Do Actions Reduce Perceived Risk? A Longitudinal Analysis of the Relationship between Risk Perception and Actions in Response to Forest Disturbance in Colorado

Hua Qin,[1,2*] Jamie Vickery[3], Hannah Brenkert-Smith[4], Barituka Bekee[1], Yanu Prasetyo[5]

[1] Division of Applied Social Sciences, University of Missouri–Columbia, Columbia, Missouri, USA

[2] School of Humanities and Social Science, The Chinese University of Hong Kong, Shenzhen, China

[3] Department of Environmental & Occupational Health Sciences, University of Washington, Seattle, Washington, USA

[4] University of Colorado, Institute of Behavioral Science, Boulder, Colorado, USA

[5] Research Center for Population, The National Research and Innovation Agency, Central Jakarta, Indonesia

Correspondence

Hua Qin, School of Humanities and Social Science, The Chinese University of Hong Kong, Shenzhen, China; Division of Applied Social Sciences, University of Missouri–Columbia, Columbia, Missouri, USA. Email: qinhuajames@cuhk.edu.cn or qinh@missouri.edu

Funding information

Decision, Risk and Management Sciences Program of the National Science Foundation, Grant/Award Number: 17339

ABSTRACT

As residents living in hazard-prone areas face on-going environmental threats, the actions they take to mitigate such risks are likely motivated by various factors. Whereas risk perception has been considered a key determinant of related behavioral responses, little is known about how risk mitigation actions influence subsequent perceived risk. In other words, do actions to prevent or mitigate risk reduce risk perception? This longitudinal study considers the dynamic relationships between risk perception and risk mitigating behavior in the context of forest disturbance in north-central Colorado. Based on panel survey data collected in 2007 and 2018, the results provide a first look at changes in perceived forest risks as they relate to individual and community actions in response to an extensive mountain pine beetle outbreak. Analysis revealed that the perception of direct forest risks (forest fire and falling trees) increased whereas indirect forest risk perception (concern on broader threats to local community) decreased across the two study phases. Higher individual or community activeness (level of actions) was associated with subsequent reductions in perceived forest fire risk, smaller increases in direct risk perception, and larger decreases in indirect risk perception. These findings contribute insights into the complex risk reappraisal process in forest hazard contexts, with direct implications for risk communication and management strategies.

KEY WORDS: community actions; individual actions; mountain pine beetles; perceived forest risks; risk perception–behavior interactions; risk reappraisal

1. INTRODUCTION

Human-environment interactions encompass various feedback loops both within and across human and natural systems (Liu et al., 2007). A typical example of such loops is the reciprocal relationship between risk perception and behavioral responses. The existing risk analysis literature includes many cross-sectional studies of the influences of risk perception on prevention and mitigation actions (or their correlations) in an environmental or ecological context, whereas the counter-effects of risk-related behavior on risk perception are generally understudied. The risk reappraisal process is based on the assumption that perceived risk is not static, but rather that it adjusts according to socio-behavioral change (Weinstein & Nicolich, 1993; Weinstein et al., 1998;). As such, taking actions that one believes will reduce risk will be followed by a reevaluation and adjustment of one's perceived risk. Longitudinal data provide a unique opportunity to expand understanding of the relationship between risk reducing behavior and subsequent risk perception, but are largely lacking (Siegrist, 2013). Such pursuits are critical for hazard-prone contexts in which the relationship between the sources of risks and the perceptions of those risks is dynamic and data collected at a single point in time may obscure the nature of this relationship.

In this study, we use longitudinal data on local responses to forest disturbance in north-central Colorado to better understand changes in risk perception related to forests hazards and levels of individual and community actions in a context in which a mountain pine beetle (MPB) outbreak has altered forest structures and health. This extensive forest disturbance in Colorado provides an important case for the study of the evolving relationship between risk perception and behavioral reactions. North-central Colorado communities continue to experience impacts from the outbreak that began in 1996, killing roughly 3.4 million acres of lodgepole (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*) forests. The MPB disturbance has also induced cascading or compounding effects on related forest risks such as forest fire, soil erosion and runoff, and invasive plant species.

Two primary research questions guide a series of analyses: (1) how do perceived forest risks and related actions change over time? And (2) what are the feedback effects of prevention or mitigation actions on forest risk perception? These questions are of particular importance in a dynamic social–ecological system in which the trajectory of the forest disturbance escalated dramatically initially and has subsequently declined. As such, MPB activity is currently minimal, while the conditions from the disturbance present ongoing sources of risk, particularly in the form of wildfire hazard. Our findings contribute insights into changing risk perception and risk mitigating behavior in forest hazard contexts, with direct implications for risk communication and management strategies. While these analyses focus on changes in forest risk perception, the risk reappraisal process that we highlight and dissect is relevant to a range of risk contexts, including other natural hazards (e.g., hurricanes and floods) as well as public health and clinical settings.

2. THE DYNAMC RELATIONSHPS BETWEEN RISK PERCEPTION AND BEHAVIOR

2.1. Conceptual approaches

Theories of risk rarely emphasize the temporal dynamics of risk perception and related behavior. Nevertheless, the interrelationships between risk perception and behavioral responses can be situated in relevant conceptual models in risk and disaster research, such as the protection motivation theory and expanded vulnerability-adaptation frameworks (Grothmann & Patt, 2005; Qin, Romero-Lankao, et al., 2015; Rogers & Prentice-Dunn, 1997; Turner et al., 2003; Weinstein

& Nicolich, 1993). These general conceptual approaches have also been widely adopted in research on forest risk perception and related individual or community actions. Socio-economic vulnerability, biophysical vulnerability, and community risk perception are conceptualized as key determinants of local actions in response to risks (e.g., forest insect disturbance, wildfire hazard) in natural resource-based community settings (Flint & Luloff, 2005). Focusing on wildfire risk, Paveglio et al. (2018) depicted a social vulnerability approach incorporating risk perception as an important component of the capabilities of communities and populations to mitigate and/or adapt to negative impacts. Scholars in wildfire social science have also built on relevant theories (particularly the protection motivation theory) to develop specific conceptual models of protection and mitigation actions that emphasize the central or mediating roles of perceived wildfire risk (Fischer et al., 2014; Martin et al., 2009; Olsen et al., 2017). Additionally, in a comprehensive framework of adaptation to climate change in fire-prone forests, perceived risk is deemed as one of the major socio-psychological factors mediating the effects of wildfire outcomes on actions (Hamilton et al., 2018). By including a two-way linkage between behavioral responses and wildfire hazard conditions, this framework suggests a feasible pathway for the feedback of risk-related behavior on risk perception. Champ and colleagues also argued that wildfire risk perception and mitigating behavior could be jointly determined, and further expanded the conceptualization of the risk perception–action relationship through highlighting the interactions between the two processes (Champ et al., 2013; Meldrum et al., 2019).

Drawing on these conceptual positions and approaches, we construct an analytical model for assessing the dynamic relationships between risk perception and behavior, particularly the risk reappraisal process, in the forest disturbance context. As shown in Figure 1, forest risk perception plays an essential role in influencing prevention or mitigation actions in response to relevant forest hazards or disturbances. We also conceptualize the potential for these actions to cause counter-effects on perceived risk. In addition, both forest risk perception and behavioral responses are influenced by several other factors, such as perceived disturbance intensity, relationship with land managers, past emergency experience, social or community interaction, perceived locus of responsibility, perceived self-efficacy, and biophysical and socio-economic risk context (Fischer et al., 2014; Flint, 2007; Hamilton et al., 2018; Martin et al., 2009; Olsen et al., 2017), as well as personal sociodemographic characteristics (e.g., age, gender, education, income, length of residence).

