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What drives household protective actions in an industrial crisis? Insights from the East Palestine train derailment

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A R T I C L E I N F O

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A B S T R A C T

Complex industrial disasters illustrate the challenges of underdeveloped public warning systems. Unlike most natural disasters, quickly identifying hazardous materials and assessing their threats is crucial for developing protective action recommendations (PARs) that guide household response in industrial crises. The 2023 East Palestine, Ohio (USA) train derailment, chemical spill, and fires revealed that gaps in rapidly identifying hazardous materials, and the threats they present, can severely impact the public warning system. As the crisis unfolded, responding agencies left crucial questions unanswered, leaving community members uncertain about their safety, the extent of environmental contamination, and what protective actions to take. It is imperative to study the drivers of household protective actions in the absence of a developed warning system and well-established PARS. To achieve this, we conducted a community survey in Ohio, Pennsylvania, and West Virginia (n = 259) in response to the East Palestine crisis. We used multivariate logistic regressions to identify statistically significant explanatory factors that predict protective action response. Our findings reveal gaps in response, where challenges identifying and communicating hazards created environmental justice concerns. We provide policy recommendations to strengthen hazard identification and outline further work to include equity as a pillar of environmental disaster response.

1. Introduction

The 2023 East Palestine, Ohio (USA) chemical spill and fires sparked a regional environmental crisis. The multi-hazard, cascading incident began on February 3, 2023, when a train derailment led to fires and the release of hazardous materials (e.g., vinyl chloride, butoxyethanol, ethylhexyl acrylate, isobutylene, butyl acrylate, and benzene) near residential areas, contaminating local creeks (EPA, 2023a; NTSB, 2024; Sullivan, 2023). Concerned about a potential railcar explosion, responding agencies conducted a vent and burn of the remaining vinyl chloride on February 6, 2023. This action released volatile organic compounds such as acrolein and benzene into the air, and deposited ash and soot across the surrounding counties (EPA, 2023a; NIEHS, 2023; NTSB, 2024; Sullivan, 2023). The impacts extended throughout the Midwest and Northeast United States, and possibly Canada (Coelho et al., 2024; Gay et al., 2024).

As the crisis unfolded, community members were uncertain about the extent of the environmental contamination and what protective actions to take. For example, gaps in identifying and communicating risks to private wells and the lack of indoor air-quality safety assessments left residents unsure how to respond (Cochrane, 2023; Frazier, 2024; Kekatos, 2023). In the absence of clear guidance, households began to take protective actions based on their own perceptions of risk. Many households sought out more information by requesting air, water, or soil sampling and testing services. However, some did not receive these services or testing results, and those who did often found the results difficult to interpret (Frazier, 2024; Hammond et al., 2023; Lenharo, 2023; Messenger, 2023). In turn, many community members became concerned about the effectiveness of environmental sampling procedures (Cochrane, 2023; Frazier, 2024; Bottar, 2023). The lack of transparency across responding agencies heightened distrust among many community members, leading to doubts about the effectiveness of public safety measures and the overall response effort (Cochrane, 2023; Messenger, 2023; Bottar, 2023).

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Such issues illustrate the importance of evidence-based, protective action recommendations (PARs) provided by authorities. The public is often first made aware of appropriate protective actions by means of public warnings, which are messages that communicate information about an emergency to the public (Lindell & Perry, 2011; Mileti & Sorensen, 1990). A well-designed warning message will accomplish several objectives including identifying specific risks, the impacted area, when to take action and when to cease action, safety guidance, and the source of the warning (Mileti & Sorensen, 1990; Wood et al., 2018). A public warning begins with hazard detection (i.e., hazard identification), guided by scientific or technical experts who assess risk and then inform emergency managers and public officials about that risk (Mileti & Sorensen, 1990). The second stage involves emergency managers integrating the risk information received and communicating risks to the public along with the recommended PARs (Mileti & Sorensen, 1990). Finally, the public response to warnings can range from compliance with the PARs, taking an alternative protective action, or taking no action at all (Mileti & Sorensen, 1990). The public warning system (i.e., the "warning network") is a sociotechnical system (Comfort & Rahayu, 2023) in which each of the detection, management, and public response subsystems is dependent on the successful execution of actions in the previous stages (Mileti & Sorensen, 1990).

