity of findings (Moon et al. 2016).

Quantitative data collection and analysis

Survey questions were developed using the resilience principles and indicators (Table 2). Five-point Likert-scales were used to measure perceptions of current resilience in 2022 and before the 2020 wildfire events, as well as the perceived level of influence these wildfire events had on changes in resilience indicators. Additionally, categorical questions were included to gauge concerns about future wildfires and ways to improve future resilience. The survey was vetted in multiple rounds with local experts including a pilot by two stakeholders, with small edits

Table 2. Resilience principles and indicators with definitions.

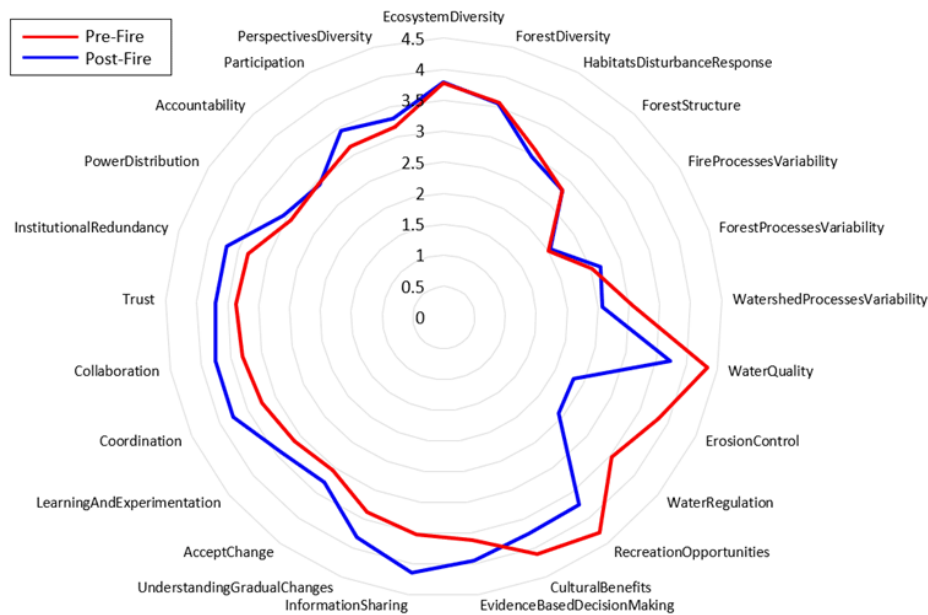
Ecological	Ecological Diversity: The number and evenness of species and ecosystem types, and their ability to respond to disturbance • Ecosystem diversity: the presence of a healthy variety of ecosystem types (e.g., alpine, forest, woodland, shrub, riparian, meadow) • Forest diversity: the presence of a healthy variety of tree species (e.g., aspen, ponderosa pine) • Habitats disturbance response: the ability for plant and animal habitats to respond to ecological disturbances Ecological Variability: Natural variability and fluctuations in ecological processes, structures, and populations • Forest structure: the representation of different size and age classes of forest (a mix of small, medium, and large trees) • Fire processes variability: the ability of wildfires (including their frequency, size, and severity) to occur within a healthy level of variability and fluctuations • Forest processes variability: the ability of non-fire processes (e.g., pest outbreaks, wind damage, ice damage) to occur within a healthy level of variability and fluctuations • Watershed processes variability: the ability of watershed processes (e.g., maintain stream flows, buffer large floods, support healthy water quality, regulate sediment movement) to occur within a healthy level of variability and fluctuations
Ecosystem Services	Ecosystem Services: Adequate provision of essential and nonessential benefits people obtain from nature • Water quality: the suitability of the water supply for human consumption (i.e., free of harmful chemical, physical, or biological components) • Erosion control: the ability of the watershed to limit hillslope erosion of sediment into receiving streams, and the ability of streams to regulate downstream transport of sediment • Water regulation: the ability of the watershed to reduce or buffer downstream flooding • Recreation opportunities: the ability to meet human demand for recreation opportunities (i.e., hiking, water sports, fishing, hunting) • Cultural benefits: the ability of the watershed to support a good quality of life for the people that live within it now and in the future
Social Dimensions	Manage Connectivity: Decision makers and stakeholders are connected to one another so that information is transferred effectively • Evidence based decision making: the integration of evidence-based information into decision making by groups, organizations, communities, and households working on wildfire, forest, and watershed management • Degree of information sharing: the degree of information sharing across groups, organizations, communities, and households working on wildfire, forest, or watershed management Manage Complex Variables and Feedbacks: Incorporation of information about long-term outcomes into decision making • Understanding of gradual changes: the level of understanding by groups, organizations, communities, and households working on wildfire, forest, and watershed management about gradual, long-term changes to the watershed (e.g., from wildfire, forest or watershed management, climate, human use, etc.) Foster Complex Adaptive Thinking: Degree of learning and experimentation by decision makers and stakeholders in response to ecological and social change • Willingness to accept change: the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to accept changes in the watershed (e.g., changing fire regimes, forest or watershed management, or climate) in their management decisions • Degree of learning and experimentation: the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to experiment with new management actions or practices (e.g., pre or post fire mitigation) in response to changes in the watershed Linking and Bonding Social Capital: The strength of relationships among decision makers and stakeholders • Level of coordination: the level of coordination (i.e., the joint determination of goals) across groups, organizations, communities, and households working on wildfire, forest, and watershed management • Level of collaboration: the level of collaboration (i.e., the voluntary helping of others to achieve goals) across groups, organizations, communities, and households working on wildfire, forest, and watershed management • Trust: the level of trust across groups, organizations, communities, and households working on wildfire, forest, and watershed management Governance: The level of redundancy in the roles and responsibilities, and the equitable participation of all decision makers and stakeholders • Institutional redundancy: the level of overlap in the groups, organizations, communities, and households working on wildfire, forest, and watershed management • Distribution of power: the equitable distribution of power across all groups, organizations, communities, and households working on wildfire, forest, and watershed management • Accountability: the level of accountability (i.e., following through on responsibilities) among all groups, organizations, communities, and households working on wildfire, forest, and watershed management • Participation: the level of participation in decision-making across all groups, organizations, communities, and households about wildfire, forest, and watershed management • Diversity of perspectives: the diversity of perspectives (e.g., ideas, views, opinions) that inform decision-making about wildfire, forest, and watershed management

made following the pre-test for clarity. The final online survey instrument was developed in Qualtrics (Appendix 4). Initial requests to complete the online survey were sent to 98 stakeholders via email in summer 2022, with two rounds of reminders sent in two-week intervals. Sixty-one stakeholders opened the survey for an engagement rate of 62%. Thirty-seven stakeholders completed the survey in its entirety for a completion rate of 38% (Table 1). This is close to the average response rate for online surveys, however, with our more targeted sample we would have expected more responses (Wu et al. 2022).

To quantify the survey data we assigned values to the Likert-scale questions similar to previous subjective SES assessment (Allen et al. 2018). For questions about the perceived resilience of the SES

pre- and post-wildfire, these quantifications were Very Poor (1), Somewhat Poor (2), Neutral (3), Somewhat Good (4), and Very Good (5). Mean scores were then calculated for 2022 resilience perceptions and pre-wildfire perceptions for all resilience indicators and mapped graphically using a spider web graph for visual comparison. A paired Wilcoxon Sign-Rank test was run to test for statistical differences at the 95% confidence level between 2022 perceived resilience and pre-wildfire perceived resilience. This analysis was chosen because it is a non-parametric test and allows for paired ordinal data (McCrum-Gardner 2008). Although the Wilcoxon Sign-Rank test illustrates if there are differences in perceived resilience over time, it does not explicitly rule out other changes that could have influenced resilience between 2020 and 2022.

Fig. 2. Mean scores for indicators based on perceived resilience pre- and post-wildfire. Values are as follows: Very Poor (1), Somewhat Poor (2), Neutral (3), Somewhat Good (4), and Very Good (5).



