Explaining Changes in Perceived Wildfire Risk Related to the Mountain Pine Beetle Outbreak in North Central Colorado

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Highlights

- Perceptions of all forest risks except for forest fire and falling trees declined.
- Respondents indicated increases in all dimensions of wildfire risk perception.
- Higher perceived tree mortality was related to increased perception of fire risk.
- Greater individual activeness corresponded to increased wildfire risk perception.
- Social-ecological indication of wildfire risk is important for forest management.

Abstract

Longitudinal studies of risk perception, while growing, remain an understudied area of risk analysis research. Natural resource-based communities provide a key backdrop for analyzing dynamic risk perceptions and related social-ecological processes. Since the mid-1990s, a mountain pine beetle (MPB) outbreak has affected roughly 3.4 million acres of north central Colorado forests. Slow-moving landscape changes have taken place as a result of the outbreak, making it a relevant case study in which to examine wildfire and forest risk perceptions over time. In 2018, we replicated and expanded a 2007 mail survey of residents about local response to the MPB outbreak in nine north central Colorado communities. Using the initial and follow-up survey data from these study communities, we examined the changing wildfire risk perception and its relationships with various aspects of local human–nature interactions. The longitudinal surveys showed that perceptions of all forest risks except for forest fire and falling trees declined across the two study phases. Respondents in the 2018 survey also indicated increases in perceived likelihood of a wildfire, perceived severity of possible wildfire damage, and general concern about wildfire hazard. The analysis suggested that evolving wildfire risk perception was strongly associated with a number of explanatory variables and personal characteristics. Higher levels of perceived tree mortality, community interaction and communication, and individual actions in response to forest risks were consistently related to greater odds of indicating increased wildfire risk perception. In general, community social vulnerability, perceived tree re-growth, satisfaction with local management entities, and age were negatively related to the likelihood of having elevated perceptions of fire risk, whereas males and forest-related occupations were associated with relatively lower odds of reporting increases in perceived wildfire risk. Significant influencing factors for change also varied across the cognitive and affective dimensions of wildfire risk perception. Findings of this research have important

implications for conceptual approaches, management and policy, as well as social-ecological indication and analysis in forest risk related areas.

Keywords: dynamic risk perception; risk perception indicators; forest insect outbreaks; wildfire risk; community risk context; longitudinal surveys

1. Introduction

Hazards and risks are ubiquitous, dynamic phenomena in modern society (Beck, 1992). Risk involves both the probability of an undesired event and the extent of negative consequences that may result from its occurring (Flint and Luloff 2005; Qin et al., 2015b). The sociopsychological and experiential aspects of environmental risks constitute an important topical area in research on disasters, risks, and vulnerability and adaptation to environmental or climate change (Bubeck et al., 2012; Kellens et al., 2013; Qin et al., 2015b). Social-ecological risk perception and related behavior are key indications of complex human–environmental interactions. Traditionally, longitudinal research on risk perception is largely lacking as previous studies mostly focused on the immediate impacts of and responses to disasters or hazards (Loewenstein and Mather, 1990; Rogers, 1997). Although understanding of the temporal dynamics of risk events has been improving in recent years, little is known about the biophysical, sociocultural, and economic processes contributing to changing risk perceptions.

Communities dependent upon natural resources for livelihoods and recreation are uniquely positioned to experience risks posed by changing environment and landscapes (Field and Burch Jr., 1991). Many natural resource-based communities are located in forested,

wildland–urban interface (WUI) areas, those places where human development meets and intermixes with wildland vegetation and that are vulnerable to various ecological disturbances and hazards. Environmental changes across multiple geographic scales can alter forest conditions, thereby increasing risks at the interface between forests and society (Dale et al., 2000; Vose et al., 2018). While forest fire or wildfire holds a dominating role in recent forest social science research, increased interests in other types of forest disturbances (insect outbreaks, invasive species, tree diseases, etc.) have also emerged (e.g., Daab and Flint, 2010; Hlásny et al., 2021; Urquhart et al., 2018). Echoing the broader field of risk analysis, there has been increasing research on the temporal changes in perceived forest risks (e.g., Qin et al., 2015a, 2021; Urquhart et al., 2017), whereas specific examinations of the factors influencing such changes are still lacking. The relationships between multiple forest disturbances are also often overlooked in human dimensions research despite the overlapping or cascading nature of these risks (Qin et al., 2015a).

Coniferous forests in western North America have been increasingly disrupted by bark beetle outbreaks (Pappas, 2013). Mountain pine beetles (MPBs) (*Dendroctonus ponderosae*) have affected vast areas of forests in north central Colorado during the past several decades. Although MPBs are endemic to Colorado forests, this outbreak is unprecedented in its severity and spatial extent. Local experience with this large-scale forest disturbance provides an important case for the study of evolving risk perceptions and related responses. We replicated and expanded a 2007 mail survey of local residents about their reactions to the MPB issue and accompanying forest risks in 2018. The present study draws on the initial and follow-up survey data to examine how wildfire risk perception changes with the beetle disturbance over time and explores key influencing factors for these changes. By connecting environmental risk perception

to notions of multifaceted human–nature relationships, we advance conceptual and empirical understanding of the temporal dynamics of risk perception. Findings of this research can also readily inform social-ecological indicator development and forest risk management approaches.

2. Theory and background literature

2.1. Temporal dynamics of risk perception

To date, few risk theories explicitly address the temporal dimension of risk perception. The constructivist or relativist approach to risk and the cultural theory of risk largely consider risk perception from a static point of view (Douglas and Wildavsky, 1982; Hannigan, 1995; Irwin, 2001). Similarly, the psychometric approach combining both objective and subjective views of risk typically examines snapshots of risk perception with cross-sectional data (Lazo et al., 2000; McDaniels et al., 1995; Slovic, 2000). A social amplification of risk framework, however, moves beyond the conventional approach and illuminates the psychological, sociocultural, institutional, and environmental processes through which risk perception and risk-related behavior are amplified or attenuated (Kasperson et al., 1988). Social learning through direct and indirect experience with risk events constantly modifies people's mental images of risk (Morgan et al., 2001; Wachinger et al., 2013). In this way, the experiential affect heuristic model of risk (risk as feelings) provides a general conceptual foundation for the study of temporal changes in risk perception (Slovic and Peters, 2006). We posit that the affective and cognitive reasoning elements of risk perception represent a key dimension of the dynamic interactions between individuals and their social and environmental contexts. People's multiple, context-based perceptions of their human–nature interactions and changes in their lived experience with local environment can inform and alter their perceived risks.

There has been increasing research interest in the dynamic processes of risk perception during the recent decades. Loewenstein and Mather (1990) found that although public concerns about social and economic issues fluctuated wildly, these risk perceptions were closely related with the actual levels of severity for relevant problems. In their work there was little evidence of decreases in risk perception associated with hazard experience, while the "surprise" pattern of change (i.e., higher concern due to the discrepancy between earlier expectations and consequences) was partially supported. Based on two national surveys in Norway, Nordfjærn and Rundmo (2010) suggested that the perceived probability of transport accidents decreased during a four-year study period (2004–2008) and tracked change in the objective risk level. Nevertheless, the perceived severity of accident consequences and the level of worry increased significantly in the 2008 survey. Additionally, several longitudinal studies traced temporal changes in public risk perception during the H1N1 pandemic, and found that perceived risk of being infected with H1N1 largely followed an inverted U-shape curve (Ibuka et al., 2010; Jones and Salathé, 2009; Sherlaw and Raude, 2013).