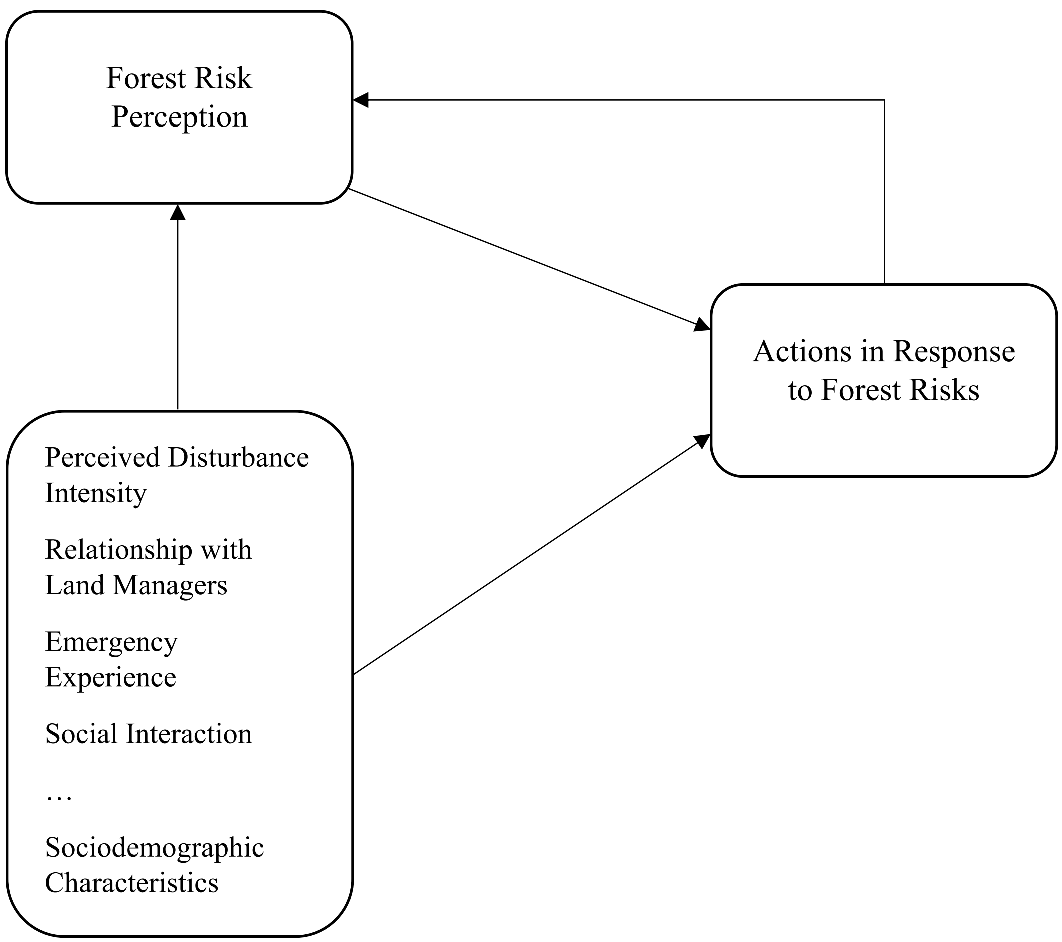


Figure 1. An analytical framework of the dynamic interrelationships between perceived forest risk and response.

Whereas risk perception is generally conceived as a key determinant of related behavioral responses, the feedback of prevention and mitigation actions on perceived risk is rather complicated. Siegrist depicted a hypothetical scenario in which residents' perceived flood risk became lower after they took precautious actions (Siegrist, 2013). Meldrum et al. (2019) also contended wildfire risk mitigation was expected to lead to reduced perception of wildfire risk, an effect mirroring the risk reappraisal hypothesis in health psychological research (Weinstein et al., 1998; Weinstein & Nicolich, 1993). However, established theoretical frameworks in risk and decision sciences, such as the social amplification of risk model (Kasperson et al., 1988), suggest a nonlinear, complex process of changing risk perception. In diverse risk settings, the actual risk reassessment outcomes of actions would depend on a range of conditions including risk characteristics, specific cognitive and affective aspects of risk perception, perceived or objective efficacy of responses, and the temporal stages of the interactive risk perception–behavior process (Qin, Sanders, Prasetyo, et al., 2021).

2.2. Previous empirical research

Longitudinal data enables analyses that take into account the changing components and processes of social–ecological systems (Stidham et al., 2014). The empirical literature on the dynamic relationships between risk perception and protective or mitigating behavior has grown rapidly in recent years. Thus far, much of the evidence for the risk reappraisal hypothesis has come from socio-behavioral medicine science. Previous studies in this area have consistently shown that preventive actions or interventions (e.g., alcohol use disorder treatment, cancer screening, and vaccination) can accordingly reduce people's perceptions of relevant risks (Brewer et al., 2004; Glenn et al., 2011; Grevenstein et al., 2015; Klepper et al., 2017; Renner et al., 2008). However, in a longitudinal analysis of health behavior during a mosquito-borne disease outbreak in Guinea, Raude et al. (2019) showed that whereas people's perceived risk of infection decreased significantly over time, those who engaged in protective behavior did not experience larger reductions in risk perception than others. A recent study of changing risk perception and actions in response to the COVID-19 pandemic in the United States also found that the risk reappraisal effect was mainly represented by the associations between higher levels of initial preventive actions and lower increases or relative stabilization in perceived COVID-19 risk (Qin, Sanders, Prasetyo, et al., 2021).

There has also been increasing research interest on the interactions between risk perception and behavioral responses in environmental hazard regimes. Respondents in a flood-prone area in Germany indicated that their perceived probability and perceived consequences of a flood emergency decreased (and to a larger extent for perceived consequences) after the adoption of flood mitigation measures (Bubeck & Botzen, 2013). Bubeck et al. (2020) also collected panel survey data from residents affected by the 2013 flood event in Germany. Whereas the researchers did not explicitly analyze the feedback effect of adaptive behavior on risk perception, their longitudinal data suggested that flood risk perception, particularly perceived probability of flooding, eventually reduced as the level of risk-reducing actions increased. Nevertheless, another panel study of flood-prone households in Australia only found limited cross-time effects of nonprotective or protective responses on the cognitive and affective risk appraisals, which reflected the high stability of risk perception during a short study period (1.5 years) and in the absence of any flood occurring or policy intervention (Seebauer & Babcicky, 2021).

Despite improved understanding of temporal changes in perceived forest risks, particularly those related to insect disturbance and wildfire hazard (Champ & Brenkert-Smith, 2016; Flint, 2007; Gordon et al., 2013; McFarlane & Witson, 2008; Qin, Brenkert-Smith, Vickery, et al., 2021; Qin, Flint, et al., 2015), research on the feedback of prevention or mitigation actions on forest risk perception has remained limited. Previous longitudinal research on the human dimensions of forest insect disturbance revealed that whereas aggregate perceived forest risk reduced over time, the trends of change varied across the perceptions of immediate threats to personal safety or property and broader threats to community or ecological well-being (Qin, Flint, et al., 2015; Qin, Brenkert-Smith, Vickery, et al., 2021). The positive relationship between forest risk perception and actions in response to insect outbreaks was no longer significant in follow-up analyses (Qin, Brenkert-Smith, Vickery, et al., 2021). Similarly, a study using a two-phase design identified different changes in perceived probability and consequences of a wildfire after extreme wildfire events (McFarlane & Witson, 2008). Mitigating behavior was found to be strongly and positively correlated with perceived probability of a wildfire but not with its perceived consequences.