A similar numeration process was done for Likert-scale survey questions asking experts about perceived influence of the 2022 wildfires on resilience indicators. For these Likert-scale questions the quantifications were Strong negative influence (1), Slight negative influence (2), No influence (3), Slight positive influence (4), and Strong positive influence (5). These numeric conversions were then used to calculate mean influence scores and standard deviations for all indicators. Indicators that were statistically significant when compared pre- and post-fire in the paired Wilcoxon Sign-Rank test were graphed together in groupings of perceived positive and negative influence using mean influence scores and standard deviations, allowing us to isolate those indicators experts perceived as changing specifically because of the 2020 wildfire events. Indicators with a mean influence score of less than three were grouped together as indicators with perceived negative influence from the 2020 wildfires, where a mean closer to one indicate the greatest negative influence from the 2020 wildfires on that resilience indicator. Indicators with a mean influence score of greater than three were grouped together as indicators that were positively influenced by the 2020 wildfires, where a mean closer to five indicates a higher perceived positive influence from the 2020 wildfires. Last, to analyze the top concerns for future resilience and factors that could improve future resilience, we totaled categorical response questions and sorted by ranking to produce a list of top concerns and recommended actions.

RESULTS

Perceived relative resilience pre- and post-2020 wildfires

Visual representation of mean indicator scores for the perceived resilience pre- and post-wildfire indicate temporal changes for several resilience indicators (Fig. 2). There was limited perceived

change pre- and post- fire for ecological indicators. The exception to this was perceived decreases in watershed processes variability. The ecosystem service indicators of water quality, erosion control, water regulation, and recreation opportunities, were all perceived as having lower resilience following the fire events. Respondents perceived higher resilience in 2022 for most social principles and indicators, with power distribution and perspectives diversity appearing unchanged.

The statistical significance of differences between the perceived resilience pre- and post-wildfire under the paired Wilcoxon Sign-Rank test closely follows that of the visual representation (Table 3). Overall, 14 of the 25 indicators had statistically significant changes in perceived resilience before and after the 2020 wildfires. The ecological and ecosystem service indicators visually different in Figure 2 were all statistically significant. For the social indicators, the statistical tests indicated that eight of the indicators were statistically different pre- and post- fire at an alpha of < 0.05 .

Perceived influence of wildfire events on changes in resilience

We found that experts perceived a statistically significant and negative influence from the 2020 wildfires on six indicators. These indicators included watershed processes variability, an ecological indicator, as well as all the ecosystem service indicators (Fig. 3). Eight of the social resilience indicators were statistically significant, and experts perceived a positive influence of the 2020 wildfires on these indicators (Fig. 3). The indicators included information sharing, understanding gradual change, degree of learning and experimentation, level of coordination, level of collaboration, trust, institutional redundancy, and participation (Fig. 3). When experts were asked directly about the influence of wildfire, three indicators that appeared different in Figure 2 and Table 3 (cultural benefits, recreation opportunities, and trust),

Table 3. Results from the paired Wilcoxon Sign-Rank test for perceived difference in resilience between 2022 and before the 2020 wildfires for all resilience indicators (N = 37). The asterisk (*) indicates statistical significance using an alpha of < 0.05.

Type	Principle	Indicators	P-value
Ecological	Ecological Diversity	Ecosystem Diversity	0.795
		Forest Diversity	1.000
		Habitats Disturbance Response	0.428
	Ecological Variability	Forest Structure	0.830
		Fire Processes Variability	0.916
		Forest Processes Variability	0.187
		Watershed Processes Variability*	0.002
Ecosystem Services	Ecosystem Service	Water Quality*	0.001
		Erosion Control*	< 0.001
		Water Regulation*	< 0.001
		Recreation Opportunities*	< 0.001
		Cultural Benefits*	0.007
Social Dimensions	Manage Connectivity	Evidence Based Decision Making	0.078
		Degree of Information Sharing*	0.001
	Manage Complex Variables and Feedbacks	Understanding Gradual Changes*	0.003
	Foster Complex Adaptive Thinking	Willingness to Accept Change	0.102
		Degree of Learning & Experimentation*	0.016
	Linking and Bonding Social Capital	Level of Coordination*	0.002
		Level of Collaboration*	0.001
		Trust*	0.011
	Governance	Institutional Redundancy*	0.017
		Distribution of Power	0.120
		Accountability	0.260
		Participation*	0.014
		Diversity of Perspectives	0.432

had high standard deviations that pass the critical line of no influence drawn at our cutoff of three. Thus, post-fire changes in these indicators are potentially not a result of the wildfire events alone (Fig. 3).

The qualitative data supports the quantitative findings on the perceived role the wildfires played in changing SES resilience. In terms of ecological and ecosystem service changes associated with the 2020 wildfire events, experts discussed the dangerous post-fire flood cycles and losses to water quality with subsequent water supply degradation. For example, one respondent stated: “I think the floods that happen post-fire are huge. I know that a lot of the work in the Poudre is for post-fire flood recovery. The floods have a large impact on ecological health and the watersheds as a whole.” Additionally, experts offered narratives around changes to water quality and supply. One respondent articulated it as: “Water supply is very concerning to me. We already don’t have enough water where we live and have been experiencing drought for many years. Compromised water quality is a big concern of mine too.”

Throughout the interviews, several experts referred to positive post-fire impacts on forests, such as wildfires creating increased heterogeneity in forests and fostering habitat improvements for large foraging species. For example, one interviewee stated: “In lodgepole pine, we are seeing an increase in diversity and variability in the burned areas.” Similarly, a respondent noted: “In some of the areas of the burn scar, that were less severe, we probably are seeing more ecological variability now.” Last, some experts considered the wildfires analogous to a mitigation treatment in low severity burn areas. As one respondent put it: “Some good outcomes from the

2020 wildfire season, we often talk about wildfires as being the most effective fuel treatments out there in terms of creating potential resilience to future wildfire.”

Experts also noted that the wildfire events had served as a catalyst for positive social changes, including for funding, partnerships, and public support. Interviewees experienced new funding opportunities after the fires, as expressed by this respondent: “Overall, the 2020 wildfire season brought us together much more and helped highlight the urgency of the work. Since then, we’ve seen a lot of really good investment, at the state level with increases in funding to our state grant programs.” The wildfire events were also viewed as increasing partnerships by strengthening existing collaborations and creating new ones. One interviewee stated this as: “The fires just strengthened our resolve to work more closely together and increase the pace and scale.” Last, the 2020 wildfires were related to increases in public buy-in by enhancing public knowledge of and support for mitigation treatments after the wildfire events. One interviewee stated: “I’ve been surprised by some community members ... who have been more receptive to some of these conversations around fire adapted communities. I think a big part of that is seeing these fires and realizing we live in the forest and the forest is changing and evolving and we need to change and adapt with it.”

Future resilience

Overwhelmingly, survey respondents were concerned or very concerned about the impact of future wildfires on SES resilience. The two main concerns expressed about future wildfire-related impacts were water quality (92%) and infrastructure (89%). In the survey, respondents perceived administering more prescribed fire as the most important factor for improving the social and ecological resilience of forests and watersheds in the future (Table 4). Thinning forests, additional funding, and allowing more wildfires to burn, if life or property were not in danger, were also perceived by large numbers of respondents as important for improving social and ecological resilience of forests and watersheds in the future. Actions associated with maintaining resilience, such as stream restoration, and transforming resilience, such as use of beaver dam analogs, were also mentioned by several respondents.