Whereas the "issue-attention cycle" model suggests that people's concerns about societal problems generally decline as they fade from public attention, environmental issues may retain public interest longer than other problems because of their visibility, extensiveness, and complex institutional and technological solutions (Downs, 1972). Using national survey data, Urquhart et al. (2017) found that the British public's concern about tree health issues lessened during 2013–2016. Likewise, two survey studies conducted at different points in time (2003 and 2005) suggested a decline in Canadian national park visitors' perception of the ecological risk induced by MPB outbreaks (McFarlane and Witson, 2008). In contrast, a panel analysis using three waves of national survey data from New Zealand revealed no significant change in public

knowledge of and concern for global warming during a one-year study period (Milfont, 2012). Results based on a panel survey of Taiwanese households also showed that perceived risk from nuclear power plants increased in the aftermath of public debates on nuclear power safety (Liu and Smith, 1990). Moreover, Visschers and Siegrist (2013) found that the level of public nuclear power risk perception in Switzerland significantly increased after the Fukushima Disaster.

A number of case studies examined dynamic risk perception on a more local or regional scale.[1] In a small city in upstate New York, Fitchen et al. (1987) found that community residents' concern over health risks from groundwater contamination was surprisingly limited and became less salient over time. Elsewhere, a longitudinal analysis of milk consumption after a contamination incident in Oahu, Hawaii also suggested a gradual decline of perceived health risk (Liu et al., 1998). Several other studies showed that people's perceived hurricane risk decreased one to two years after Hurricanes Katrina and Rita compared to immediately after the disasters (Baker et al., 2009; Shaw and Baker, 2010; Trumbo et al., 2014). However, some scholars detected a strong staying power of community risk perception relating to environmental hazards such as hurricane waves and the accidents or siting of industrial facilities (Cross, 1990; Rogers, 1997). Local residents' perceptions of such environmental risks tended to be raised or maintained by risk communication efforts and catastrophic events (McComas, 2003; Su et al., 2015).

Although wildfire social science research mostly uses a cross-sectional approach (McCaffrey et al., 2013), there is growing evidence on how people's perceptions of fire risk and management change over time. Using panel survey data from different study sites and time periods, Shindler, Toman and colleagues found that attitudes towards major forest fire

[1] Some previous studies have also explored the dynamics of risk perception under specific circumstances such as workers' responses to chemical labeling (Viscusi and O'Connor, 1984) and military sailors' risk assessment during an international operation (Kobbeltved et al., 2005).

management practices (prescribed fire and mechanized thinning) remained relatively stable over time (Shindler and Toman, 2003; Toman et al., 2014). Another recent longitudinal analysis showed that respondents' perceived probability of a wildfire was largely unchanged whereas perceived consequences of a wildfire increased to an extent after local wildfire events (Champ and Brenkert-Smith, 2016). Additionally, several studies examined changing wildfire risk perception in the context of forest disturbance by beetles, and consistently revealed a high retention of local forest/grass fire risk perception despite the generally decreased levels of perceived forest risks over time (Flint, 2007; Gordon et al., 2013; Qin et al., 2015a; Qin and Flint, 2017).

2.2 Influencing factors of forest risk perception

Forest risk can be understood as the probability that loss or damage to human lives, properties, or things valued will ensue from a forest disturbance or hazard such as a wildland fire or an insect outbreak. Beyond technical assessments of risk by forest management professionals, people who live in or near changing forest landscapes are more likely to see the chance for loss through a subjective lens based on their own experience and sociocultural context (Irwin, 2001; Skår, 2010). The wildfire social science literature reveals that residents' assessments of their own property's characteristics may not align with professional risk evaluations of the same characteristics (Meldrum et al., 2015); however, one's perception of wildfire risk is influenced by a number of factors including knowledge of the hazard, experience, social interaction, and perceived consequences (Dickinson et al., 2015; Fischer, 2011; Martin et al., 2011; McGee et al., 2009). Critically, and further demonstrating the dynamic nature of risk perception, is work which

finds that perceptions interact with risk mitigating behaviors that alter the conditions and subsequent perceptions of risk (Meldrum et al., 2019).

More broadly, a community-based conceptual model of forest risk perception (see Fig. 1) postulates multiple aspects of local human–nature relationships and experience as key influencing factors, including local risk context, forest-related environmental values, perceived forest disturbance intensity, relationship with land managers, hazard experience, community interaction and communication, and risk-related actions (Flint, 2007; Qin and Flint, 2010). Social constructivist and social structural perspectives on risk emphasize the contextual and cultural influences on individual risk perception (Dake, 1992; Douglas and Wildavsky, 1982; Renn, 1992). Community residents' forest risk perception is situated in a broader risk context, which includes local social vulnerability conditions in relation to sociodemographic and economic characteristics as well as biophysical hazard settings based on environmental factors such as vegetative cover, fuel loading, and insect outbreaks (Flint, 2007). Both biophysical and socioeconomic vulnerabilities can raise levels of forest risk perception among local residents.

Moreover, forest risk perception is affected by an array of other individual or community attributes and processes. First, individuals' forest-related environmental values influence their sense of self and of a local place (Jorgensen and Stedman, 2001; Williams and Vaske, 2003) as well as feelings of order or disorder amidst experiences (Giddens, 1991; Schroeder, 2007) and through these, related risk perceptions. Therefore, more anthropocentric values are expected to be associated with higher levels of perceived forest risks. Second, perceived forest disturbance intensity can have a larger role in affecting risk perception than actual biophysical change. This construct reflects the importance of both environmental factors and social construction in influencing the impacts of risks (Lockie and Measham, 2012; Savage, 1993; Wachinger et al.,

2013). A high level of perceived proximity to forest hazards is likely to increase forest risk perception. Third, given the mediating role of land managers for mitigating forest risks, the relationship between community residents and land managers is important to risk perception. The level of trust or confidence in risk management agencies has been shown to minimize concern about possible risks (Lidskog, 2000; Peters et al., 1997; Wachinger et al., 2013). Forest risk perception is expected to be low when relationships with land managers are characterized by high levels of satisfaction.

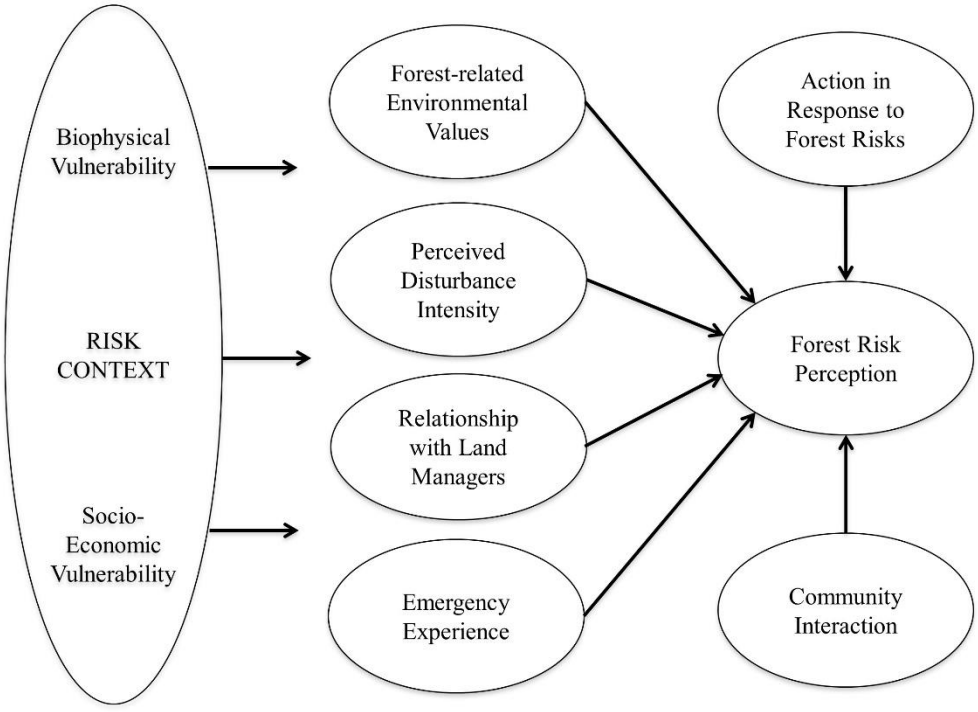

Fig. 1. A conceptual framework of forest risk perception. While these processes are assumed to function bidirectionally, the framework reflects the unidirectional focus of the research at hand. Source: expanded from conceptual model by Flint (2007).