Public response to warnings and adherence to official PARs have been extensively studied through the Protective Action Decision Model (PADM) which provides insight on how individual risk perceptions and experiences influence action (Lindell & Perry, 2011). Research on the PADM has resulted in comprehensive recommendations for effective risk communication (i.e., the information exchange about risks between individuals, groups, and institutions in a crisis; NRC, 1989). Such recommendations have been applied to build theory that explores the effectiveness of official warnings and adherence to evacuation orders (Gladwin et al., 2001), intent to shelter in-place, (Heath et al., 2018) and water safety PARs (Hyman et al., 2022; Lindell et al., 2000; Lindell et al., 2017, Lindell, Huang, & Prater, 2017; Lindell et al., 2015). Most previous literature has explored the determinants of protective actions in natural disasters (e.g., Lazo et al., 2015; Nagele & Trainor, 2012; Strahan & Watson, 2019; Terpstra & Lindell, 2013) and water crises (e.g., Hyman et al., 2022; Lindell et al., 2017) with some limited research on evacuation in industrial disasters (e.g., Heath et al., 2018; Hou et al., 2024). These studies typically investigate protective actions from within the framework of official warnings and well-established PARS (e.g., evacuation orders, boil-water notices). However, not all hazards present a systematic framework through which hazard detection, communication of risk, and public warnings occur. Mileti and Sorensen (1990) noted that while many public warning systems, such as those for hurricanes, nuclear incidents, and tsunamis, are well-developed with established PARs, other classes of hazard have relatively underdeveloped warning systems (e.g., transportation incidents, hazardous material disasters). Our study departs from existing research by examining trends in protective actions taken to address household contamination after industrial disasters. This context represents an underdeveloped warning system, as identified by Mileti and Sorensen (1990) where complex environmental sampling and testing may be required to identify hazards and official PARs may be absent (e.g., Heath et al., 2018; Lukacs et al., 2017; Whelton et al., 2017). Here, we explore the theoretical differences between developed and underdeveloped public warning systems.

Industrial disasters, like the East Palestine train derailment, chemical spill, and fires, illustrate the challenges of underdeveloped warning systems, which often demand quick, ad-hoc responses with limited information (Mileti & Sorensen, 1990). The fundamental problem underlying these incidents involves identifying the chemicals present and determining the threats that they present (Mileti & Sorensen, 1990). These issues are complicated during multi-hazard, cascading events involving multiple contaminants and pathways of exposure—in the case of East Palestine this includes water and atmospheric transport and deposition, chemical compound synthesis or breakdown in the environment, and incomplete combustion (Coelho et al., 2024). Determining safe levels of exposure to industrial chemicals and their compounds requires scientific study and risk assessment. However, in the United States, thousands of potential contaminants remain unregulated. For example, when the *Toxic Substances Control Act* (TSCA) was enacted about 84,000 chemicals were exempted, meaning that safety data were not mandated for their production (EPA, 2024; Schmidt, 2016). Similarly, the *Safe Drinking Water Act* (SDWA) only regulates around 90 possible contaminants (Weinmeyer et al., 2017). Without regulation, standards for measurement may not be defined, and research on health and environmental impacts are often limited. Consequently, these gaps impact the identification of hazardous materials and their associated threats in industrial disasters (Mileti & Sorensen, 1990), which, in turn, limit the ability to identify appropriate PARs for community response (e.g., Denison, 2014; Lukacs et al., 2017; Whelton et al., 2017).