In qualitative discussions about future resilience, many experts first set the stage by discussing current barriers and challenges to actions that would lead to adaptive and transformative resilience to wildfires. For barriers on public lands, informants cited policies limiting treatments in wilderness areas as a top concern. On private lands they saw limited connectivity of projects and the need for individual land ownership buy-in as major barriers. On both private and public lands, respondents expressed frustration at limited treatment sizes. The most common theme from interviewees about barriers was related to prescribed fire. Barriers included the forest’s structure being too dense to receive fire safely, limits to social license, and policy or insurance barriers. One example of this was the statement: “There have been some challenges with burning with prescribed burning ... it’s because of policies rather than desire ... [we] need better laws and insurance for implementing prescribed burns.”

In response to what was needed to adapt and transform future resilience and address barriers, experts identified three main social components. First, informants stressed the need to engage more with local communities to develop community plans tailored to

Fig. 3. Perceived influence of 2020 wildfires on resilience indicators for the Poudre and Big Thompson watersheds social-ecological system (mean $\pm$ standard deviation).

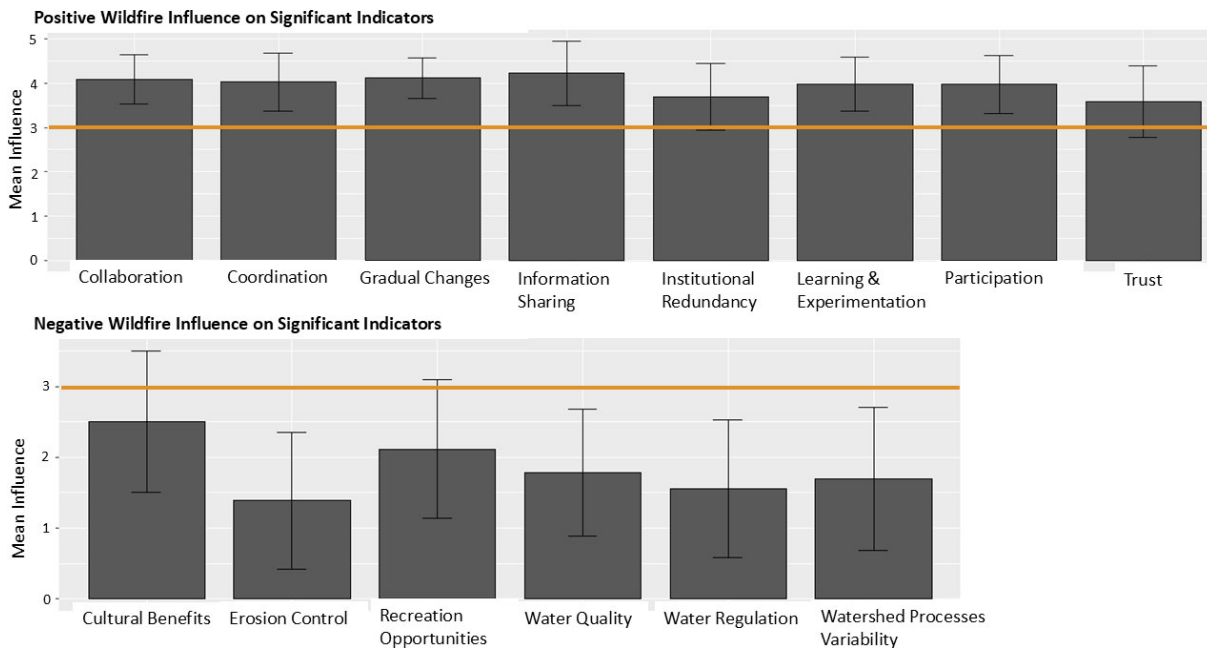


Table 4. Ranking of most important actions for future social and ecological resilience by respondent counts (N = 37).

Ranking	Future action	Count
1	Administering more prescribed fire	17
2	Thinning more forests	15
3	Additional funding	14
4	Allowing more wildfires to burn (if life or property are not in danger)	14
5	More stream restoration and stabilization projects post-fire	12
6	Beaver restoration	12

local norms and contexts. This was expressed by one respondent as: “We really have to educate and engage the public ... The more we do get the public involved and give them buy in, I think we’re going to see some real change happen.” Second, informants viewed increasing the level of collaboration across different land ownership types, agency types, and between the watersheds, as critical to landscape resilience. For example, one informant stated: “We need to continue to increase the amount of coordination because certain agencies can only manage certain private, federal, or state lands and things. Continuing to have them coordinate across boundaries ... would continue to improve the resilience.” Last, experts mentioned the need to be allowed to diversify how they use existing wildfire mitigation funding. They expressed a need to be able to pay for organizational administrative tasks in addition to implementation and monitoring. This was stated as: “What I’ve heard over and over again, is that somebody has to write the grant proposals, somebody has to organize, somebody has to do fundraising. We need to invest in those, somebody’s.”

Finally, interviewees also identified several ecological actions needed to adapt and transform future resilience. Prescribed fire

as a fuel management strategy came up most frequently in conversations with experts as the most needed and effective management action and only natural analogue to wildfire with multiple ecological benefits. Some informants also mentioned less common wildfire management actions to enhance resilience. These included increasing the use of tools such as Potential Operational Delineations (PODs), which are a more recent planning strategy used to characterize fire risks and provide prioritization of wildfire response strategies across landscapes before fires start. One respondent stated: “I think it’s a matter of doing point protection, doing connecting treatments where we can take those old fire perimeters and connect them through targeted treatments along POD boundaries.” Additionally, some stakeholders felt future resilience could be enhanced by using beaver dam analogs that can alter the hydrology of the landscape and create a wetter post-fire refugia for wildlife.

DISCUSSION

This study characterized experts’ perceived changes in ecological, ecosystem service, and social resilience in northern Colorado in response to historic wildfire events. We used mixed methods to couple quantitative rankings of perceived resilience with in-depth discussions of the perceived changes in this system. Experts perceived that wildfires (1) did not significantly change the ecological values of SES resilience, except for watershed processes variability; (2) had a strong negative influence on the ecosystem service principle of SES resilience; and (3) had positive influence on social principles of SES resilience. Experts felt that future resilience to wildfire could be improved through more investment in adaptive and transformative approaches (McWethy et al. 2019), such as use of prescribed fire and increased collaboration and planning.

Because our findings characterize SES resilience for a specific place and time in response to specific disturbance events, generalization to other systems should be done with caution. Our findings will be most applicable to other western U.S. forested watersheds experiencing severe wildfire where watershed services are at risk. Our results reflect the experts who participated and may have differed with different stakeholder representation, and we note that we had overrepresentation of government actors and few private businesses represented. Furthermore, our study did not include community perspectives and it is likely that citizen perceptions would differ from experts involved in watershed protection. Specifically, perceptions of social resilience indicators may have differed if community members were part of our study, given potential community-scale power dynamics and differences in perceptions between leaders and citizens after wildfire (Mockrin et al. 2020). An additional limitation is a lack of baseline data on perceived resilience, and our expert elicitation on pre-wildfire conditions may be subject to recall bias.

Despite these caveats, our findings on experts' perceptions of SES resilience before and after wildfire contribute knowledge to how stakeholders think disturbance events influence ecological, ecosystem service, and social dimensions of natural resources management. These perceptions are important because they directly inform management actions (Bennett et al. 2017) and, therefore, future resilience. Below we explore the relationship between the subjective measures of resilience we found in this study and objective measures of post-fire resilience, discuss stakeholder recommendations for improving future SES resilience in wildfire-prone watersheds, and reflect on the use of subjective indicators in resilience assessments and future research needs.

Perceived changes in SES resilience from wildfire

Ecological

Results from the experts surveyed in our study showed no statistically significant difference in the perception of ecological changes pre- and post-wildfire events. Limited statistical significance in quantitative data likely reflects the counterbalance created by both positive and negative perceptions of changes in the ecological system after the wildfires. Our qualitative data elucidated these different perspectives. Experts mentioned wildfire-driven degradations such as habitat loss and limited forest regeneration, especially in high severity burn areas, while at the same time noting how wildfire served as a catalyst for ecological variability, fostering greater heterogeneity of forest types across the landscape in other areas.