Next, past experience with environmental disturbances or crises also contributes to increased knowledge and awareness of environmental processes (Elrick-Barr et al., 2015;

Hannigan, 1995; Wachinger et al., 2013). Emergency experience at the individual and community levels can thus promote risk perceptions and motivate responses in times of need. Additionally, social science research on risks suggests that risk perception is influenced by social interaction and information processes (Brenkert-Smith et al., 2013; Masuda and Garvin, 2006; Scherer and Cho, 2003). Community interaction and communication involve participation in community organizations, events, and governance as well as formal and informal sources of information about local issues including forest risks. Where higher levels of interaction and communication are found, local residents' forest risk perception tends to be elevated. Finally, the relationship between risk perception and related behavior represents a mutual and dynamic process (Bubeck et al., 2012; Bubeck and Botzen, 2013; Siegrist, 2013). While risk perception is often found to be a key determinant of prevention or mitigation measures, such behaviors can have feedback effects on one's perceived risk as per the risk reappraisal hypothesis (Weinstein et al., 1998; Weinstein and Nicolich, 1993). Thus, community residents' actions in response to forest disturbances are also expected to play a role in affecting forest risk perception.

2.3 Synthesis

Previous disaster and risk studies have depicted different evolvement patterns of risk perception across various social-ecological sectors, time spans, and spatial scales. On the other hand, the literature on community and natural resources has identified primary determinants of the perception of forest risks including wildfire risk. Thus far, there has been relatively little research on the factors influencing temporal changes of risk perception. In this study, we build on relevant theoretical and empirical work to examine community and individual characteristics associated with the dynamic perception of beetle-related wildfire risk in north central Colorado.

3. Material and methods

3.1 Study area

Since 1996 north central Colorado has experienced an extensive MPB outbreak that killed about 3.4 million acres of lodgepole (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*) trees. A combination of factors contributed to the spread and magnitude of the outbreak, such as large, dense swaths of mature, same-aged lodgepole and ponderosa pine forests alongside multiple years of drought and warmer winter temperatures. Although new MPB infestation activity has slowed in recent years, Colorado forests are still facing a range of changes and impacts in ecological and socioeconomic sectors, such as wildlife habitat, soil erosion, and tourism and recreation, as a result of beetle-induced tree mortality (Negrón and Cain, 2019). Meanwhile, Colorado community residents in WUI areas are often threatened by natural and human-induced wildfire ignitions and related hazards. Thus, the combination of such biophysical and socioeconomic characteristics makes north central Colorado an important setting for studying the temporal changes in forest and wildland fire risk perception.

3.2 Data collection

Local residents in nine WUI communities from north central Colorado were surveyed about their perceptions and actions in response to the MPB outbreak in 2007 (see Fig. 2). These study communities were selected based on secondary data and in consultation with regional US Forest Service (USFS) informants to broadly represent an array of local community contexts. Using a modified tailored design method (Dillman et al., 2014), we administered a follow-up mail survey with the 1,346 original respondents from 2007 and 3,000 additional households randomly selected from a new mailing address database purchased from USADATA Inc. in

2018. The survey instrument was informed by thematic content analysis of key informant interviews conducted across the study communities in both study phases. The 1,130 completed surveys yielded a response rate of 32.4% after accounting for undeliverable mail. Of these surveys, 460 were returned by those who also participated in the 2007 study. Additionally, secondary biophysical and socioeconomic data were collected from relevant sources to update the measures of the study communities' contextual characteristics.

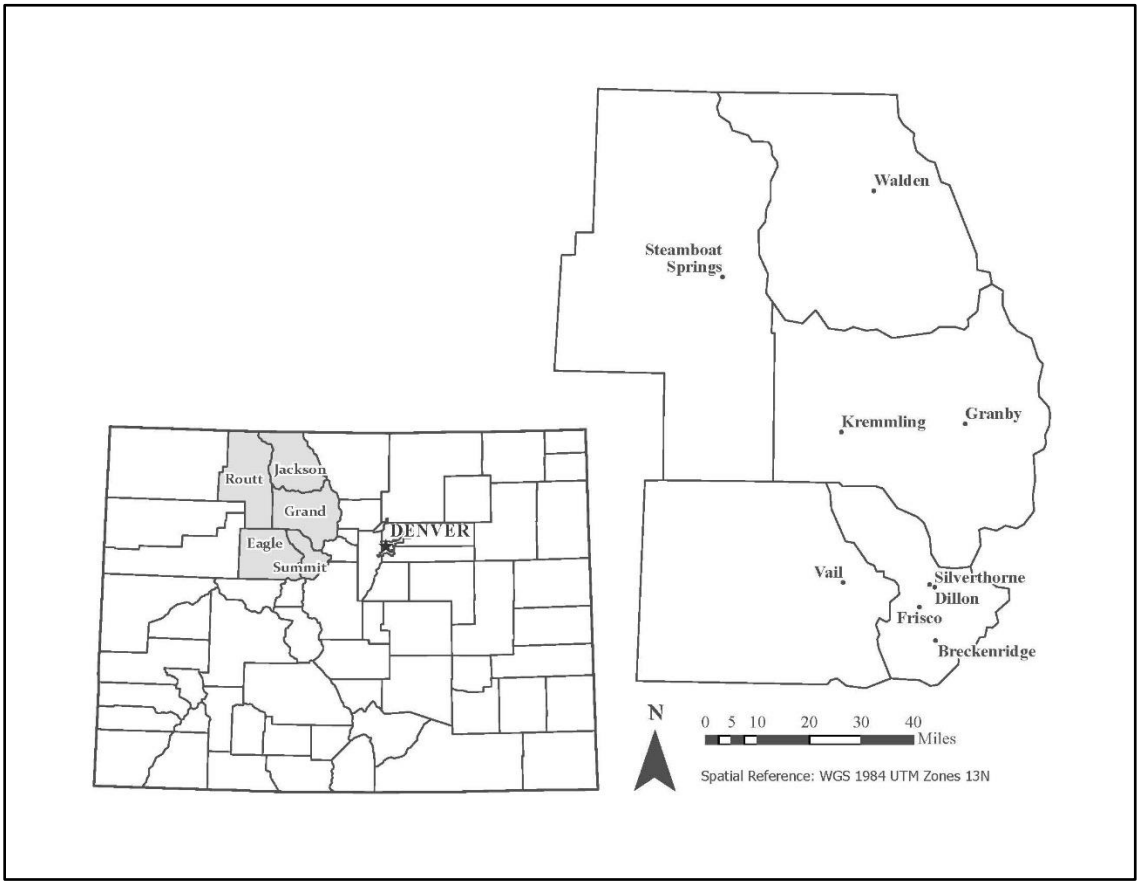

Fig. 2. Map of north central Colorado and the study communities. Reprinted from Qin et al.: Changing perceptions and actions in response to forest disturbance by mountain pine beetles in north central Colorado, *Journal of Forestry*, 2021, 1–13, by permission of Oxford University Press on behalf of the Society of American Foresters. The four borders of the State of Colorado are at 37°N, 41°N, 102°03'W, and 109°03'W, respectively.

3.3 Measurement of variables

Forest risk perception was measured with a scale from 1 (not concerned) to 5 (extremely concerned) in both surveys. We asked respondents how concerned they were about a series of forest risks for their communities as a result of the beetle outbreak and changes in forest health, such as forest fire, falling trees, decline in wildlife habitat, loss of forests as an economic resource, loss of scenic/aesthetic quality, and impact on property values. In the 2018 survey, respondents also answered how likely they thought a wildfire or forest fire might start on or spread to their properties and how severe the damage to their homes would be if there was a wildfire (possible responses ranging from "1" not likely/not at all severe to "5" very likely/very severe). An alternative approach to the longitudinal analysis of risk perception is to explicitly inquire about changes in risk perception in cross-sectional surveys (Bubeck and Botzen, 2013). Thus, in 2018 respondents were also asked to indicate *change in perceived likelihood of a wildfire*, *change in perceived severity of possible wildfire damage*, and *change in general concern about wildfire hazard* during the past years using a 5-point scale ("1" strongly decreased to "3" stayed the same to "5" strongly increased).[2] These self-reported changes in different dimensions of wildfire risk perception were used as the main outcome variables in this study.