Given the joint determination of perceived risk and behavioral responses, Champ et al. (2013) conducted simultaneous modeling of cross-sectional data and demonstrated that residents with greater wildfire risk perceptions also reported higher levels of mitigation actions. Using parcel-level fire vulnerability assessment as a proximate of mitigation actions, Meldrum et al. (2019) showed that less vulnerable property conditions (equivalent with more mitigation) were associated with lower perceived likelihood and potential damage of a wildfire. Their results suggested dual-directional interactions between the perception of wildfire risk and the level of mitigation on a parcel. In summary, existing literature suggests a rather complicated interactive risk perception–behavior process in individual and community responses to forest disturbances. In this study, we use panel survey data on Colorado residents' reactions to the MBP outbreak to further examine the risk reappraisal outcomes of prevention and mitigation actions.

3. METHODS

3.1. Data collection

The MPB-affected region includes nine fire-prone communities at the focus of this study: Breckenridge, Dillon, Frisco, Granby, Kremmling, Silverthorne, Steamboat Springs, Vail, and Walden (see Figure 2). Together, these study communities reflect varied local contexts and MPB outbreak experiences throughout north-central Colorado. This research was part of a re-study of Colorado community residents' perceptions of and responses to the impacts of the MPB disturbance. For the larger project, we adopted a mixed method approach that included key informant interviews, household mail surveys, and secondary data analysis using biophysical and socioeconomic data to gather insights into local contextual characteristics. This paper focuses on longitudinal results from two phases of household mail surveys disseminated throughout the nine study communities. We used a modified tailored design approach to inform the design and implementation of the surveys. This approach entailed three waves of survey mailing (each with unique cover letters), thank you and reminder postcards, follow-up phone calls to non-respondents as well as announcements in local newspapers. The household surveys first distributed in 2007 (Phase 1) had in total 1,346 respondents. The follow-up survey, which took place in 2018 (Phase 2), was administered to all the original 2007 respondents (1,346) as well as an additional 3,000 households that were selected randomly from addresses provided by a proprietary USADATA mailing address database. While the follow-up survey instrument largely paralleled the original 2007 survey, we added items that were informed by findings from key informant interviews conducted across the study region from 2017–2018. The second wave of the household survey yielded a total of 1,130 completed surveys (32.4% response rate after accounting for undeliverable mail). Data collected from the 460 respondents who participated in both surveys were merged into a panel dataset used in this study.

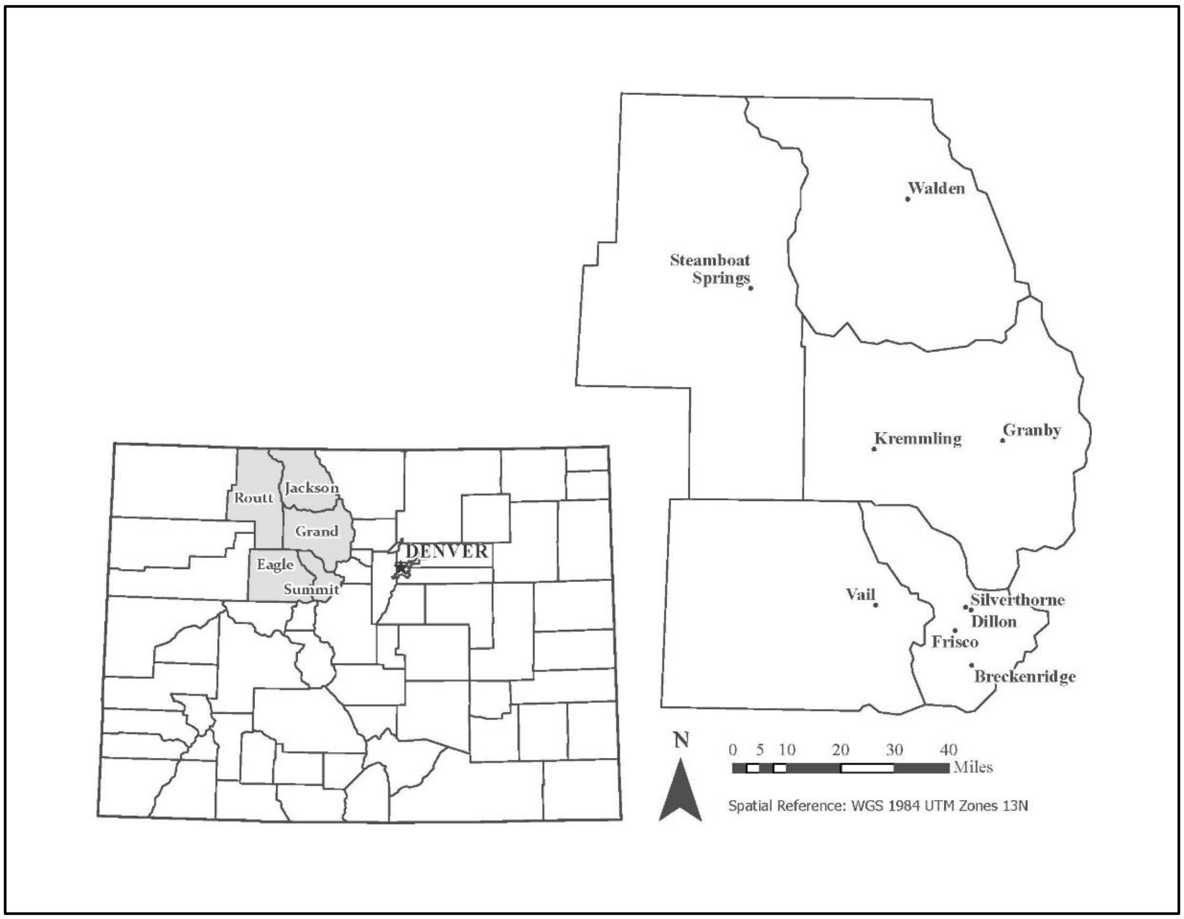


Figure 2. Map of north-central Colorado and the study communities. Reprinted with kind permission from Oxford University Press: Qin, Brenkert-Smith, Vickery, et al., 2021

3.2. Measurement of variables

The analyses for this research mainly included a series of variables related to various aspects of local reactions to the MPB outbreak: forest risk perception, perceived proximity to disturbance, relationship with land managers, emergency experience, community communication and interaction, and beetle-related actions. Many of these variables were composite indicators based on results of exploratory factor analyses of answers to relevant survey questions. Table 1 provides more detail into how these variables were defined and measured.