Expert views from this study reflect objective assessments of wildfire showing both positive and negative influences on resilience depending on fire severity. Wildfire events catalyze forest composition changes and can in some cases lead to conversion of forests to non-forests (Chambers et al. 2016, Davis et al. 2023). These conversions occur during high-severity fires when a lack of tree regeneration results in a persistent non-forest vegetation type (Coop et al. 2020). High severity burns can also alter sediment transportation, flow levels, and water temperature, permanently changing aquatic species composition (Rieman and Clayton 1997).

Alternatively, increased variation of fire severity between events has been shown to promote biodiversity and provide niche habitats particularly for avian and pollinator species (Kotliar et al. 2007, Kelly and Brotons, 2017). In cases of low severity frequent fire, wildfires regulate fire processes variability by maintaining understory density at levels that decrease frequency of large-scale high severity fire (Larson et al. 2013, Pausas and Keeley 2019). Similarly, shorter fire return intervals have been linked to increased heterogeneity of forest types and stand variability (Prichard et al. 2017).

The exception to the above narrative is that stakeholders perceived the 2020 wildfire events as having a negative influence on watershed processes variability. Stakeholders viewed fire as weakening the watershed's ability to maintain stream flows, buffer large floods, and support water quality. Objective assessments have highlighted the role fire plays in water quality contamination, loss of sediment regulation processes, alterations to streamflow, and aquatic habitat degradation (Rhoades et al. 2019). In sum, the limited quantitative changes in ecological indicators in this study likely reflects the counterbalance of both positive and negative changes from the 2020 wildfire events because of heterogeneity in burn severity and forest types at the watershed scale.

Ecosystem services

Our results point to a definitive perception by experts of a negative influence of the 2020 wildfire events on all ecosystem service indicators. Qualitatively, stakeholders highlighted the damages to water quality, loss of recreation opportunities, and concerns for public safety surrounding the floods that follow wildfires. This negative perception of the influence on ecosystem services probably reflects the study sites' importance as a source water system (Writer et al. 2014, Gannon et al. 2019). Both watersheds contain national or state parks, and large areas of national forest, many of which were impacted by the 2020 wildfires. A socio-cultural valuation of ecosystem services in the study area found that water quality, biodiversity, and recreation were highly valued by local residents (Chamberlain and Jones 2024). Furthermore, cultural values in favor of protected areas, wildlife, and biodiversity protection are rising across the western U.S. (Manfredo et al. 2021).

Expert perceptions that wildfire events decrease resilience through the loss of ecosystem services of erosion control, water quality, and water regulation are congruent with findings of existing objective assessments of watershed services after fires. Studies have shown that wildfires create large social and economic costs from the loss of clean water supply (Kinoshita et al. 2016, Jones et al. 2022). These perceived losses reflect the negative impacts fire has to water provisioning and regulating services through the altering of nutrient and sediment regulating cycles with subsequent alterations to water provisioning services (Rhoades et al. 2011, Vukomanovic and Steelman 2019). Impacts of post-fire erosion are also well documented (Robinne et al. 2020), with wildfire increasing sedimentation in spring runoffs and subsequent water quality losses (Writer et al. 2014, Wohl et al. 2022). Thus, although experts perceived mixed changes in ecological resilience in this study, the consequences of these

wildfire events on the forested watersheds for people, through the provision of ecosystem service benefits, was overwhelmingly negative.

Social dimensions of natural resources

In our study, experts perceived a statistically significant increase in 8 out of the 13 social indicators due to the 2020 wildfires. Interviewees discussed the role of wildfire in catalyzing beneficial changes to funding, strengthened partnerships, and increased public attention and support for mitigation. Informants noted that the wildfires brought partners together and strengthened collaboration. Stakeholders who experienced the High Park Fire in 2012 reflected that social capital had increased following this earlier event, which led to increased fire preparedness in 2020. Our findings are in line with objective assessments of social capital that show stakeholders can build connections, trust, and act collectively in response to disturbance events in ways that foster innovation and information sharing (Fischer and Jasny 2017). Previous research also underscores the relationship between strength of existing social capital and improved wildfire preparedness (Bihari and Ryan 2012, McCaffrey 2015). Our finding that experts perceived that wildfire served as a catalyst for improved social resilience in this study area supports what has been observed across the western U.S., that wildfire disturbance events can lead to collective action responses in many contexts (Bennett et al. 2014, Roberts et al. 2019, Morgan et al. 2023).

Experts also perceived that the wildfire events of 2020 catalyzed greater levels of institutional redundancy and participation. This perceived improvement in governance structure is important given the role polycentricity and adaptive governance play in improving future SES resilience (Biggs et al. 2012, Cosens and Williams 2012). Stakeholders also perceived that wildfire events catalyzed a greater level of understanding of gradual changes within the system and a need to foster fire adaptivity on a systems level. These findings suggest that stakeholders are starting to move beyond basic resilience to embrace mindsets and practices that can lead to adaptive and transformative resilience (McWethy et al. 2019). In contrast, experts perceived little changes in power, accountability, and diversity of perspectives. This may reflect the existing homogeneity within wildfire management networks, barriers between different land ownership types, and local demography (Fischer and Jasny 2017). Overall, the 2020 wildfire events were perceived as enhancing social resilience in this study area.

Strengthening future SES resilience

Our results, and expert opinions about what future actions are needed to improve resilience, provide some guidance on how to adapt and transform resilience in western U.S. forested watersheds in the face of climate change. First, stakeholders noted a strong preference for more prescribed fire as a wildfire treatment. Prescribed fire has a known role for decreasing the size and severity of future wildfires if an existing treatment and a new wildfire overlap spatially (Restaino and Peterson 2013, Kalies and Yocom Kent 2016). In the short term, prescribed fire reduces surface fuels and fire hazards and can decrease tree mortality (Kalies and Yocom Kent 2016, van Mantgem et al. 2016). Prescribed fire is unmatched in its surrogacy to wildfires and provides the most comparable analogue (Stephens et al. 2012). Although informants noted the many strengths of prescribed fire,

they also highlighted known barriers, in particular insurance, liability, and policy barriers (Wonkka et al. 2015, Schultz et al. 2019). Thus, although more prescribed fire in the western U.S. would help transform resilience (McWethy et al. 2019), and the experts in our study articulated this, more effort on transforming institutional barriers is needed to advance future wildfire resilience.

Second, stakeholders also suggested prioritizing the protection and restoration of ecosystem services, specifically water quality and supply. Post-fire mitigation actions were perceived as very important by stakeholders to speed up the recovery of ecosystem services. Stakeholders desired more resources be dedicated to post-fire aerial mulching as well as stream restoration and stabilization, with the goal of sediment stabilization. Although mulching is accepted as a short-term treatment to lessen post-fire erosion of sloped landscapes when water supplies are at heightened risk, it does not necessarily stand up to larger storm events (Wagenbrenner et al. 2006, Cerdà and Robichaud 2009). Like mulching, the use of physical barriers within streams and hillsides have been used to limit the impacts of post-fire erosion and sedimentation (González-Romero et al. 2022). However, informants also noted a desire to employ more adaptive and transformative approaches to improve future resilience of ecosystem services. This included use of beaver dam analogs. Although the impact of beaver dam analogs as a post-fire mitigation treatment on resilience is an area of present exploration, their use pre-fire has been linked to increased pockets of intact riparian refugia in the face of wildfire, thus offering a potential role in fostering post-fire resilience (Fairfax and Whittle 2020).