Independent variables in the analysis were based on the data collected in 2018, and were structured by key components of the conceptual model of forest risk perception discussed in Section 2.2. Community risk context was measured by two variables representing the biophysical and socioeconomic vulnerability conditions. The indicator of *community biophysical vulnerability* was built with ArcGIS using the 2006–2017 forest mortality data originated from aerial insect surveys conducted by the USFS Rocky Mountain Region and the forest spatial data

[2] The survey question for the *change in general concern about wildfire hazard* variable was "Has your concern about wildfire hazard changed with the mountain pine beetle outbreak in Colorado forests?"

in the National Land Cover Database (NLCD) 2011. It represents the proportions of trees affected by beetles within a 15-mile radius around each study community. The construction of the *community social vulnerability* indictor largely followed the analytical approach developed in Cutter et al. (2003). We first collected data related to the dominant variables of major social vulnerability dimensions for all census places in Colorado, and transformed variable values into a range of 0–1.[3] The final index was then calculated as the mean of these normalized variables.

Survey respondents indicated their agreement or disagreement with a series of statements about forests and forest management in Colorado on a scale of "1" strongly disagree to "5" strongly agree. Exploratory factor analysis revealed a cluster of seven statements particularly related to respondents' views of forest resources and industry, such as "forests should be managed to meet as many human needs as possible," "forests should have the right to exist for their own sake, regardless of human concerns and uses" (reverse-coded), and "forests that are not used for the benefits of humans are a waste of our natural resources." A composite measure of *forest-related environmental view* was generated by computing the average value of these items (alpha reliability coefficient = 0.72; higher values representing more anthropocentric views).

Two independent variables are specifically related to the level of perceived forest disturbance intensity. Respondents were asked to describe *perceived tree mortality* related to beetles and *perceived re-growth of trees* in and around their communities (response options ranging from "1" no pines are dead/no natural re-growth to "5" almost all pines are dead/much natural re-growth).

[3] These variables were per capita income (directionality reversed), median age, number of commercial establishments per square mile, % employed in extractive industries, % housing units that are mobile homes, % African American, % Hispanic, % Native American, % Asian, % employed in service occupations, and % employed in transportation, communication and public utilities. Relevant sociodemographic, income, employment, and housing data were collected from the American Community Surveys 2017. The four normalized variables related to race and ethnicity were first aggregated by taking an average.

Relationship with land managers was represented by respondents' satisfaction or dissatisfaction with relevant management entities ("1" very dissatisfied to "5" very satisfied) regarding how the MPB outbreak was handled. Two aggregate indicators were created based on results of exploratory factor analysis and the means of responses to relevant questions: *satisfaction with local entities* (e.g., private landowners, local fire departments, private logging companies) and *satisfaction with governmental entities* (e.g., city government, Colorado State Forest Service, Bureau of Land Management) (alpha reliability coefficient = 0.65 and 0.88, respectively).

The survey also asked whether respondents themselves or their communities had experienced a list of emergency situations including nearby wildfire in the last ten years. Dichotomous measures of *personal wildfire experience* and *community wildfire experience* ("0" no and "1" yes) were coded according to the responses. Community interaction and communication were measured by two composite indicators: the total *number of information sources* and the level of *community participation* (alpha reliability coefficient = 0.65 and 0.74, respectively). Both variables were constructed by summing responses ("0" no and "1" yes) to questions on the use of various information sources regarding forest issues (e.g., newspapers, local fire department, word of mouth) and questions on participation in a list of general community activities, such as attending a local community event or working with others to deal with a community issue.

Activeness in response to forest risks was operationalized as the level of personal and/or group actions taken to mitigate beetle-related risks. These include efforts particularly related to wildfire prevention (e.g., clearing vegetation near structures, using fire resistant building material), as well as those addressing broader forest issues (e.g., participating in a community

effort to clear trees, attending a beetle task force meeting).[4] Following exploratory factor analysis, answers to these questions ("0" no and "1" yes) were summed accordingly as the *individual activeness* and *community activeness* indicators (alpha reliability coefficient = 0.66 and 0.72, respectively).

Additionally, in order to explore possible effects of respondents' personal characteristics on changes in risk perception, the 2018 survey also included questions on several sociodemographic and socioeconomic factors: *age* (in years), *gender* ("0" male and "1" female), *residence status* ("0" longer-term residents = years lived in community ≧ 10; "1" newer residents otherwise), *educational attainment* (six categories ranging from "less than a high school degree" to "advanced degree"), annual *household income* (eight levels ranging from "less than $15,000" to "$150,000 or more"), previous/current employment in a *forest-related occupation* ("0" no and "1" yes), and previous/current involvement in *agricultural production* ("0" no and "1" yes).

3.4 Data analytical procedures

The analysis presented here mainly draws on the full survey dataset from 2018 (N=1,130), but also involves the 2007 full survey dataset (N=1,346) and a panel dataset (N=460) that includes those respondents to both surveys. Relevant findings for individual study communities are published elsewhere (Qin et al., 2019). The primary unit and level of analysis for this study is the individual. We first examined the survey sample characteristics and descriptive statistics of major variables, particularly the three measuring changes in different aspects of wildfire risk perception. Next, we analyzed temporal changes in forest risk perceptions

[4] The re-survey in 2018 included all action items in the 2007 survey and also asked respondents whether they had their properties evaluated for wildfire risk.

using the full 2007 and 2018 survey datasets as well as the panel data. Since the two full survey samples include both paired and independent observations (Qin et al., 2017), the corrected *z*-test and the paired *t*-test were used in the trend and panel analyses, respectively.

After checking the bivariate correlations between dependent and independent variables using Spearman's rho and the Mann-Whitney U test,[5] we evaluated ordinal regression models of changes in perceived wildfire likelihood, perceived severity of potential wildfire damage, and general concern about wildfire hazard. Only the 2018 full survey dataset (N=1,130) was used in this stage of analysis. The data was first tested for multicollinearity issues and the assumption of ordinal logistic regression with proportional odds.[6] Additionally, since survey respondents were nested within different study communities, we conducted a likelihood ratio test for each dependent variable, comparing the deviances of a random intercept-only model and an alternative model in which the effect of intercept was fixed. This was equivalent to an assessment of whether the outcome variables varied significantly across the nine study communities. A multilevel approach was used in the ordinal regression analysis when the test indicated a statistically significant random effect of the intercept. In order to highlight key explanatory factors of changing risk perception, we also produced three reduced models by systematically removing all insignificant independent variables from the full ordinal regression models. This stepwise selection process involved deleting the variable with the largest *p* value each round and rerunning the regression analysis until a model only included statistically significant variables.

[5] We adopted these analytical techniques considering the ordinal nature of some variables and also crosschecked the variable correlations with correspondent parametric statistics (Pearson's *r* and the independent *t*-test).
[6] No multicollinearity problem was identified. We combined the first two points ("1" and "2") on the scales of the three dependent variables based on the results of full likelihood ratio tests (tests of parallel lines). The assumption of proportional odds was generally met after these adjustments. The recoded variables were thus used in the bivariate and multivariate analyses.