TABLE 1 Measurement of major variables

Variable	Measurement
Direct risk perception[ab]	Composite measure representing level of concern regarding direct/immediate forest risks induced by the MPB disturbance, including forest fire and falling trees. This was created using the mean response value for this cluster of two forest risks (1=not concerned to 5=extremely concerned).
Indirect risk perception[ab]	Composite measure representing level of concern regarding indirect/broader forest risks induced by the MPB disturbance, including decline in wildlife habitat, impact on livestock grazing, increased erosion and runoff, invasive plant species, loss of forests as an economic resource, loss of scenic/aesthetic quality, loss of tourism and recreation opportunities, loss of community identity tied to the forest, and impact on property values. This was created using the mean response value for this cluster of nine forest risks (1=not concerned to 5=extremely concerned).
General forest risk perception[a]	Composite measure representing level of concern regarding all forest risks included in the previous two variables. This was created using the mean response value for all 11 questions on perceived forest risks (1=not concerned to 5=extremely concerned).
Change in direct risk perception[c]	Difference score of direct risk perception across the two study phases
Change in indirect risk perception[c]	Difference score of indirect risk perception across the two study phases
Perceived tree mortality	Variable measured on a scale from 1=no pines are dead and 5=almost all pines are dead

Satisfaction with local land managers[a]	Composite indicator representing level of satisfaction with five local land management entities regarding their response to the MPB outbreak, including private individuals and landowners, local fire departments, private logging companies, developers, and homeowner associations. This was created using the mean response value for this cluster of land managers (1=very dissatisfied to 5=very satisfied).
Satisfaction with governmental land managers[a]	Composite indicator representing level of satisfaction with five governmental land management entities regarding their response to the MPB outbreak, including city government, county government, Colorado State Forest Service, Bureau of Land Management, and U.S. Forest Service. This was created using the mean response value for this cluster of land managers (1=very dissatisfied to 5=very satisfied).
Personal experience with emergencies	Variable constructed through a summation of answers (0=no and 1=yes) as to whether a respondent personally experienced nearby wildfire, avalanche/landslide, flooding, and toxic contamination (min=0; max=4)
Community experience with emergencies	Variable constructed through a summation of answers (0=no and 1=yes) as to whether a respondent's community experienced nearby wildfire, avalanche/landslide, flooding, and toxic contamination (min=0; max=4)
Number of information sources	Variable constructed through a summation of responses (0=no and 1=yes) as to whether respondents used various information sources (e.g., newspapers, word of mouth, local fire department, Colorado State Forest Service) to learn about forest issues (min=0; max=15)
Community participation	Variable constructed through a summation of responses (0=no and 1=yes) pertaining to respondents' participation in a range of community activities, such as attending a local community event, working with others to deal with a community issue, and serving as an officer in a community organization (min=0; max=7)
Individual actions	Variable capturing personal actions taken to prevent or mitigate beetle-related forest risks: (1) removing beetle killed trees from personal property; (2) contributing money to Homeowner Association efforts to clear trees; (3) actively watering trees to prevent beetles from killing trees; (4) spraying trees on personal property with chemicals or insecticides; (5) clearing vegetation near structures for defensible space against wildfire; (6) using fire resistant building materials for structures; and (7) planted or transplanted trees. Dichotomous responses to these questions (0=no and 1=yes) were summed to create this measure (min=0; max=7).

Community actions	Variable capturing participation in community actions in response to beetle-related forest risks: (1) participated in a neighborhood or community effort to clear trees; (2) attending a public informational meeting; (3) helping with clearing or maintaining public trails; (4) consulting with public officials or foresters; (5) attending a beetle task force meeting; (6) participating in group efforts to preserve natural forests; and (7) participating in group efforts to promote resource utilization. Dichotomous responses to these questions (0=no and 1=yes) were summed to create this measure (min=0; max=7).
All actions	Variable capturing both individual and community actions taken to prevent or mitigate beetle-related forest risks. Dichotomous responses to relevant questions (0=no and 1=yes) were summed to create this measure (min=0; max=13).
Socio-demographic characteristics	Age (in years), gender (1=female, 0=male), educational attainment (1=less than a high school diploma to 6=advanced degree), household income (1=less than $15,000/year to 8=$150,000/year or more), and length of residence (in years)

Abbreviation: MPB, mountain pine beetle.
[a]Exploratory factor analysis guided variable groupings in the creation of composite measures. Cronbach's alpha statistics of all composite variables indicated satisfactory internal consistency ($\alpha \geqq 0.7$).
[b]Respondents were asked how concerned they were about a series of forest risks as a result of the MPB outbreak and accompanying changes in forest health.
[c]We used the first difference score approach to measure temporal changes as there was no negative cross-time correlation for any of the risk perception indictors.

3.3. Data analysis procedures

We first assessed potential non-response bias in the panel data by comparing socio-demographic characteristics of respondents and non-respondents to the resurveys as well as their answers to major questions in the 2007 survey. The Wilcoxon matched-pair signed-rank test and its parametric counterpart – the paired *t*-test – were then used to determine whether perceived forest risks, perception of tree mortality, satisfaction with management entities, experience with emergencies, information sources, community participation, and local activeness (level of actions) changed between the two study phases. Next, we conducted regressions of changes in direct and indirect risk perceptions on individual and community actions while accounting for the effects of other predictor variables of risk perception and main socio-demographic indicators (all the independent and control variables were from Phase 2 survey). The regression analysis used a Tobit approach as the two dependent variables had truncated ranges of values. In addition to the full regression models, we produced alternative, reduced models which only included the two activeness measures (individual/community actions) and significant statistical controls.

To better examine the interactions between risk perception and behavior, we used cross-lagged path models to check both within- and across-time correlations between perceived forest risks and beetle-related actions while controlling for temporal autoregressive effects. Each model included a pair of risk perception and activeness indicators (i.e., direct/indirect/general risk perception and individual/community/all actions). Finally, the feedback effects of behavioral responses on perceived risk were further evaluated by a series of repeated measures Analysis of Covariance (ANCOVA) models of risk perception indicators. Relevant activeness measures for Phase 1, the study phase factor, and their interaction items were key explanatory variables in the models, whereas the effects of major socio-demographic characteristics were accounted for in the analysis. The risk reappraisal effects of actions were detected by the statistical significance of these interaction terms.

4. RESULTS

4.1. Characteristics of panel respondents

Table 2 summarizes the major socio-demographic characteristics of panel survey participants. In Phase 2, these respondents had a mean age of 63.3 and lived in their communities for an average of 29.5 years.[1] Females accounted for about 45.0% in this sample. More than 60.0% of the respondents completed a bachelor's degree or higher level of education, whereas nearly 55.0% of them reported an annual household income of $75,000 or more. Overall, the personal characteristics of panel respondents were very consistent across the two study phases, although the proportions of those in higher income categories were slightly larger in Phase 2 than in Phase 1. Like the full survey samples in both phases, most of the respondents (about 96.0%) in the panel dataset were white. A comparison of the panel respondents with those non-continuing respondents from Phase 1 showed no substantial difference in socio-demographic background between the two subgroups except that panel participants had relatively higher educational attainment than the non-responders.[2]

[1] Considering potential differences between newer and longer-term residents in their reactions to the MPB outbreak, we also checked the relationship between changes in perceived forest risks and Phase 1 residence status ("0" longer-term residents = 10 or more years lived in community; "1" newer residents otherwise). No significant difference was found between the two subgroups in the change score of any risk perception measure. Because of the moderate size of the panel survey sample, we chose to not include length of residence or residence status in the multivariate statistical analysis.

[2] The analysis also showed that these two groups of respondents were not significantly different in direct risk perception, indirect risk perception, and general forest risk perception in Phase 1. Compared to non-panel respondents, panel participants reported relatively higher levels of community actions (and thus all actions as well), community emergency experience, reliance on information sources, and participation in community activities. No significant difference was found between them regarding answers to other major questions.