In addition to on-the-ground mitigation actions, stakeholders identified planning, collaboration, and fundraising as important for improving future resilience to wildfire. In terms of planning, informants wanted continued and accelerated use of risk management tools such as PODS for improving incident response (Greiner et al. 2020). Additionally, stakeholders perceived a need for developing more fire-adapted community plans. Such plans need to consider local social norms and pre-existing perceptions of fire and fire mitigation (Paveglio et al. 2016). Experts also viewed fostering greater citizen acceptance of mitigation actions as a key part of planning. Citizen acceptance of mitigation actions has been linked to the public's familiarity with the action and trust in the implementing agency (McCaffrey et al. 2013), and more social science-informed communication and outreach could help achieve greater social license for prescribed fire. Related to collaboration, stakeholders expressed a need to increase partnerships with different types of agencies and organizations to improve social networks. A collaborative approach is crucial for effective disturbance response and improves pre- and post-fire planning effectiveness (Schultz and Moseley 2019). Finally, in terms of funding, stakeholders noted the need for increases in funding as well as changes to how funding is used, specifically the widening of permitted tasks within administered funds.

Subjective indicators of resilience and future research

The subjective indicators used in this study provide local decision makers with a relative baseline of resilience for the study area and inform future management actions that could be taken to enhance resilience. As discussed above, expert perceptions of resilience

reflected objective assessments of SES resilience in important ways, but there are also important caveats to keep in mind in the use of subjective metrics moving forward.

First, although experts understood the nuanced changes to ecological conditions from fire, stakeholder perceptions cannot capture the site-specific information on where these positive and negative changes occurred to target specific management actions. Thus, subjective indicators may be less useful than objective metrics in addressing changes to ecological resilience. Subjective indicators may be more useful for measuring changes to ecosystem service and social components of resilience. Experts readily pointed out the negative impacts to ecosystem services from fire that were in line with objective assessments. Because ecosystem services capture the benefits people value from ecosystem processes and functions, using subjective indicators to capture these changes can be a relatively cost-effective way to identify locally driven priorities (Woodhouse et al. 2015). Similarly, using subjective indicators to measure social resilience captures how people view social capital and governance, and can identify barriers and opportunities to improve collaboration.

Second, expert perceptions of how to strengthen future resilience may not account for the full complexity, variability, and uncertainty that occur in wildfire-prone watersheds. As noted in the above discussion, not all management suggestions provided by people in this study have objective evidence supporting their efficacy. It would be important to couple the suggestions from experts for strengthening future resilience with adaptive management principles to monitor, evaluate, learn, and refine management strategies in this SES (Rist et al. 2012).

Looking forward, an important future research need is to compare subjective indicators across experts and community members to test how they are similar or different. It would also be useful to compare subjective and objective indicators of resilience in the same study site because we had to rely on published literature to compare our subjective responses to objective measures.

CONCLUSION

This study characterized subjective views experts hold on SES resilience in response to large and severe wildfires. It helps fill a gap in applied understanding of how people perceive the impact of large, severe wildfires on resilience components across spatial and temporal dimensions. As our results show, experts perceived wildfire events as simultaneously decreasing and increasing different components of systems resilience. This underscores the need to disaggregate measures of resilience into different components or principles, as we have done in this study. Experts perceived wildfire as having mixed influence on ecological resilience, and our results highlight the importance of considering the appropriate ecological scale in which to measure resilience because of heterogeneity in burn severity and ecological impacts of wildfires. Although ecologically some wildfire can be beneficial, our results also suggest that experts perceive the influence of wildfire on ecosystem service benefits more negatively. Additionally, our results highlight that experts perceived wildfire as leading to some social transformations in governance and collective action, which in the future, should enhance ecological and ecosystem service components of systems resilience. Although not a substitute for objective indicators of resilience, we find that experts' perceptions of resilience are in line

with many objective assessments of SES resilience. Thus, perceptions of resilience can provide a complementary set of information that can be used to develop a baseline of relative resilience and inform management decisions about how to strengthen resilience. In the case of wildfire-prone watersheds, putting more prescribed fire on the landscape, protecting watershed services, and enhancing collaborations and planning efforts are stakeholder priorities for enhancing future resilience.

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Data Availability:

The data and code that support the findings of this study are available on request from the corresponding author, AC. None of the data and code are publicly available because they contain information that could compromise the privacy of research participants as individuals and within the context as employees within their respective organizations. Ethical approval for this research study was granted by Colorado State University (IRB #3584).

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Appendix 1- Resilience Principles and Indicators Development

Table A.1 lists the resilience principles that were used to develop resilience indicators used in this study. The principles come from Salt and Walker (2006) and Biggs (2012). In areas of overlap, principles were combined, but in areas without overlap, individual principles were retained. This method was chosen to include the greatest total number of principles. The total number of merged principles is eight.

Table A.1. Original resilience principles and merged principles used in this study. *Green for principle with origin from Biggs (2012), and blue for principle with origin from Salt and Walker (2006).*

Merged Resilience Principles	Original Resilience Principles
Ecological Diversity	Biological Diversity Maintain Diversity & Redundancy
Ecological Variability	Ecological Variability
Ecosystem Services	Ecosystem Services
Manage Connectivity	Modularity Manage Connectivity
Manage Complex Variables & Feedbacks	Manage Slow Variables & Feedbacks Acknowledging Slow Variables Tight Feedbacks
Foster Complex Adaptive Thinking	Foster Complex Adaptive Thinking Encourage Learning Innovation
Linking and Bonding Social Capital	Social Capital
Governance	Overlap in Governance Promote Polycentric Governance Broaden Participation

Using these eight resilience principles, we developed specific indicators through a literature review and expert knowledge that reflect each principle and the study focus of wildfire and water. As a starting point we used two recently published papers that developed their own set of subjective measures of resilience and that listed their indicators in their published paper (Allen et al., 2018; Salomon et al., 2019). We revised these two published lists of indicators based on expert knowledge of the local system, and specific characteristics of wildfire and water. After we developed a first draft of indicators for each of the eight principles, we had the list peer-reviewed by experts with backgrounds in

forestry and wildfire (2), hydrology and post-fire watershed response (2), economics and social science (2), and by professionals active in wildfire mitigation and watershed protection (2) in the study area. We used this expert feedback to revise our initial list of indicators, leading to the final set used in the interview and survey instruments (Table 2 of the main paper).

Appendix 2 - Interview Guide

Introduction:

1. Can you state your name, and briefly describe your organization and your role in your organization?
 - a. What watershed(s) does your organization focus on?
2. In your work do you use the term resilience, and if so how do you define it?
3. How would you characterize the ecological and social health of your watershed(s) today (2022) using the following eight resilience principles?
 - a. What factors or events do you think have shaped the ecological and social health of your watershed(s) today?

Wildfire Events and Resilience:

4. Can you tell me about the ecological and social health of your respective watershed(s) before the Cameron Peak and East Troublesome Fires of 2020?
 - a. Specifically, how have the eight resilience principles changed due to these specific wildfire events, if they have changed at all?

Governance, Management Actions, and Resilience:

5. What type of pre- or post-wildfire mitigation actions (e.g., thinning, mulching, etc.) are being implemented in your watershed(s)?
 - a. Did the Cameron Peak and East Troublesome Fires of 2020 change the type or scale of mitigation actions?
 - b. How do you think these different mitigation actions influence the ecological and social health of your watershed(s)?
 - c. Are there some mitigation actions that have more influence on these resilience principles than others?

6. How would you describe the relationship between your organization and other organizations working on wildfire in your watershed(s)? Is there collaboration and coordination amongst your organization and others, and or any joint or shared resources?
 - a. Have there been any changes in these relationships before and after the Cameron Peak and East Troublesome Fires of 2020?
 - b. How do you think these relationships between organizations working in your watershed(s) influence the eight resilience principles?

Future Resilience:

7. What concerns you most about wildfire events in your watershed(s)? What concerns you less about wildfire events in your watershed.
8. Can you describe to me where you would like the ecological and social health of your watershed(s) to be in 5-10 years? Are there any principles or indicators you like to see prioritized in the next 5-10 years?
9. What factors, management actions, or policies would most likely help you get to this level of ecological and social health in your watershed(s)?
 - a. Are there changes in the use of pre- or post-wildfire mitigation actions that you think could improve the resilience of your watershed(s)?
 - b. Are there any additional actions, not currently being used, that you think could improve future resilience (e.g., climate assisted tree migration)?
 - c. Are there changes in relationships across organizations that you think could enhance future resilience in your watershed(s)?