4. Results

4.1 Characteristics of survey respondents

Table 1 presents the aggregate personal characteristics of the 2018 survey respondents. The average age of all respondents was about 60. Female and male respondents accounted for 46.7% and 53.3%, respectively, in the total sample. Survey respondents reported living in their communities for an average of almost 26 years, and a large majority of them (86.1%) lived in their community for ten or more years. The educational level of the 2018 survey sample as a whole was high, with 68.5% of all respondents having attained four-year college degrees or more. The average household income level of surveyed households was between $50,000 – $74,999 and $75,000 – $99,999. Additionally, just over 18.0% of respondents had previous employment in occupations related to forest management or forest products, while 25.4% had previous involvement in agricultural production.[7] Overall, although respondents to the 2018 survey were relatively older and had longer length of residence than those in 2007, these two survey samples are largely comparable with each other as a considerable proportion of the follow-up survey (about 41.0%) was completed by respondents from the first study phase. We also checked potential non-response bias in the panel survey data by comparing the sociodemographic characteristics and forest risk perceptions of 2007 respondents and non-

[7] The survey also included questions on race/ethnicity and political views. A large majority of the respondents (96.3%) were white. The survey sample as a whole held balanced political views. Nearly 39.0% of respondents described their views as liberal or moderate-liberal, 22.5% as moderate, and 38.8% as moderate-conservative or conservative. These two variables were removed from the final analysis as they did not improve the performance of statistical models. See Qin et al. (2019) for a full presentation of survey results.

respondents to the re-survey. The two subgroups of original participants generally showed no significant difference in these aspects.[8]

Table 1

Sociodemographic characteristics of survey respondents

Variable	Mean or Percent	*N*
Age	59.7	1103
18 – 39	9.9%	
40 – 64	48.4%	
65 and over	41.7%	
Gender		1113
Female	46.7%	
Male	53.3%	
Years in community	25.9	1120
Educational attainment[a]		1113
High school degree or lower	7.6%	
Some college or post high school training	16.9%	
Two-year technical or associate degree	7.0%	
Four-year college degree (BA/BS)	39.9%	
Advanced degree (i.e. Master's, JD, MD, PhD)	28.6%	
Total household income[a]		1090
Less than $35,000	11.4%	
$35,000 to $49,999	8.9%	
$50,000 to $74,999	17.0%	
$75,000 to $99,999	16.9%	
$100,000 or $149,999	16.1%	
$150,000 or more	14.3%	
Don't wish to specify or don't know	15.6%	

[a] Some original categories of educational attainment and total household income were combined together in the summary of results.

[8] We did not weight the survey data according to sociodemographic information for each study community because the analysis used aggregate data and no substantial non-response bias was identified. There was also generally no significant difference between continued and new participants in the 2018 survey regarding sociodemographic characteristics and answers to major questions except that those panel respondents were relatively older than new participants.

4.2 Changes in perceived local forest risks

A summary of the temporal changes in perceived local forest risks is provided in Table 2. The comparisons based on the full and panel data both showed that although perceptions of nearly all of the beetle-related forest risks lessened over the study period, there was no significant change in the concern about forest fire.[9] Survey respondents in 2018 indicated even higher levels of falling tree risk than those from 2007. The 2018 survey data also provided a more nuanced view of local residents' wildfire risk perception and its temporal dynamics. As shown in Fig. 3, about 33.3% of these respondents perceived likely or very likely wildfire occurrence, 60.9% expected severe or very severe wildfire damage, and 85.8% felt concerned or extremely concerned about local forest fire risk. A majority of the whole sample indicated increased or strongly increased levels of perceived likelihood of a wildfire and perceived severity of possible wildfire damage (61.1% and 57.0%, respectively), while over a third of the respondents (34.2% and 39.2%, respectively) answered that their perceptions of such risks stayed unchanged. Although the perception of community forest fire risk remained largely the same, most respondents (86.4%) reported increased or strongly increased general concerns about wildfire hazard (for both their communities and themselves) related to the MPB outbreak in Colorado forests. Further analysis using the panel dataset also showed that the self-reported

[9] An analysis of the forest mortality data showed that the percentage of local forests killed by beetles increased substantially in all study communities in 2007–2017. Records from the Federal Wildland Fire Occurrence Database (https://wildfire.cr.usgs.gov/firehistory/data.html) also suggested an increasing trend in the total wildfire acres of Colorado during this time period, particularly in 2012–2017. Colorado then had its largest wildfire season on record in 2020. Survey respondents perceived a close connection between the MPB outbreak and wildfire hazard. They were asked how strongly they thought a series of factors contributed to the risk of wildfire in their areas (possible responses ranging from "1" does not contribute to "5" strongly contributes). Among the six listed factors (changes to the forest due to beetle kill, changes in summer precipitation, changes in winter precipitation, changes in seasonal temperatures, prescribed burns, housing development in forested areas), forest change due to beetle kill was viewed as the strongest contributor to local wildfire risk, with 87.5% of respondents selecting "4" or "5" for this item (26.1% and 61.4%, respectively).

changes in general wildfire concern and the observed changes in perceived local forest fire risk were highly correlated.

Table 2

Temporal changes in perceived local forest risks

Variable	Full data		Panel data	
	Phase I	Phase II	Phase I	Phase II
Forest fire	4.46	4.41	4.45	4.45
Falling trees	3.65***	3.92***	3.57***	3.97***
Decline in wildlife habitat	3.72***	3.43***	3.68**	3.50**
Impact on livestock grazing	2.68***	2.38***	2.67**	2.47**
Increased erosion and runoff	3.82***	3.38***	3.80***	3.45***
Invasive plant species	3.75***	3.47***	3.79***	3.57***
Loss of forests as an economic resource	3.59***	3.07***	3.47***	3.19***
Loss of scenic/aesthetic quality	4.23***	3.71***	4.21***	3.76***
Loss of tourism and recreation opportunities	3.55***	2.80***	3.49***	2.87***
Loss of community identity tied to the forest	3.53***	2.78***	3.51***	2.89***
Impact on property values	3.68***	2.87***	3.67***	2.99***
N	1346	1130	460	460

Given as variable means. All variables were measured on a 5-piont scale ("1" not concerned to "5" extremely concerned). The corrected *z*-test and the paired *t*-test were used in the analyses of the full and panel data, respectively. The paired *t*-test statistics were cross-checked with the Wilcoxon matched-pair signed-rank test statistics. The two types of tests produced consistent results in terms of variable changes and their significance levels.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Secondary data analysis revealed that several study communities (Granby, Kremmling, and Walden) had relatively higher levels of biophysical and socioeconomic vulnerability than the other communities (Breckenridge, Dillon, Frisco, Silverthorne, Steamboat Springs, Vail) in both study phases (Qin et al., 2021). Further analysis of the full and panel survey datasets found that there was no substantial difference regarding changes in the perceptions of non-fire forest risks between the two community groups, but the higher-vulnerability community cluster showed a significant decline in perceived forest fire risk. In 2018, respondents from both community clusters reported similar wildfire concern and change, whereas those from communities with less

vulnerable conditions indicated relatively higher levels of perceived wildfire likelihood and severity as well as larger increases in these perceived risks.