After the East Palestine chemical spill and fires, very few (if any) PARS were provided to guide households. For example, to the authors' knowledge, no studies were conducted about the efficacy of air purifiers for the chemicals that may have entered homes, and there was limited financial support or recommendations for relocation. Additionally, guidance on sampling and testing, particularly for indoor air quality standards and long-term impacts to well water, were lacking. Other guidance was often unclear or conflicting between responding agencies (Frazier, 2024; Hammond et al., 2023; Lenharo, 2023; Messenger, 2023). Unlike disaster contexts with developed warning systems, the absence of official warnings and PARS after the East Palestine chemical spill and fires created increased uncertainty for residents as they made protective action decisions. By studying determinants of protective actions after the East Palestine crisis, we can explore how the PADM holds when there are few PARs to guide the actions taken.

We explore three protective actions after the East Palestine train derailment, chemical spill, and fires: requesting sampling and testing, relocation, and using air purifiers/changing filters. These actions were chosen to reflect broad community concerns about household contamination across the impacted area, based on guidance from our community partners, initial reports from responding agencies, and the media (Cochrane, 2023; Hammond et al., 2023; Kekatos, 2023; Lenharo, 2023; Messenger, 2023; Sullivan, 2023). These household protective actions were not restricted to a single geographic area or exposure pathway but instead represent general measures implemented throughout the study region. Further, households are likely to choose protective actions that require fewer resources (Lindell, Huang, & Prater, 2017). By including both costly actions like relocation (Paul et al., 2023; Araya et al., 2019) and lower-cost actions like replacing HVAC air filters or using new air purification systems, we can capture extremes in resource-based decision-making (Lindell & Perry, 2004). We also investigate information seeking-behaviors that support these decisions (Lindell & Perry, 2011).

To understand what spurred household protective action decision-making after the East Palestine train derailment, chemical spill, and fires, we conducted a community survey in the impacted area covering Ohio, Pennsylvania, and West Virginia (n = 259). We applied multivariate logistic regressions to model explanatory factors that predict protective action responses. Specifically, we characterized explanatory factors as social cues, environmental cues, and individual perceptions of risk, as identified in the PADM. Environmental cues are individual experiences in the physical environment (i.e., of sights, smells, or sounds) that can be interpreted as threats (Lindell & Perry, 2011). Social cues are behaviors observed within the community, or information accessed or interpreted through intermediate sources, that play a role in decision-making (Lindell & Perry, 2004). Risk perceptions are shaped by past experiences and beliefs about hazards, trust in expert knowledge, and the perceived effectiveness of organizations responding to the crisis (Lindell & Perry, 2004, 2011). The PADM provides a framework for exploring how these explanatory factors influence protective action response. Building on this framework, we advance the PADM by studying its application during industrial disasters with underdeveloped warning systems. Here, we explore how gaps in identifying and communicating hazards may impact the public warning system, thereby affecting public health and safety.

2. Determinants of household protective action

We propose six hypotheses to examine the factors influencing decisions to take protective action. These factors include environmental and social cues (e.g., Lindell & Perry, 2004, 2011), individual risk perceptions (e.g., Grothmann & Reusswig, 2006; Reynolds, 2011), risk communication by authorities (e.g., Hyman et al., 2022; Lindell et al., 2017; Mileti & Sorensen, 1990), and sociodemographic characteristics (e.g., Lindell, Huang, & Prater, 2017; Tierney, 2014). These hypotheses draw from existing literature, which has primarily focused on protective action within the context of official warnings and PARS during natural disasters and water crises, with some limited research on evacuation in industrial disasters. Additionally, research on equity in disasters helps motivate these hypotheses (e.g., Chavez et al., 2017; Finucane et al., 2023).