Final Reflection and Next Steps:

10. In the next step of our research, we want to send a survey on these indicators to other stakeholders who work on watershed and wildfire mitigation in the Poudre River and Big Thompson River Watershed. Is there anyone within your organization you would recommend we send this survey to?

a. If so, would you be willing to provide us with their contact information

11. What organizations do you recommend we prioritize surveying?

a. Do you have a contact you are willing to share at that organization?

Semi-structured interviews took no less than 45 minutes and no more than 60 minutes.

Appendix 3 - Qualitative Data Code Tree

Themes	Parent Codes	Descriptor Codes
5/10 vision		
Defining resilience		
Barriers/difficulties	Barriers to prescribed burning	
	Differences between watersheds	
	Expanding WUI population	
	Legacy settlement effects	
	Limited treatment size	
	Navigating policy	
	Population and tourism boom	
	Land ownership barriers	Private landowners
		Public land barriers
Mitigation actions		
	Driving factors	
		Driven by communities
		Driven by monitoring past management
		Driven by water supply / watershed priority
	Effectiveness of prescribed fire	
		Combined effects with thinning
		Cost-effective
		Ecologically most beneficial

Improving in

Increasing in scale

Creative solutions

Social license

Wildfire as a treatment including use of PODs

Types of mitigation actions

Home-hardening

Mixed method

Mulching

Replanting

Stream restoration

Thinning

Needs- social

Adaptivity and learning by practitioners

Changes in partnership

Citizen acceptance and buy in

Increases in funding/ changes to funding

Science backed decision making

Staff capacity

Negative ecological impacts

2013 floods/ fire flood cycles

Climate change

Degraded ecosystem services

Fuel loads

Increasing fire severity

Insects and beetle kill

Limited regeneration

Water quality/ supply degradations

Partnership

Based on different land ownership

Build capacity

Can withstand setbacks

Driven by aligned goals

Facilitating social license

Facilitating spread of funds

Importance of stakeholder connectivity

Strength of partnerships

Take time to build

Wildfire as a catalyst

For ecological variability

For funding

For partnership

For public attention and support

For ramping up mitigation actions

Appendix D: Survey Instrument

Start of Block: Default Question Block

Thank you for your interest in this survey. The purpose of this survey is to gain insight into how you characterize past, present, and future resilience in your watershed and understand more about management actions that alter resilience. Results from this survey will be analyzed with responses from others working on watershed management and wildfire mitigation in these watersheds.

Please keep in mind that your participation is voluntary, and your responses will remain confidential, as we will not attach your name or organization to your responses. We estimate that this survey will take less than 30 minutes to complete. By clicking “yes” below, you indicate that you have read and understand the information provided above, that you willingly agree to participate, and that you may withdraw your consent at any time. Feel free to contact either [REDACTED] at [REDACTED] or [REDACTED] at [REDACTED], with any questions or concerns you may have about our research.

Do you consent to taking this survey?

☐ Yes (1)

☐ No (2)

Skip To: End of Survey If Q1 = No

End of Block: Default Question Block

Start of Block: Introduction

Which of the following best characterizes your organization? Please select the most applicable.

☐ Government Agency (1)

☐ Private Business (2)

☐ Coalition or NGO (3)

☐ Academic or Research Group (4)

☐ City or County Government (5)

☐ Water Utility (6)

☐ Other (7) _____

What is your role in your organization? Click as many that apply.

☐

Managerial (oversee operations, manage projects, etc.) (1)

☐

Carry out on the ground management actions (administer restoration projects, conduct field work, etc.) (2)

☐

Mainly planning based (draft plans, conduct environmental impact statements etc.) (3)

☐

Develop funding (pool funds, connect with donors, administer funds, etc.) (4)

☐

Outreach/ education (educate public on watershed issues, educate stakeholders on projects, etc.) (6)

☐

Research (develop and implement research projects, etc.) (7)

☐

Other (5) _____

About how many years have you worked for this organization?

For the purpose of this study we are interested in the **Big Thompson River and Poudre River watersheds**. In order to most effectively learn about each watershed, we ask that for this survey you pick the watershed you are more familiar with for your responses. Which watershed will your answers focus on?

☐

I will be responding for the Big Thompson watershed (1)

☐

I will be responding for the Poudre watershed (2)

End of Block: Introduction

Start of Block: Current Resilience

In this section, we aim to understand how you view present day (2022) resilience in your primary watershed. For the following table, please read each statement and answer how you rank the health or the current state of your watershed.

Presently, in 2022, how would you rank the average or general state of each of the following indicators in the watershed you selected to report on?

Scale: Very Poor (1) Somewhat Poor (2) Neutral (3) Somewhat Good (4) Very Good (5)

(clickable grid) with indicators of:

- the presence of a healthy variety of ecosystem types (e.g., alpine, forest, woodland, shrub, riparian, meadow) (1)
- the presence of a healthy variety of tree species (e.g., aspen, ponderosa pine) (2)
- the ability for plant and animal habitats to respond to ecological disturbances (3)
- the representation of different size of age classes (a mix of small, medium, and large trees) (4)
- the ability of wildfires (including their frequency, size, and severity) to occur within a healthy level of variability (5)
- the ability of non-fire processes (e.g., pest outbreaks, wind damage, ice damage) to occur within a healthy level of variability (6)
- the ability of watershed processes (e.g., maintain stream flows, buffer large floods, support healthy water quality, regulate sediment movement) to occur within a healthy level of variability (7)
- the suitability of the water supply for human consumption (i.e., free of harmful chemical, physical, or biological components) (8)
- the ability of the watershed to limit hillslope erosion of sediment into receiving streams, and the ability of streams to regulate downstream transport of sediment (9)

- the ability of the watershed to reduce or buffer downstream flooding (10)
- the ability to meet human demand for recreation opportunities (i.e., hiking, water sports, fishing, hunting) (11)
- the ability of the watershed to support a good quality of life for the people that live within it now and in the future (12)
- the integration of evidence-based information into decision making by groups, organizations, communities, and households working on wildfire, forest, and watershed management (13)
- the degree of information sharing across groups, organizations, communities, and households working on wildfire, forest, or watershed management (14)
- the level of understanding by groups, organizations, communities, and households working on wildfire, forest, and watershed management about gradual, long-term changes to the watershed (e.g., from wildfire, forest or watershed management, climate, human use, etc.) (15)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to accept changes in the watershed (e.g, changing fire regimes, forest or watershed management, or climate) in their management decisions (16)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to experiment with new management actions or practices (e.g., pre- or post-fire mitigation) in response to changes in the watershed (17)
- the joint determination of goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (18)
- the voluntary helping of others to achieve goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (19)
- the level of trust across groups, organizations, communities, and households working on wildfire, forest, and watershed management (20)

- the level of overlap in the groups, organizations, communities, and households working on wildfire, forest, and watershed management (21)
- the equitable distribution of power across all groups, organizations, communities, and households working on wildfire, forest, and watershed management (22)
- the level of accountability (i.e., following through on responsibilities) among all groups, organizations, communities, and households working on wildfire, forest, and watershed management (23)
- the level of participation in decision-making across all groups, organizations, communities, and households about wildfire, forest, and watershed management (24)
- the diversity of perspectives (e.g., ideas, views, opinions) that inform decision-making about wildfire, forest, and watershed management (25)

In this section we want to understand your thoughts on how wildfires impact the resilience and health of your primary watershed. There will be two tables in this section. The first asks about health and functionality of your primary watershed before the 2020 wildfires (*Cameron Peak Fire and East Troublesome Fire*). The second asks about how influential the 2020 fires were for creating changes to the health and functionality of your primary watershed.