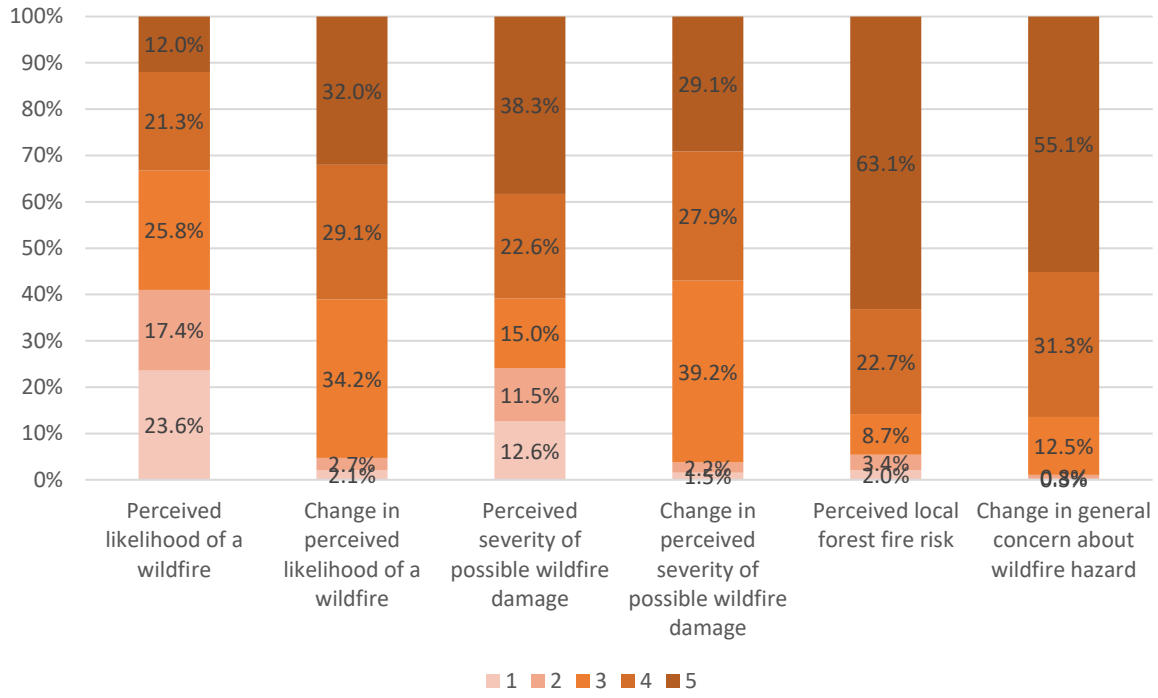

Fig. 3. Wildfire risk perceptions and changes. Notes: All variables were measured on a 5-piont scale (perceived likelihood of a wildfire: "1" not likely to "5" very likely; perceived severity of possible wildfire damage: "1" not at all severe to "5" very severe; perceived local forest fire risk: "1" not concerned to "5" extremely concerned; change in perceived likelihood of a wildfire, change in perceived severity of possible wildfire damage, and change in general concern about wildfire hazard: "1" strongly decreased to "3" stayed the same to "5" strongly increased).

4.3 Bivariate and multivariate analyses

Table 3 summarizes the bivariate correlations between major variables in the analysis.[10] The three dependent variables, particularly change in perceived wildfire likelihood and change in perceived severity of wildfire damage, were positively and closely related with each other. All independent variables except for age and residence status were significantly related with at least

[10] Because of the exploratory nature of the analysis, we also noted marginally significant statistics ($p < 0.10$) in the results.

one of the three dimensions of changing wildfire risk perception. Perceived tree mortality, personal wildfire experience, number of information sources, individual and community activeness, and gender were related with all three dependent variables in consistent manners. Some variables (e.g., social or biophysical vulnerability, satisfaction with local land managers) showed similar correlations with changes in perceived likelihood and severity of a wildfire, but were related differently or unrelated with change in general concern about wildfire hazard. Others were significantly correlated with only one of the dependent variables (mostly change in general concern about wildfire).

Results of the ordinal regression analysis are summarized in Table 4. Multilevel modeling was used for the first two outcome variables (change in perceived likelihood of a wildfire and change in perceived severity of possible wildfire damage) since likelihood ratio tests detected significant random components of the intercepts. Overall, the full and reduced models showed similar patterns of significant predictors across changes in the three aspects of perceived wildfire risk. There was good model fit as assessed by comparisons of these models with corresponding intercept-only models. Biophysical vulnerability, satisfaction with governmental land management entities, community wildfire experience, community activeness, educational attainment, household income, and involvement in agricultural production were not included in any of the reduced models. As in the bivariate correlation analysis, perceived tree mortality, individual actions, and gender were significantly (or almost significantly) associated with all three dependent variables in this multivariate analysis stage. Perceived tree re-growth and forest-related occupation also had a significant or marginally significant effect in each reduced model.

Table 3

Bivariate correlations between major variables

Variable	Change in perceived likelihood of a wildfire[a]	Change in perceived severity of possible wildfire damage[a]	Change in general concern about wildfire hazard[a]
Change in perceived likelihood of a wildfire	—	—	—
Change in perceived severity of possible wildfire damage	0.735***	—	—
Change in general concern about wildfire hazard	0.396***	0.394***	—
Community biophysical vulnerability	-0.091**	-0.106***	0.080**
Community social vulnerability	-0.105***	-0.123***	0.074*
Forest-related environmental view	-0.090**	-0.103***	0.035
Perceived tree mortality	0.093**	0.066*	0.155***
Perceived re-growth of trees	-0.041	-0.058(*)	-0.120***
Satisfaction with local entities	-0.060*	-0.074*	-0.004
Satisfaction with governmental entities	0.031	0.048	-0.060*
Personal wildfire experience (yes=0)[ab]	-3.555***	-2.907**	-3.968***
Community wildfire experience (yes=0)[ab]	-1.522	-1.328	-2.230*
Number of information sources	0.124***	0.144***	0.110***
Community participation	0.122***	0.102***	0.043
Individual activeness	0.226***	0.195***	0.085**
Community activeness	0.155***	0.143***	0.089**
Age	-0.056(*)	-0.007	-0.022
Gender (male=0)[b]	4.623***	4.702***	2.518*
Residence status (longer-term resident=0)[b]	-0.042	1.500	1.288
Educational attainment	0.058(*)	0.096**	-0.069*
Household income	0.078*	0.069*	-0.066*
Forest-related occupation (yes=0)[ab]	2.740**	2.860**	0.526
Agricultural production (yes=0)[ab]	1.330	2.362*	-0.122

Given as Spearman's rho correlation coefficients (for correlations between ordinal and ordinal/numerical variables) or standardized Mann-Whitney U test statistics (for correlations between dichotomous and ordinal variables). These statistics were cross-checked with Pearson's *r* and the independent *t*-test statistics, respectively. The different types of tests produced consistent results in terms of variable correlations and their significance levels.

[a] Dichotomous variables with "0" no/"1" yes values were reversely coded for the ease of interpreting their coefficients in ordinal regression models.

[b] The standardized Mann-Whitney U test statistic was positive when the "1" group had a greater mean rank than the "0" group. When the opposite was true, the test statistic was negative.

(*)$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Based on the results of the final reduced models, for a one-unit increase in the level of perceived tree mortality, the odds of having relatively increased levels of perceived likelihood of a wildfire, perceived severity of wildfire damage, and general concern about wildfire hazard became 1.519, 1.424, and 1.483 times higher, respectively. Similarly, the odds of reporting elevated perceptions of wildfire likelihood and severity as well as general wildfire concern increased by a respective factor of 1.173, 1.133, and 1.057 for each unit increase in individual activeness. In contrast, an increase in the extent of perceived tree re-growth was associated with a decrease in the odds of having higher values on the three measures of wildfire risk perception change. The odds of females having increased levels of perceived likelihood and severity of a wildfire and general wildfire concern were 1.707, 1.599, and 1.349 times those of males (reciprocals of coefficients' natural exponentials), respectively. Additionally, employment in an occupation related to forest management or forest products showed a negative effect on the indication of more positive net changes in different aspects of wildfire risk perception.

Several independent variables were present in two of the three reduced models. An increase of 0.10 in the community social vulnerability index reduced a respondent's odds of reporting increased perceived likelihood of a wildfire and perceived severity of possible damage by an individual factor of 1.894 and 2.183 [reciprocals of Exp(0.10 * coefficients)]. Each unit increase in the satisfaction with local land managers was also associated with a decrease in the likelihood of showing increases in these two dependent variables with an odds ratio of 0.823 and 0.787, respectively. More participation in community activities corresponded to greater odds of indicating higher levels of perceived wildfire likelihood and severity, whereas the number of information sources was positively related with the likelihood of exhibiting increases in perceived severity of wildfire damage and general concern about wildfire hazard. Increasing age

was also significantly or nearly significantly associated with a reduction in the odds of having greater perceived wildfire likelihood and wildfire concern over time.

Furthermore, the results highlight several variables related to change in specific dimensions of wildfire risk perception. A more anthropocentric forest-related environmental view had an almost significant relationship with higher likelihood of indicating increased general wildfire concern. Likewise, respondents who personally experienced wildfire hazard were 1.616 times more likely to report an increase in general wildfire concern than those without such experience. The odds of newer residents reporting more salient perception of possible wildfire damage were also 1.432 times that of longer-term residents.