2.1. Environmental cues

Environmental cues, such as unusual sights, smells, and sounds, are often used to gauge environmental quality when individuals cannot directly detect chemical or biological contaminants (CDC 2017; Lindell & Perry, 2004, 2011; McGuire, 1995). Research generally shows that how people perceive their environment affects their willingness to reduce their risk exposure (Johnson & Scicchitano, 2000). Information derived from the physical environment could prompt protective action if these cues are interpreted or confirmed as threats (Lindell & Perry, 2004, 2011). Environmental cues may act as substitutes for warnings by providing immediate, intuitive signals about potential hazards, as has been explored in research on evacuation during industrial disasters (Heath et al., 2018; Hou et al., 2024). Persistent health impacts and odors also can serve as justification for taking protective action when measurement standards are undefined or when monitoring strategies fail to detect hazards, as exemplified in the case of a 2014 West Virginia Chemical Spill (e.g., Denison, 2014; Lukacs et al., 2017; Whelton et al., 2017). Therefore, we propose:

Hypothesis 1 (H1). Environmental cues, such as the presence of soot and unusual odors in the home, have a statistically significant predictive relationship with decisions to take protective action.

2.2. Social cues

Social cues from a variety of sources (e.g., observations of others' behaviors, informal communications, and the receipt of information from various sources) can signal potential threats and prompt protective action response (Lindell & Perry, 2004, 2011). The ability to gather and adapt to updated information from media sources or peer networks during crises is a foundational skill (Cafer et al., 2019; Lindell & Perry, 2004; Engle, 2011). Information provided by the media, community organizations, and public forums often helps to build consensus on the interpretation of environmental cues and fosters collective willingness to take protective action (Reynolds, 2011).

A growing body of literature on disaster equity demonstrates that problems related to transparency, the functioning of government, and inequitable access to information impedes the ability of individuals and communities to adapt in a crisis (Chavez et al., 2017; Comfort & Rahayu, 2023; Emrich et al., 2022; Finucane et al., 2023; Wirtz & Birkmeyer, 2015). For example, during the 2014 Flint Water Crisis, local and state authorities did not respond to information requests and displayed an unwillingness to acknowledge limitations and errors in identifying hazards (Chavez et al., 2017). These potential links between protective action and perceptions of social equity motivate new avenues of exploration as most literature on the PADM has focused on how communication from community organizations, peer groups, or the media drives protective action response (e.g., Hyman et al., 2022; Lindell et al., 2015; McBride et al., 2019). Therefore, we propose:

Hypothesis 2 (H2). Social cues, such as information access, perceptions of equity and fairness, and levels of community engagement, have a statistically significant predictive relationship with decisions to take protective action.

2.3. Risk communication effectiveness

Effective risk communication depends on the detection of hazards (Mileti & Sorensen, 1990) and the strength of the scientific evidence underlying the risks (Comfort & Rahayu, 2023; Fischhoff & Krishnamurti, 2021). In some cases, controversy in the scientific community, exemplified through challenges in identifying hazards and communicating uncertainty, may result in conflicting or unclear messages to the public (Fischhoff & Krishnamurti, 2021; Johnson & Scicchitano, 2000; Reynolds, 2011). This may lead the public to seek additional information, like requesting sampling and testing. In other cases, risk communication may be delayed or absent (e.g., Funk, 2024). Government organizations may fracture under the pressures of a crisis, leading to a lack of accountability or ineffective government response (Cole & Fellows, 2008; Comfort & Rahayu, 2023). In the absence of public warnings and PARS, or in cases of conflicting messages, public perceptions of ineffective risk communication may drive protective action. These actions may or may not be consistent with the hazard, depending instead on perceptions of the effectiveness of organizations responding to the crisis. Therefore, we propose:

Hypothesis 3 (H3). Perceptions of ineffective risk communication have a statistically significant predictive relationship with protective action response.

2.4. Risk communication and warnings about general home safety, water safety, or evacuation

Receiving warnings or guidance about general home safety, water safety, or evacuation may influence the protective actions under study. We use the receipt of these warnings as a benchmark for comparing and discussing previous work that investigates protective actions taken in contexts with official warnings and PARS (Hyman et al., 2022; Lindell et al., 2017). It is important to note, however, that these are not 'official warnings' guiding the three specific protective actions under study, but rather informal indicators or cues that may influence decision-making in the absence of formal guidance.