BEFORE the 2020 wildfires (*Cameron Peak Fire and East Troublesome Fire*) how would you rank the current state of each of the following indicators in your watershed?

Scale: Very Poor (1) Somewhat Poor (2) Neutral (3) Somewhat Good (4) Very Good (5)

(Clickable grid) with indicators of:

- the presence of a healthy variety of ecosystem types (e.g., alpine, forest, woodland, shrub, riparian, meadow) (1)

- the presence of a healthy variety of tree species (e.g., aspen, ponderosa pine) (2)
- the ability for plant and animal habitats to respond to ecological disturbances (3)
- the representation of different size of age classes (a mix of small, medium, and large trees) (4)
- the ability of wildfires (including their frequency, size, and severity) to occur within a healthy level of variability (5)
- the ability of non-fire processes (e.g., pest outbreaks, wind damage, ice damage) to occur within a healthy level of variability (6)
- the ability of watershed processes (e.g., maintain stream flows, buffer large floods, support healthy water quality, regulate sediment movement) to occur within a healthy level of variability (7)
- the suitability of the water supply for human consumption (i.e., free of harmful chemical, physical, or biological components) (8)
- the ability of the watershed to limit hillslope erosion of sediment into receiving streams, and the ability of streams to regulate downstream transport of sediment (9)
- the ability of the watershed to reduce or buffer downstream flooding (10)
- the ability to meet human demand for recreation opportunities (i.e., hiking, water sports, fishing, hunting) (11)
- the ability of the watershed to support a good quality of life for the people that live within it now and in the future (12)
- the integration of evidence-based information into decision making by groups, organizations, communities, and households working on wildfire, forest, and watershed management (13)
- the degree of information sharing across groups, organizations, communities, and households working on wildfire, forest, or watershed management (14)

- the level of understanding by groups, organizations, communities, and households working on wildfire, forest, and watershed management about gradual, long-term changes to the watershed (e.g., from wildfire, forest or watershed management, climate, human use, etc.) (15)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to accept changes in the watershed (e.g, changing fire regimes, forest or watershed management, or climate) in their management decisions (16)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to experiment with new management actions or practices (e.g., pre- or post-fire mitigation) in response to changes in the watershed (17)
- the joint determination of goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (18)
- the voluntary helping of others to achieve goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (19)
- the level of trust across groups, organizations, communities, and households working on wildfire, forest, and watershed management (20)
- the level of overlap in the groups, organizations, communities, and households working on wildfire, forest, and watershed management (21)
- the equitable distribution of power across all groups, organizations, communities, and households working on wildfire, forest, and watershed management (22)
- the level of accountability (i.e., following through on responsibilities) among all groups, organizations, communities, and households working on wildfire, forest, and watershed management (23)
- the level of participation in decision-making across all groups, organizations, communities, and households about wildfire, forest, and watershed management (24)

- the diversity of perspectives (e.g., ideas, views, opinions) that inform decision-making about wildfire, forest, and watershed management (25)

In this section we want to understand your thoughts on how influential the 2020 wildfires were on changes in social and ecological health.

The **influence** of the 2020 wildfires (*Cameron Peak Fire and East Troublesome Fire*) on each of the following indicators has been...

Scale: Strong negative influence (1) Slight negative influence (2) No influence (3) Slight positive influence (4) Strong positive influence (5)

(Clickable grid) with indicators of:

- the presence of a healthy variety of ecosystem types (e.g., alpine, forest, woodland, shrub, riparian, meadow) (1)
- the presence of a healthy variety of tree species (e.g., aspen, ponderosa pine) (2)
- the ability for plant and animal habitats to respond to ecological disturbances (3)
- the representation of different size of age classes (a mix of small, medium, and large trees) (4)
- the ability of wildfires (including their frequency, size, and severity) to occur within a healthy level of variability (5)
- the ability of non-fire processes (e.g., pest outbreaks, wind damage, ice damage) to occur within a healthy level of variability (6)
- the ability of watershed processes (e.g., maintain stream flows, buffer large floods, support healthy water quality, regulate sediment movement) to occur within a healthy level of variability (7)

- the suitability of the water supply for human consumption (i.e., free of harmful chemical, physical, or biological components) (8)
- the ability of the watershed to limit hillslope erosion of sediment into receiving streams, and the ability of streams to regulate downstream transport of sediment (9)
- the ability of the watershed to reduce or buffer downstream flooding (10)
- the ability to meet human demand for recreation opportunities (i.e., hiking, water sports, fishing, hunting) (11)
- the ability of the watershed to support a good quality of life for the people that live within it now and in the future (12)
- the integration of evidence-based information into decision making by groups, organizations, communities, and households working on wildfire, forest, and watershed management (13)
- the degree of information sharing across groups, organizations, communities, and households working on wildfire, forest, or watershed management (14)
- the level of understanding by groups, organizations, communities, and households working on wildfire, forest, and watershed management about gradual, long-term changes to the watershed (e.g., from wildfire, forest or watershed management, climate, human use, etc.) (15)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to accept changes in the watershed (e.g, changing fire regimes, forest or watershed management, or climate) in their management decisions (16)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to experiment with new management actions or practices (e.g., pre- or post-fire mitigation) in response to changes in the watershed (17)
- the joint determination of goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (18)

- the voluntary helping of others to achieve goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (19)
- the level of trust across groups, organizations, communities, and households working on wildfire, forest, and watershed management (20)
- the level of overlap in the groups, organizations, communities, and households working on wildfire, forest, and watershed management (21)
- the equitable distribution of power across all groups, organizations, communities, and households working on wildfire, forest, and watershed management (22)
- the level of accountability (i.e., following through on responsibilities) among all groups, organizations, communities, and households working on wildfire, forest, and watershed management (23)
- the level of participation in decision-making across all groups, organizations, communities, and households about wildfire, forest, and watershed management (24)
- the diversity of perspectives (e.g., ideas, views, opinions) that inform decision-making about wildfire, forest, and watershed management (25)

In this section we would like to understand your opinion and perception on how **administering pre-wildfire mitigation actions** in your watershed has influenced the current level of ecological and social health for your watershed. Pre-wildfire mitigation actions include:

- administering prescribed burning
- creating defensible space
- thinning forests (by hand and mechanical)

The influence of **pre-wildfire mitigation actions** on each of the following indicators has been...

Scale: Strong negative influence (1) Slight negative influence (2) No influence (3) Slight positive influence (4) Strong positive influence (5)

(Clickable grid) with indicators of:

- the presence of a healthy variety of ecosystem types (e.g., alpine, forest, woodland, shrub, riparian, meadow) (1)
- the presence of a healthy variety of tree species (e.g., aspen, ponderosa pine) (2)
- the ability for plant and animal habitats to respond to ecological disturbances (3)
- the representation of different size of age classes (a mix of small, medium, and large trees) (4)
- the ability of wildfires (including their frequency, size, and severity) to occur within a healthy level of variability (5)
- the ability of non-fire processes (e.g., pest outbreaks, wind damage, ice damage) to occur within a healthy level of variability (6)
- the ability of watershed processes (e.g., maintain stream flows, buffer large floods, support healthy water quality, regulate sediment movement) to occur within a healthy level of variability (7)
- the suitability of the water supply for human consumption (i.e., free of harmful chemical, physical, or biological components) (8)
- the ability of the watershed to limit hillslope erosion of sediment into receiving streams, and the ability of streams to regulate downstream transport of sediment (9)
- the ability of the watershed to reduce or buffer downstream flooding (10)
- the ability to meet human demand for recreation opportunities (i.e., hiking, water sports, fishing, hunting) (11)