TABLE 2 Socio-demographic characteristics of panel respondents

Variable	Phase 1 (mean or percent)	Phase 2 (mean or percent)
Age	52.2	63.3
Gender		
Female	43.0%	44.3%
Male	57.0%	55.7%
Years in community	19.6	29.5
Educational attainment		
High school degree or lower	9.7%	8.6%
Some college or technical/associate degree	28.1%	28.3%
Bachelor's degree or higher	62.2%	63.2%
Total household income		
Less than $35,000	12.1%	12.5%
$35,000 to $74,999	40.0%	32.5%
$75,000 to $149,999	35.5%	40.0%
$150,000 or more	12.4%	14.9%

Note: Some original categories of education attainment and total household income were combined together in the summary of results.

4.2. Changes in major variables

As shown in Table 3, the perceptions of all forest risks except for forest fire and falling trees declined significantly over the 10-year study period. Perceived forest fire risk remained at a rather high level, whereas the concern about falling trees increased. As a result, there was a significant increase in the direct risk perception variable, but the levels of indirect risk perception and aggregate forest risk perception lowered. By contrast, the values of the individual and total activeness indicators (individual actions and all actions) showed an increase between Phases 1 and 2, and the level of community actions stayed the same. The analysis also revealed increases in perceived tree mortality and satisfaction with local and governmental land managers, as well as reductions in personal and community experience with emergencies and community participation.

TABLE 3 Temporal changes in risk perception and activeness measures and other major variables

Variable	Phase 1	Phase 2
Direct risk perception	4.02^{***}	4.21^{***}
Forest fire	4.45	4.45
Falling trees	3.57^{***}	3.97^{***}
Indirect risk perception	3.59^{***}	3.19^{***}
Increased erosion and runoff	3.80^{***}	3.45^{***}
Loss of tourism and recreation opportunities	3.49^{***}	2.87^{***}
Loss of community identity tied to the forest	3.51^{***}	2.89^{***}
Impact on property values	3.67^{***}	2.99^{***}
General forest risk perception	3.67^{***}	3.39^{***}
Individual actions	2.50^{**}	2.74^{**}
Community actions	1.63	1.63
All actions	4.13^{*}	4.37^{*}
Perceived tree mortality	3.08^{***}	3.43^{***}
Satisfaction with local land managers	2.97^{***}	3.13^{***}
Satisfaction with governmental land managers	2.70^{***}	3.17^{***}
Personal experience with emergencies	1.30^{**}	1.10^{**}
Community experience with emergencies	2.41^{***}	2.03^{***}
Number of information sources	6.32	6.16
Community participation	4.50^{***}	3.82^{***}

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

4.3. Tobit regression models

The results of the Tobit regression models of changes in direct and indirect risk perceptions are presented in Table IV. The Tobit regression coefficients represent the linear effects of predictors on the uncensored latent dependent variables instead of observed outcome measures. Thus, we here focus on the direction of variable relationships rather than the adjustment in the absolute change value of direct or indirect risk perception for each unit change in individual or community activeness. The level of community actions showed a significant and negative effect in the full model of change in indirect risk perception. In the reduced models, the individual and community activeness measures were negatively related to changes in direct and indirect risk perceptions, respectively. Additionally, perceived tree mortality and age were consistently related to changes in both direct and indirect risk perceptions (albeit in opposite directions). Higher levels of satisfaction with government entities, community emergency experience, and household income corresponded to larger decreases (or smaller increases) in indirect risk perception. Community participation also had a negative and almost significant effect on the change score for this perception.

TABLE 4 Tobit regression models of changes in direct and indirect risk perceptions

Variable	Change in direct risk perception		Change in indirect risk perception	
	Full model	Reduced model	Full model	Reduced model
Intercept	1.291^{*}	0.756^{*}	0.704	0.588
Individual actions	-0.043	-0.054^{*}	0.001	0.007
Community actions	0.020	0.029	-0.060^{*}	-0.057^{*}
Perceived tree mortality	0.132^{*}	0.142^{**}	$0.091^{(*)}$	$0.092^{(*)}$
Satisfaction with local entities	0.011		-0.076	
Satisfaction with governmental entities	-0.049		-0.124^{*}	-0.134^{*}
Personal emergency experience	-0.007		0.043	
Community emergency experience	-0.035		-0.122^{**}	-0.109^{**}
Number of information sources	-0.004		0.010	
Community participation	-0.014		$0.043^{(*)}$	$0.041^{(*)}$
Age	-0.017^{***}	-0.015^{***}	-0.006	$-0.007^{(*)}$
Gender (Female = 1)	-0.016		0.110	
Educational attainment	-0.024		-0.032	
Household income	0.002		-0.041	-0.054^{*}
N	346[a]	439	345[a]	346[a]

Note: Independent and control variables in the analysis were from Phase 2. We noted marginally significant results considering the exploratory nature of this study.

[a]The lower *N*s for these three models were due to the higher percentage of missing data (18.5%) for the household income variable. Two of the possible answers to the question on total household income ("Don't know" and "Don't wish to specify") were coded as missing values in the analysis. We ran Little's Missing Completely at Random Test for all major variables and identified no issue with the pattern of missing data.

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

4.4. Cross-lagged Path Models

Based on findings of the Tobit regression analysis, our path modeling focused on the within- and across-time linkages for three pairs of risk perception and activeness measures: (A) direct risk perception and individual actions; (B) indirect risk perception and community actions; and (C) general forest risk perception and all actions (see Figure 3). All three models indicated significant temporal autocorrelations for variables in the analysis. Total activeness in Phase 1 had a negative and almost significant effect on general risk perception in Phase 2 (Figure 3C). The feedback effects of actions on perceived risk in the other two models were also negative but did not reach statistical significance. Additionally, there was a strong, positive cross-time path from direct risk perception in Phase 1 to individual activeness in Phase 2 (Figure 3A). The within-time variable correlation for Phase 1 was positive and significant in each model. However, only direct risk perception and individual activeness remained positively correlated in Phase 2 (Figure 3A).