Table 4

Comparisons of the ordinal regression models

Variable	Change in perceived likelihood of a wildfire[a]		Change in perceived severity of possible wildfire damage[a]		Change in general concern about wildfire hazard[b]	
	Full model B (Exp(B))	Reduced model B (Exp(B))	Full model B (Exp(B))	Reduced model B (Exp(B))	Full model B (Exp(B))	Reduced model B (Exp(B))
Community Risk Context						
Community biophysical vulnerability	-0.244 (0.784)		0.215 (1.240)		1.482 (4.404)	
Community social vulnerability	-5.155 (0.006)	-6.386 (0.002)*	-7.269 (0.001)	-7.805 (0.0004)***	-4.795 (0.008)	
Environmental Values						
Forest-related environmental view	-0.022 (0.978)		-0.019 (0.981)		0.192 (1.212)	0.174 (1.190)$^{(*)}$
Perceived Disturbance Intensity						
Perceived tree mortality	0.410 (1.507)***	0.418 (1.519)***	0.360 (1.434)***	0.353 (1.424)***	0.369 (1.446)***	0.394 (1.483)***
Perceived re-growth of trees	-0.101 (0.904)	-0.169 (0.845)*	-0.093 (0.911)	-0.163 (0.850)**	-0.314 (0.731)***	-0.320 (0.726)***
Relationship with Land Managers						
Satisfaction with local entities	-0.167 (0.846)*	-0.195 (0.823)*	-0.303 (0.738)**	-0.240 (0.787)*	-0.063 (0.939)	
Satisfaction with governmental entities	-0.058 (0.944)		-0.062 (0.940)		-0.068 (0.934)	
Emergency Experience						
Personal wildfire experience (ref=no)	0.139 (1.149)		0.087 (1.090)		0.344 (1.411)*	0.480 (1.616)***
Community wildfire experience (ref=no)	-0.149 (0.861)		-0.139 (0.871)		0.266 (1.305)	
Community Interaction and Communication						
Number of information sources	0.029 (1.029)		0.065 (1.067)**	0.057 (1.059)*	0.059 (1.060)*	0.078 (1.081)***
Community participation	0.070 (1.073)	0.097 (1.101)*	0.071 (1.074)	0.075 (1.078)*	0.049 (1.050)	
Actions in Response to Forest Risks						
Individual activeness	0.160 (1.174)***	0.159 (1.173)***	0.131 (1.139)*	0.125 (1.133)**	0.076 (1.079)$^{(*)}$	0.055 (1.057)$^{(*)}$
Community activeness	-0.010 (0.990)		-0.048 (0.953)		-0.024 (0.976)	
Personal Characteristics						
Age	-0.010 (0.990)**	-0.007 (0.993)*	0.003 (1.003)		-0.006 (0.994)	-0.009 (0.991)$^{(*)}$

Gender (ref=female)	-0.484 (0.617)***	-0.535 (0.586)***	-0.508 (0.602)***	-0.469 (0.625)***	-0.342 (0.710)*	-0.299 (0.741)*
Residence status (ref=newer resident)	0.121 (1.129)		-0.264 (0.768)$^{(*)}$	-0.359 (0.698)*	-0.274 (0.761)	
Educational attainment	0.009 (1.009)		0.049 (1.050)		-0.045 (0.956)	
Household income	0.041 (1.042)		0.031 (1.032)		-0.039 (0.962)	
Forest-related occupation (ref=no)	-0.315 (0.730)$^{(*)}$	-0.289 (0.749)$^{(*)}$	-0.215 (0.807)	-0.203 (0.816)*	-0.271 (0.763)	-0.307 (0.736)$^{(*)}$
Agricultural production (ref=no)	0.198 (1.219)		0.086 (1.090)		-0.131 (0.877)	
N	815	1033	814	1034	821	1049
Deviance	9237.858	11521.158	9425.507	11749.568	1533.993	1987.925
Likelihood ratio chi-square (df)	2577.139 (20)***	293.840 (9)***	2678.186 (20)***	354.125 (10)***	83.604 (20)***	99.509 (9)***

Given as fixed coefficients and natural exponentials of coefficients.

[a] Multilevel ordinal regression modeling

[b] Ordinal logistic regression modeling

$^{(*)}p < 0.10$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

5. Discussion

In summary, these findings suggest that changing wildfire risk perception is affected by specific indicators representing key constructs in the adopted conceptual model of forest risk perception (see Fig.1). The analysis revealed that changes in different sectors of wildfire risk perception shared a group of common explanatory factors. Perceived tree mortality and perceived re-growth of trees were associated with the three outcome variables in consistent ways, suggesting a strengthening effect of perceived forest disturbance intensity on wildfire risk perception. Altogether, the two measures of community interaction and communication (community participation and the number of information sources) had positive effects on perceived wildfire likelihood and severity as well as general wildfire concern. Nevertheless, with respect to actions in response to forest risks, individual activeness holds a relatively more important role than community activeness in shaping the increasing trend of perceived wildfire risk. This is likely due to the fact that forest fire or wildfire is mainly considered as an immediate threat to personal safety and property rather than a broader threat to community well-being. Additionally, gender and forest-related occupation were the only two sociodemographic indicators having a tangible influence on changes in all of the dependent variables.

The results also show that significant explanatory factors of reported changes vary across different dimensions of wildfire risk perception. On one hand, community social vulnerability and satisfaction with local land managers were particularly relevant to changes in the two cognitive or analytical aspects of risk perception: perceived likelihood of a wildfire and perceived severity of possible wildfire damage. This is understandable as both of these two explanators are closely related to local social structures and institutions. On the other hand, two factors directly based on emotional and experiential processes, forest-related environmental

views and personal wildfire experience, only exhibited an influence on change in the more affective dimension of risk perception – general concern about wildfire hazard. Moreover, there are some notable discrepancies between the two models of cognitive risk perception even though they are similar with each other in terms of significant predictors. Age was negatively associated with the odds of indicating heightened perceived wildfire likelihood, while the reliance on information sources and the length of residence reinforced and constrained increases in perceived severity of wildfire consequences, respectively.[11]

Further multivariate analysis showed that the two cognitive indicators of wildfire risk perception and their corresponding change variables were not related with exactly the same factors. For example, community social vulnerability and community participation were associated with change in perceived likelihood of a wildfire, but were not significant in their relationship to the level of perceived wildfire likelihood. Anthropocentric forest-related views and community wildfire experience were negatively and significantly associated with perceived severity of wildfire damage but not with change in such concern. However, perceived tree mortality and re-growth, individual activeness, and gender were consistently related to both wildfire risk perception measures and their reported changes.

Whereas research on the human dimensions of forest insect disturbance generally involves perceived wildfire risk, existing literature in this area mainly focuses on the effects of wildfire risk perception on individual or community actions, the determinants of perceived risk, and its change over time (e.g., Flint, 2007; Gordon et al. 2013; Qin et al. 2015a, 2021). The

[11] Similar with the initial survey in 2007 (Qin, 2016), the follow-up survey also showed that the two resident groups based on years lived in community were significantly different with respect to a number of major variables in the analysis. These differences between newer and longer-term residents were consistent with the association between residence status and perceived severity of possible wildfire damage, including newer residents' relatively lower satisfaction with local land managers, higher level of personal wildfire experience (almost statistically significant), higher educational attainment, and less involvement in agricultural production.

present study further expands this knowledge base by including different aspects of risk perception and by exploring factors associated with changes in perceived wildfire risk. It is not surprising that many constructs in the conceptual model of forest risk perception (e.g., perceived disturbance intensity, community interaction and communication, and actions in response to forest risks) played important roles in explaining reported changes in perceived wildfire risk. The positive associations found between individual activeness and the three change indicators suggest that the interactions between risk perception and behavior are more complicated than what the risk reappraisal hypothesis typically implies (Weinstein et al., 1998). The results on community risk context and emergency experience also echo those from relevant previous studies on changing forest risk perception. A related longitudinal analysis showed that respondents from the higher-vulnerability community cluster had decreased forest fire risk perception over time and exhibited smaller changes in many aspects of reactions to the MPB issue than those from the lower-vulnerability community group (Qin et al., 2021). In addition, Flint (2007) suggested a large-scale forest fire led to a coalescence of community risk perception about wildfire in Homer, Alaska, but the pre- and post-fire levels of local perceived fire risk were not significantly different. Champ and Brenkert-Smith (2016) also found that fire experience was not strongly related to perceived probability or consequences of a wildfire.