- the ability of the watershed to support a good quality of life for the people that live within it now and in the future (12)
- the integration of evidence-based information into decision making by groups, organizations, communities, and households working on wildfire, forest, and watershed management (13)
- the degree of information sharing across groups, organizations, communities, and households working on wildfire, forest, or watershed management (14)
- the level of understanding by groups, organizations, communities, and households working on wildfire, forest, and watershed management about gradual, long-term changes to the watershed (e.g., from wildfire, forest or watershed management, climate, human use, etc.) (15)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to accept changes in the watershed (e.g, changing fire regimes, forest or watershed management, or climate) in their management decisions (16)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to experiment with new management actions or practices (e.g., pre- or post-fire mitigation) in response to changes in the watershed (17)
- the joint determination of goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (18)
- the voluntary helping of others to achieve goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (19)
- the level of trust across groups, organizations, communities, and households working on wildfire, forest, and watershed management (20)
- the level of overlap in the groups, organizations, communities, and households working on wildfire, forest, and watershed management (21)

- the equitable distribution of power across all groups, organizations, communities, and households working on wildfire, forest, and watershed management (22)
- the level of accountability (i.e., following through on responsibilities) among all groups, organizations, communities, and households working on wildfire, forest, and watershed management (23)
- the level of participation in decision-making across all groups, organizations, communities, and households about wildfire, forest, and watershed management (24)
- the diversity of perspectives (e.g., ideas, views, opinions) that inform decision-making about wildfire, forest, and watershed management (25)

In this section we would like to understand your opinion and perception on how administering **post-wildfire mitigation actions** in your watershed has influenced the current level of ecological and social health for your watershed. Post-wildfire mitigation actions include:

- mulching post-fire landscapes
- reforesting post-fire landscapes
- stream restoration and stabilization projects post-fire

The influence of **post-wildfire mitigation actions** on each of the following indicators has been...

Scale: Strong negative influence (1) Slight negative influence (2) No influence (3) Slight positive influence (4) Strong positive influence (5)

(Clickable grid) with indicators of:

- the presence of a healthy variety of ecosystem types (e.g., alpine, forest, woodland, shrub, riparian, meadow) (1)

- the presence of a healthy variety of tree species (e.g., aspen, ponderosa pine) (2)
- the ability for plant and animal habitats to respond to ecological disturbances (3)
- the representation of different size of age classes (a mix of small, medium, and large trees) (4)
- the ability of wildfires (including their frequency, size, and severity) to occur within a healthy level of variability (5)
- the ability of non-fire processes (e.g., pest outbreaks, wind damage, ice damage) to occur within a healthy level of variability (6)
- the ability of watershed processes (e.g., maintain stream flows, buffer large floods, support healthy water quality, regulate sediment movement) to occur within a healthy level of variability (7)
- the suitability of the water supply for human consumption (i.e., free of harmful chemical, physical, or biological components) (8)
- the ability of the watershed to limit hillslope erosion of sediment into receiving streams, and the ability of streams to regulate downstream transport of sediment (9)
- the ability of the watershed to reduce or buffer downstream flooding (10)
- the ability to meet human demand for recreation opportunities (i.e., hiking, water sports, fishing, hunting) (11)
- the ability of the watershed to support a good quality of life for the people that live within it now and in the future (12)
- the integration of evidence-based information into decision making by groups, organizations, communities, and households working on wildfire, forest, and watershed management (13)
- the degree of information sharing across groups, organizations, communities, and households working on wildfire, forest, or watershed management (14)

- the level of understanding by groups, organizations, communities, and households working on wildfire, forest, and watershed management about gradual, long-term changes to the watershed (e.g., from wildfire, forest or watershed management, climate, human use, etc.) (15)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to accept changes in the watershed (e.g, changing fire regimes, forest or watershed management, or climate) in their management decisions (16)
- the willingness and ability of groups, organizations, communities, and households working on wildfire, forest, and watershed management to experiment with new management actions or practices (e.g., pre- or post-fire mitigation) in response to changes in the watershed (17)
- the joint determination of goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (18)
- the voluntary helping of others to achieve goals across groups, organizations, communities, and households working on wildfire, forest, and watershed management (19)
- the level of trust across groups, organizations, communities, and households working on wildfire, forest, and watershed management (20)
- the level of overlap in the groups, organizations, communities, and households working on wildfire, forest, and watershed management (21)
- the equitable distribution of power across all groups, organizations, communities, and households working on wildfire, forest, and watershed management (22)
- the level of accountability (i.e., following through on responsibilities) among all groups, organizations, communities, and households working on wildfire, forest, and watershed management (23)
- the level of participation in decision-making across all groups, organizations, communities, and households about wildfire, forest, and watershed management (24)

- the diversity of perspectives (e.g., ideas, views, opinions) that inform decision-making about wildfire, forest, and watershed management (25)

Please rank the level of influence you think these three post-wildfire mitigation actions have had on increasing ecological and social health in your watershed. Click and drag them into a new rank order of 1, 2, and 3 (where 1 indicates the action has had more of a positive influence on ecological and social health).

_____ mulching post-fire landscapes (1)

_____ reforesting post-fire landscapes (4)

_____ stream restoration and stabilization projects post-fire (5)

In this final section we want to understand your concerns about the future and how resilience could be improved in your primary watershed.

How concerned is your organization about the impact future wildfire could have in the forests and watersheds where you work? Impacts can be either direct (e.g., damaging infrastructure, destroying habitat) or indirect (e.g., altering water quality, reducing biodiversity).

☐ Not concerned (1)

☐ Somewhat concerned (2)

☐ Concerned (3)

☐ Very concerned (4)

Skip To: Q29 If Q24 = Not concerned

Which of the following future wildfire-related impacts are of concern for the forests and watersheds where you work? Please select all that apply.

☐

Water quality impacts (e.g., turbidity, ash, nutrients, dissolved oxygen, algal blooms, etc.) (1)

☐

Forest impacts (e.g., changes in biodiversity, species recovery, soil water retention, etc.) (2)

☐

Hydrologic impacts (e.g., channel scouring or sedimentation, timing or volume of runoff, etc.) (3)

☐

Infrastructure impacts (e.g., damage to homes, equipment, reservoir sedimentation, etc.) (4)

☐

Recreation impacts (e.g., damage to trails, rivers, campgrounds, etc.) (5)

☐

Other: (6) _____

Which of the following factors do you think would have the most impact on improving the ecological and social health of the forests and watersheds where you work? **Please select the top three that you think are most important.**

- ☐ administering more prescribed burning (1)
- ☐ creating more defensible space (2)
- ☐ thinning more forests (by hand and mechanical) (3)
- ☐ suppressing more active wildfire (4)
- ☐ mulching more post-fire landscapes (5)
- ☐ reforesting more post-fire landscapes (6)
- ☐ more stream restoration and stabilization projects post-fire (7)
- ☐ beaver restoration (8)
- ☐ climate assisted tree migration (9)
- ☐ allowing more wildfires to burn (if life or property are not in danger) (10)
- ☐ additional funding (11)
- ☐ improved collaboration and coordination in wildfire mitigation planning (12)
- ☐ changes to building codes on how homes are built (13)

- ☐ changes to zoning codes on where homes can be built (14)
 - ☐ more education and outreach to private land managers (15)
 - ☐ better integration of science into decision-making (16)
 - ☐ monitoring outcomes of management actions (17)
 - ☐ changes in dynamics of political influence in natural resource management (18)
-

Are there any other management strategies or inputs not listed above that you think would be useful for improving resilience in the future in the watersheds where you work?

Do you want us to send you a write up of the project results when they are ready?

☐ Yes, please provide preferred email address (1)

☐ No (2)

Thank you for your time and input. Your insights are very valuable to our research team. If you have any additional comments or questions please leave them here.

Additional Notes on Survey Completion

Survey took participants an average of 30 minutes to complete. Sixty-one stakeholders opened the survey for an engagement rate of 62%. Thirty-seven stakeholders completed the survey in its entirety for a completion rate of 38%.