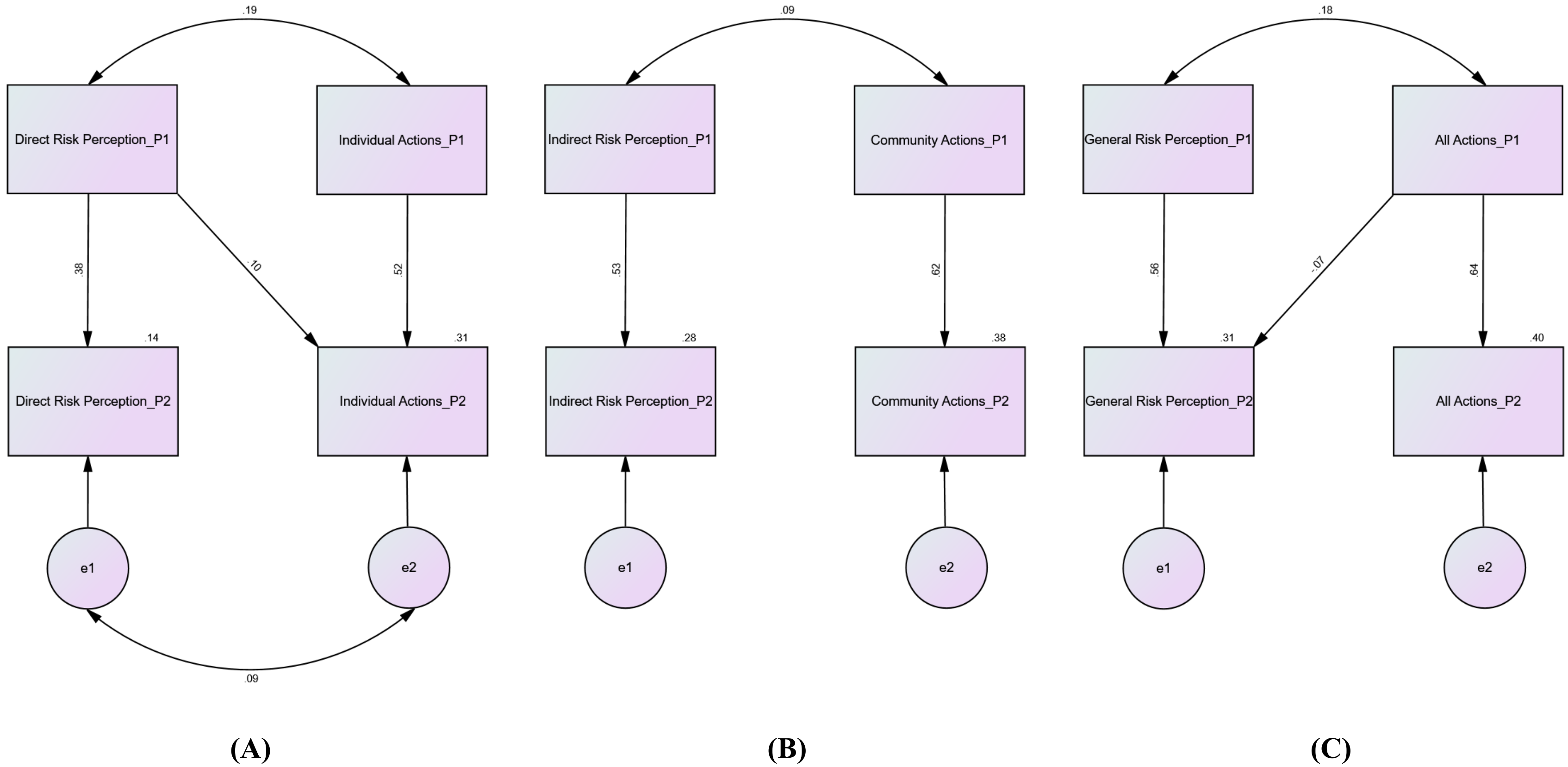


Figure 3. Path model of cross-lagged relationships between forest risk perception and activeness. Direct risk perception indicators were first transformed accordingly as they had negatively skewed distributions. P1 and P2 stand for Phase 1 and Phase 2, respectively. Values associated with paths are standardized estimates, while e1 and e2 are error terms. All estimates included in the models were significant at the .05 or higher level, except for the path from All Actions_P1 to General Risk Perception_P2. Results indicated good fitness for the three models: (a) direct risk perception and individual actions (χ^2 = 1.048, df = 1, p = 0.306; RMSEA = 0.010; CFI = 1.000); (b) indirect risk perception and community actions (χ^2 = 2.446, df = 3, p = 0.485; RMSEA = 0.000; CFI = 1.000); and (c) general forest risk perception and total actions (χ^2 = 2.504, df = 2, p = 0.286; RMSEA = 0.023; CFI = 0.999). Abbreviations: RMSEA, Root Mean Square Error of Approximation; CFI, Comparative Fit Index

4.5. Repeated measures ANCOVA models

The repeated measures ANCOVA analysis specifically examined the risk appraisal effects of local responses. According to Table V, the interaction terms of Phase 1 activeness measures and study phase were negative and significant in all three models, indicating strong feedback of actions on risk perception. Figure 4 provides a detailed visualization of such processes. While perceived direct forest risk generally increased over time, respondents who initially took more individual actions showed smaller increases in this perceived risk than others in Phase 2 (Figure 4A). Further analysis revealed that those characterized as more active had lower perception of forest fire risk in Phase 2 compared to Phase 1, but those with lower individual activeness in Phase 1 had increased concern about forest fire in Phase 2 (Figure 4B). The patterns of varied trends of changing risk perception were similar for the interaction effects in the other two models in Table V. Respondents with higher levels of community and total actions in Phase 1 had larger reductions in indirect risk perception and aggregate perception of forest risks over time, respectively (Figs. 4C and 4D).

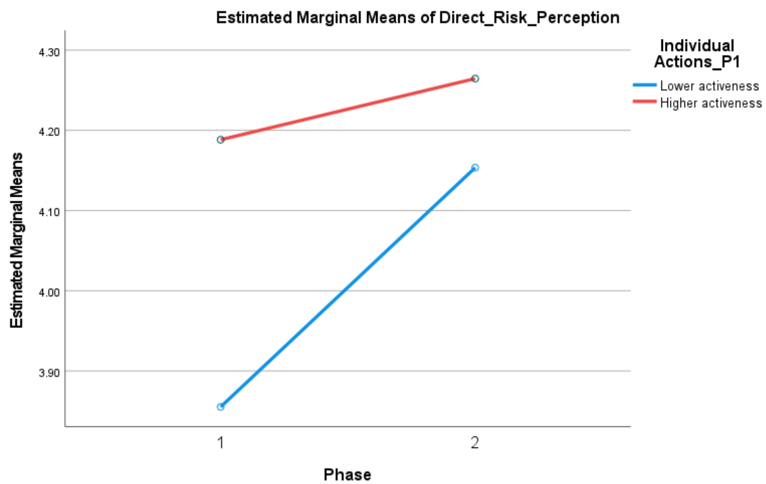
TABLE 5 Repeated measures ANCOVA models of risk perception indicators

Variable	General forest risk perception	Direct risk perception	Indirect risk perception
Intercept	3.901***	4.380***	3.872***
Phase 2 (ref = Phase 1)	-0.121(*)	0.393***	-0.314***
Actions_P1[a]	0.056***	0.096***	0.070**
Phase 2 * Actions_P1 (ref = Phase 1 * Actions_P1)	-0.038**	-0.077**	-0.045*
Age	0.005(*)	0.001	0.007*
Gender (ref=female)	-0.296***	-0.249***	-0.314***
Educational attainment	-0.129***	-0.116***	-0.127***
N	454	454	453

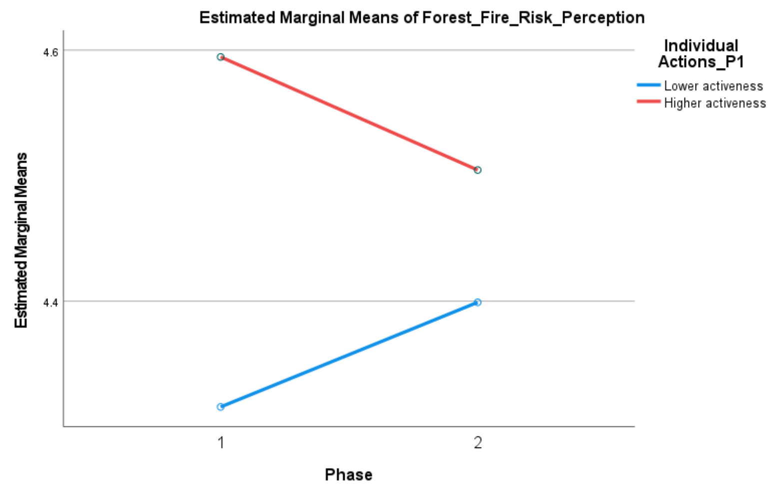
Note: Socio-demographic indicators (age, gender, and education) were from Phase 1. Household income was removed from this analysis as its inclusion did not improve model fitness. We noted marginally significant results considering the exploratory nature of this study.