6. Research and policy implications

Thus far, there has been limited theoretical work related to the temporal dynamics of risk perception. The issue-attention cycle model implies that time is the most important determinant of changing risk perception (Downs, 1972). According to the social amplification of risk framework (Kasperson et al., 1988), the interactions of risk events with sociopsychological and

economic processes can lead to substantial temporal and spatial extension or contraction of perceived risks and actions. The risk reappraisal proposition also describes a negative feedback effect of risk-related behavior on risk perception (Siegrist, 2013; Weinstein et al., 1998; Weinstein and Nicolich, 1993). Additionally, a biophysical, sociodemographic, and sociocultural matrix approach to the interactions between society, fire, and forests provides a broad framework for understanding changing landscapes and wildfire risk perception (Gordon et al., 2013; Luloff et al., 2007). Building on these important perspectives, this research extends a community-oriented approach to forest risk perception and generates evidence for the development of holistic conceptual frameworks of dynamic risk perception, particularly evolving perceptions of localized ecological risks.

It is well established among forest and wildfire managers that ecological conditions are subject to changes that function on different temporal scales. Studies such as this highlight the fact that the social experience of and response to those ecological changes are also subject to temporal variations that are influenced by a range of community- and individual-level conditions. Whereas work in this arena is still relatively limited, the findings of this research demonstrate that such considerations can informed forest risk management and communication. Because of altered species composition and fuel accumulation, the risk of highly intensive and/or severe fires in bark beetle-affected areas is expected to change across different periods of forest disturbances (Jenkins et al., 2008). Tracking wildfire risk perceptions of local residents in response to landscape change are thus especially important for coordinating fire risk management and fostering public acceptability. The analysis identified specific factors that promoted or limited increases or decreases in the perception of wildfire risk (e.g., perceived disturbance intensity and individual activeness for greater odds of increased perception;

satisfaction with local entities, age, and males for lower chance of increased perception). Such insights can support well-designed risk communication and mitigation strategies incorporating local concerns, beliefs, and actions. Moreover, an inclusive and dynamic risk assessment approach can allow land managers to identify potential areas of convergence and divergence between community risk perceptions and technical risk evaluations, and to proactively respond to changing social and cultural regimes of forest risks.

This study can also suggest several directions for further longitudinal research on the perceptions of and response to forest risks. As this exploratory analysis involved a 10-year time span, future investigations can examine factors associated with changes in wildfire risk perception over a shorter study period. Following up with original survey respondents at a smaller interval should help to increase the sample size and quality of panel data. Quick-response studies after major wildfire events (e.g., the 2020 Colorado wildfire season) can also provide additional evaluations of the effects of specific factors such as fire experience and perspectives on the response of land managers. Under some special circumstances (e.g., highly transient communities, long time spans between study phases), it would be more meaningful to collect trend data from all new, randomly selected participants to improve the representativeness of re-survey samples.

The risk perception change variables in this analysis were based on survey respondents' self-reported information. Our research design showcases that cross-sectional surveys could be tailored to complement longitudinal risk perception research (Bubeck and Botzen, 2013). Nevertheless, panel data collected at different points in time from the same participants should provide more objective observations of actual changes, and improve understanding of the factors influencing changing risk perception as well as the dynamic relationships between risk

perception and behavioral responses. Combining quantitative with qualitative data and replicating or adapting these longitudinal analyses for other environmental risks (e.g., floods, hurricanes) can also provide further evidence and insights on relevant issues.

Finally, this research can provide implications for the social-ecological indication of wildfire risk and related aspects of forest insect disturbance. Ecological and environmental indicators are typically defined as quantitative representations of an ecosystem's conditions and responses to driven forces (Descoteaux et al., 2019). Social-ecological indicators in longitudinal research can be especially useful for assessing complex societal–environmental interactions and for supporting policy and decision-making. Risk perception is often operationalized in various ways because of different disciplinary orientations and research traditions. This inconsistency in measurement may partially explain the mixed findings on the temporal scenarios of risk perception and on the relationships between risk perception and other relevant factors (e.g., risk behavior, trust in or relationship with risk management entities). Following recent progress in risk and vulnerability studies, we differentiated wildfire risk perception into three interrelated but distinct dimensions: perceived likelihood of a wildfire, perceived severity of possible wildfire damage, and general concern about wildfire hazard. The last indicator captures a larger scale (i.e., both individual/household and community) than the preceding two. Descriptive analysis suggested that perceived wildfire likelihood and severity had more variant patterns than general wildfire concern in terms of magnitudes and changes. Because measures of cognitive risk perception components are relatively established, future risk analysis can benefit from refined measurement of the affective or emotional realm of risk perception.

Besides different measures of perceived wildfire and related forest risks, the literature on human dimensions of forest insect disturbance has employed a range of other indicators of

residents' attitudes, values, experience, and actions as well as community characteristics. These representations can all be organized under key constructs (e.g., risk context, exposure, sensitivity, adaptive capacity, and impacts) or sectors (e.g., sociocultural, socioeconomic, and biophysical) of a general scheme such as the multifaceted vulnerability framework (Romero Lankao and Qin, 2011) or the interactional matrix approach (Luloff et al., 2007). The cross-sectional and longitudinal indication of most of these aspects, particularly those at the community level (e.g., landscape change, wildfire behavior, and community vulnerability), can be enhanced by richer and more locally-specific qualitative data. Additionally, the efforts to build cumulative knowledge in the human dimensions research is still hindered to a large extent by incompatible research designs, variable operationalization, and data practices across individual case studies. As variables may function as a type of currency in facilitating the exchange and synthesis of data from different studies (Qin et al., 2014), the harmonization and standardization of key indicators and methods can greatly advance the integration of interdisciplinary social science research in this field and the development of evidence-based natural resource management approaches.

7. Conclusions

Existing risk analysis literature has depicted the complex temporal dynamics of social and ecological risk perceptions. This research advances longitudinal risk studies through exploring changing wildfire risk perception and its influencing factors in the context of the MPB outbreak in north central Colorado. Although wildfire risk concern was found to be rather stable across the study communities, respondents indicated substantial changes in the cognitive and affective dimensions of wildfire risk perception at the individual level. The analysis suggested

that evolving perception of wildfire risk was strongly associated with a number of explanatory variables and personal characteristics. Higher levels of perceived tree mortality, community interaction and communication, and individual actions in response to forest risks were consistently related to greater odds of indicating increased wildfire risk perception. In general, community social vulnerability, perceived tree re-growth, satisfaction with local management entities, and age were negatively related to the likelihood of having elevated perceptions of fire risk, whereas males and forest-related occupations were associated with relatively lower odds of reporting increases in perceived wildfire risk. Significant influencing factors for change also varied across the cognitive and affective dimensions of wildfire risk perception. This study applies an extended community-oriented approach to perceived forest risks, and calls for integrative theory, indication, and research to understand dynamic risk perception. Findings demonstrate that considerations of changing perceptions of forest and wildfire risks can help to ensure that management decisions align with and are informed by insights from social and ecological change.

CRediT authorship contribution statement

Hua Qin: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Project administration, Writing - Review & Editing. **Hannah Brenkert-Smith**: Conceptualization, Methodology, Investigation, Project administration, Writing - Review & Editing. **Christine Sanders**: Investigation, Visualization, Writing - Review & Editing. **Jamie Vickery**: Investigation, Visualization, Writing - Review & Editing. **Martha Bass**: Investigation, Visualization, Writing - Review & Editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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