[a]The total, individual, and community activeness measures from Phase 1 (P1) were used as the Actions_P1 variable in these three models, respectively.

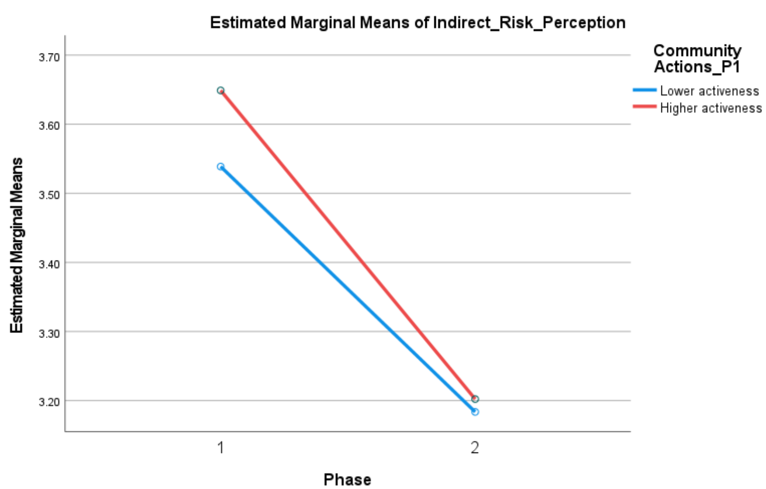
(*)$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$


Estimated Marginal Means of Direct_Risk_Perception
Individual Actions_P1
Lower activeness
Higher activeness
Estimated Marginal Means
4.30
4.20
4.10
4.00
3.90
1
2
Phase

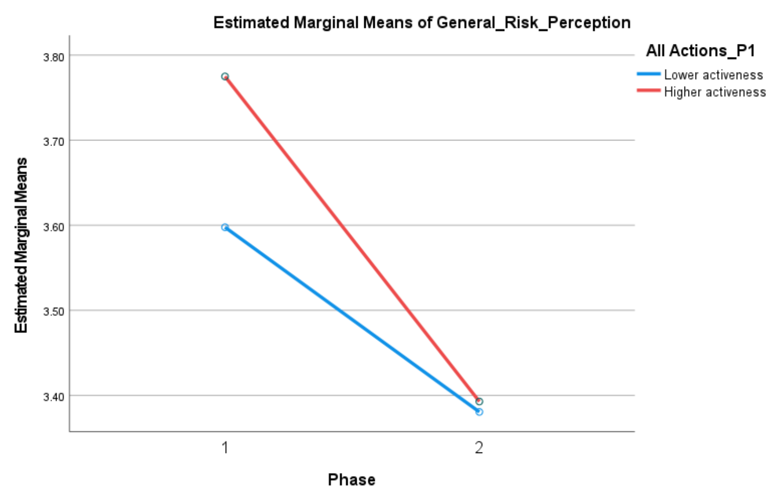
(A)


Estimated Marginal Means of Forest_Fire_Risk_Perception
Individual Actions_P1
Lower activeness
Higher activeness
Estimated Marginal Means
4.6
4.4
1
2
Phase

(B)


Estimated Marginal Means of Indirect_Risk_Perception
Community Actions_P1
Lower activeness
Higher activeness
Estimated Marginal Means
3.70
3.60
3.50
3.40
3.30
3.20
1
2
Phase

(C)


Estimated Marginal Means of General_Risk_Perception
All Actions_P1
Lower activeness
Higher activeness
Estimated Marginal Means
3.80
3.70
3.60
3.50
3.40
1
2
Phase

(D)

Figure 4. Interaction effects of Phase 1 (P1) activeness measures and study phase on risk perception indicators: (a) direct risk perception; (b) forest fire risk perception; (c) indirect risk perception; and (d) general risk perception. To facilitate the visualization of interaction effects, the activeness indicators for Phase 1 were first converted to a dichotomous variable and then included with the study phase factor in the mixed Analysis of Variance (ANOVA) analysis. The interaction effect of Phase 1 individual actions and study phase on direct risk perception was in a similar pattern as that on perceived falling tree risk (not displayed).

5. DISCUSSION

In this study we analyzed the relationship between perceived forest risks and beetle-related responses through multiple procedures. Combining the findings from these different analyses can provide a more complete assessment of the dynamic risk perception–behavior interactions in the MPB disturbance context. In our research design, risk perception associated with broader, indirect threats (indirect risk perception) held a relatively more important role than direct risk perception (associated with forest fire and falling trees) in defining the trend of general perceived forest risks. The paired-*t* tests showed that there were significant increases in direct risk perception and individual actions in response to the MPB outbreak, whereas the temporal change patterns of indirect and general forest risk perceptions differed from those of community and total activeness indicators (see Table 3). These results are generally consistent with those of the cross-lagged path analysis. In Phase 2, the within-time correlation between direct risk perception and individual activeness was stronger than that between indirect risk perception and community actions or between general risk perception and all actions.[3] Cross-time linkages in the path models were largely limited because of the moderate sample size of the panel dataset (see Figure 3). The behavior motivation effect of risk perception was particularly obvious in the interactions between direct risk perception and individual actions (Figure 3A). Only the model of aggregate risk perception and all actions suggested a potential risk reappraisal process (Figure 3C). This may be attributed to the relatively larger variations of the total activeness measure as compared to those of the individual and community activeness indicators.

[3]Multivariate analyses based on full survey datasets from the two study phases also revealed that general forest risk perception was positively associated with both individual and community actions in the 2007 survey, but not related to either activeness measure in the 2018 resurvey.

These analyses involving only risk perception and activeness variables were complemented by statistical models controlling for other factors. The Tobit regressions showed that the levels of individual and community actions had negative effects on changes in direct and indirect risk perceptions, respectively. This is understandable as direct risk perception is particularly related to threats to personal safety and properties, whereas indirect risk perception represents concerns on broader, community-level interests and well-being. The risk reappraisal processes in local responses to the MBP outbreak were further illustrated in the final stage of data analysis. Higher initial levels of relevant activeness measures were associated with subsequent reductions in perceived forest fire risk, smaller increases in direct risk perception, and larger decreases in indirect and general risk perceptions. To a large extent, results of the repeated measures ANCOVA models depicted the underlying mechanisms for the patterns of within- and cross-time linkages identified in the cross-lagged path models. For example, the strong interaction effects of Phase 1 community or total activeness and study phase on indirect or general risk perception (Figs. 4C,D) mirrored the loss of significant correlations between these variables over time in the path analysis (Figs. 3B,C). Respondents with different levels of initial community or all actions indicated similar indirect or general risk perception in Phase 2. The distinctive feedback effects of individual actions on perceived forest fire and falling tree risks can also partially explain the relatively weaker effect of individual actions on change in direct risk perception in contrast with the influence of community actions on change in indirect risk perception (see full and reduced models in Table 4).

There has been limited empirical evaluation of the risk reappraisal hypothesis in non-health science settings. Following this hypothesis, community residents with greater levels of actions in response to the beetle disturbance were expected to have lower perceived forest risks over time, all else being equal. In addition to the simplistic scenario of reduced risk perception, the analyses suggested that risk reappraisal effects might also take the form of smaller or qualified increases of perceived risk (Figure 4A) in broader hazard contexts other than those health risks with effective protective measures (e.g., screening, vaccination, or substance misuse treatment). This result is largely in line with those of a previous study of the changing relationships between perceived COVID-19 risk and behavioral responses during the early period of the new coronavirus pandemic (Qin, Sanders, Prasetyo, et al., 2021). That analysis found that greater levels of preventive actions led to slower increases, larger decreases, or relative stabilization in perceived likelihood of infection, perceived harmfulness if infected, and anxious emotion at different study stages.[4]

Meanwhile, not all previous research confirmed the applicability of the risk reappraisal hypothesis in explaining temporal changes in risk perception (Raude et al., 2019). Altogether, these findings suggest that risk reappraisal effects are contingent on a range of factors, including the types of risk, the specific aspects of risk perception, the characteristics and efficacies of responses, the stages of evolving risk regimes, and socio-cultural conditions. The resulted outcomes tend to be more complicated than typically conceived when the perceived risk of interest generally displays an increasing trend and when precautionary actions cannot completely or effectively reduce relevant risk. In future research, well-designed systematic reviews and meta-analyses can help to identify common patterns of risk reappraisal across various risk contexts (Qin & Grigsby, 2016).

[4] Vaccination was not included as a preventive measure in this study as COVID-19 vaccines were not available at the time of data collection.

Moreover, the affect heuristic, or the reliance on feelings to guide risk decisions in addition to logical reasoning, is acknowledged in risk theory (Slovic & Peters, 2006). Our survey instrument used rather general measurement of concerns about forest risks related to the MPB outbreak. Further research can advance understanding of risk perception–behavior interactions by focusing on both cognitive and affective risk perceptions associated with oft-studied hazards such as wildfires and floods. As risk reappraisal is closely related to the behavior motivation and relative accuracy (risk perception accurately reflects risk behavior or actual risk) hypotheses (Brewer et al., 2004; Weinstein et al., 1998; Weinstein & Nicolich, 1993), integrative analyses encompassing all these processes can also provide a more holistic view of the dynamic relationships between perceived ecological risks and behavioral responses.

Results of the Tobit regression analysis can also shed light on other important factors influencing changes in risk perception. Greater perceived tree mortality and younger age were related to higher change scores for both direct and indirect risk perceptions. Satisfaction with government entities, community emergency experience, and household income also exhibited a negative effect in the model of change in indirect risk perception. Because of the varied approaches used in panel data analysis (e.g., first-difference or fixed effects regression, random effects maximum likelihood models), some previous longitudinal studies of perceived forest risks mainly examined factors affecting risk perception instead of its temporal changes (Champ & Brenkert-Smith, 2016; Qin, Flint, et al., 2015). An alternate approach to measure evolving perceived risk is to explicitly ask respondents about whether and/or how their risk perceptions have changed over time (Bubeck & Botzen, 2013). Using such data, Qin, Brenkert-Smith, Sanders, et al. (2021) found that higher levels of perceived disturbance intensity, personal wildfire experience, information use, and individual actions, as well as younger ages, females, and non-involvement in forest-related occupations were associated with greater odds of reporting increased concern about wildfire hazard. In a non-forest risk context, Trumbo et al. (2014) showed that respondents with more hurricane experience and lower household income tended to indicate greater hurricane risk perception over time. Two comparable longitudinal analyses of the public perceptions of Zika and Ebola risks in the United States. also revealed factors that reduced the declines of perceived personal or national Zika risk (trust in the Centers for Disease Control and Prevention, Zika news following, and Zika knowledge) and perceived national Ebola risk (perceived likelihood of a large outbreak), as well as those that increased the drop in the perception of the U.S. Ebola risk ("Ebola as a near miss" belief, Ebola knowledge) (Johnson & Mayorga, 2020; Mayorga & Johnson, 2019). More empirical research is still needed in this area in order to synthesize individual case studies to identify general patterns of the determinants of temporal variations in risk perception.

6. CONCLUSIONS

Human–nature relationships, including ecological risk perception and related behavior, are inherently dynamic as they are the products of lived experience of environmental change. Residents living in hazard-prone areas are encouraged to take action to reduce the likelihood of hazard-related damages or losses. Little is known, however, about how actions that change the conditions of a hazard may subsequently influence perceptions of the risk posed by the hazard. In other words, does action to prevent or mitigate risk reduce perceived risk? Here, we examine the risk reappraisal processes among survey respondents in communities that have experienced exacerbated forest risks due to a large-scale insect disturbance. The MPB outbreak provides us with an opportunity to explore how perceived forest risks changed over time during a long-term, anchoring event that altered the forest landscape and whether these risk perceptions are influenced by behavioral responses at both individual and community levels.

Understanding the reciprocal relationship between perceived risk and risk reduction actions constitutes an important contribution to the insights that can help shape education and outreach promoting risk mitigation activities. For example, whereas a forest disturbance such as the one in north-central Colorado may focus fire-prone communities toward specific risk reduction highlighted by the disturbance, fire prevention would constitute a major part of local risk management as the region remains at relatively high wildfire risk. If the implementation of typical risk mitigating activities (e.g., clearing of vegetative fuels for wildfire) leads to reduced risk perception then it may follow that some risk reduction activities should be framed as maintenance activities to reflect the need for on-going engagement, once initiated. Further, if other risk reduction activities can be implemented to completion (e.g., replacement of roof with ignition resistant materials), then educational outreach may need to develop ways to focus on actions that complement the investment in such longer-term responses to guard against an attenuated sense of urgency that reduced risk perception may bring.

A panel data collection approach is key to understanding risk reappraisal, as it enables us to dissect the relationships between risk perception and behavior at and across multiple points in time. This longitudinal research on risk perception and actions in response to a major forest insect disturbance suggests that behavioral responses may either cause greater reduction in perceived risk or limit its elevation in complex ecological risk contexts. To our best knowledge, this is the first study to directly assess the feedback effects of prevention or mitigation actions on risk perception in forest risk contexts. The results partially support and extend the risk reappraisal hypothesis which has been mainly tested in the fields of health psychology and behavioral medicine. Therefore, this research not only expands the empirical evidence base for the varied consequences of risk reappraisal, but it also contributes to the further development of conceptual approaches to the dynamic relationships between risk perception and behavior.

ACKNOWLEDGMENTS

This research was supported by the Decision, Risk and Management Sciences Program of the National Science Foundation (Award #1733990), and seed funding from the Research Council of the University of Missouri-Columbia, the Research Board of the University of Missouri System, and the Richard Wallace Faculty Incentive Grants program of the Mizzou Alumni Association. The authors would like to especially thank the support of participating residents from the study communities in north-central Colorado, Dr. Courtney G. Flint at the Utah State University, Dr. Daniel Williams at the U.S. Forest Service, and members of the High Country Forest Collaborative and the Northwest Colorado Council of Governments. Assistance provided by Christine Sanders, Martha Bass, Elizabeth Prentice, and Quyen Nguyen is also sincerely appreciated. This research was approved by the MU Institutional Review Board (Project Number: 2002228). The work of Hua Qin in this research was also partially supported by the USDA National Institute of Food and Agriculture, Hatch Project #1005128. Jamie Vickery and Hannah Brenkert-Smith contributed equally to this article. At the time the research was conducted, Jamie Vickery was with the Natural Hazards Center at the University of Colorado Boulder and Yanu Prasetyo was with the Division of Applied Social Sciences at the University of Missouri-Columbia.

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