Research on the PADM reveals that public response to warnings may vary. For instance, during the 2010 Boston Water Crisis, 39% of respondents did not follow the recommended protective action (boiling water) despite being instructed to do so (Lindell et al., 2015; Lindell, Huang, & Prater, 2017). Similarly, other studies show upwards of 60% did not think it was necessary to comply with evacuation orders after a hypothetical hurricane in South Florida (Gladwin et al., 2001). The literature shows that people are more likely to attribute the responsibility to provide guidance to the government if they do not know what protective action to take or if protective actions involve resource requirements and monetary cost (LeClerc & Joslyn, 2015; Lindell & Perry, 2004, 2011). However, inconsistent messaging and faulty information can create mistrust (Quinn et al., 2005; Reynolds, 2011) leading to uncertainty in information communicated by the government (Johnson & Scicchitano, 2000). In the absence of warnings and PARS, some research shows that the public may believe in personal responsibility when it comes to taking action (Fischhoff & Krishnamurti, 2021; Grothmann & Reusswig, 2006). Therefore, we propose:

Hypothesis 4 (H4). There are statistically significant predictive relationships between receiving warnings about general home safety, water safety, or evacuation and protective action response.

2.5. Risk perceptions

People may change how they receive, process, and act on information based on their perceptions of risk (Reynolds, 2011). Research has shown that individual risk perceptions, while not always, can be a substantial predictor of protective action response (Grothmann & Reusswig, 2006; Hyman et al., 2022; Lindell & Perry, 2011; Lindell, Huang, & Prater, 2017; McBride et al., 2019). Risk perceptions can be reflective of trust in the government response, affecting information seeking and processing, resource access, and protective action behaviors (Dargin et al., 2020; Ertan et al., 2022; Liu & Mehta, 2021; Mehta et al., 2017). The complexity of hazard identification and environmental risk assessment involves a degree of trust in the experts (e.g., in providing accurate information and evidence) (Hyman et al., 2022; Johnson & Scicchitano, 2000). Trust and expert knowledge are closely linked, yet it's unclear which drives the other (Arlikatti et al., 2007; Hyman et al., 2022). Therefore, we propose:

Hypothesis 5 (H5). Risk perceptions about trust and expert knowledge have a statistically significant predictive relationship with decisions to take protective action.

2.6. Sociodemographic characteristics

Furthermore, factors such as gender, age, ethnicity, income, and education may also influence the decision to take protective action (Lindell & Perry, 2004). However, the literature remains unclear about the specific relationships between demographic characteristics and protective actions (Hyman et al., 2022; Lindell, Huang, & Prater, 2017). Some studies suggest that women and members of minority groups may express more concern about risks (Harris et al., 2006; Liddell et al., 2020; Tierney, 2014). Other findings show that both older (> 60 years) and younger (< 20 years) populations are less concerned about risk and disaster preparedness (Dyregrov et al., 2021; FEMA, 2024; Pasion et al., 2020). However, many studies find this evidence weak and inconsistent, and results are mostly inconclusive (e.g., Lindell, 2013; Lindell & Perry, 2000; Lindell, Huang, & Prater, 2017). Therefore, we will propose that:

Hypothesis 6 (H5). Sociodemographic factors have no statistically significant predictive relationship with decisions to take protective action.

By exploring these hypotheses, we will improve our understanding of protection action in underdeveloped warning systems, allowing for comparison to research on disasters with official warnings and PARS (e.g., boil water notice, evacuation; Hyman et al., 2022; Lindell et al., 2017).

3. Methods

On February 3, 2023, a Norfolk Southern train derailed in East Palestine, Ohio. While most of its 149 rail cars carried non-hazardous cargo, investigators reported that approximately 36 cars derailed in total, with 11 of them carrying hazardous material (Messenger, 2023; Sullivan, 2023). Reports show that over 1.1 million pounds (almost 500 t) of carcinogenic compounds were released into the surrounding air, water, and soil (Eisner & McMillan, 2023). Residents from East Palestine and the surrounding counties were impacted, some evacuating or relocating due to persistent health effects, while many more experienced indirect impacts, economic challenges, and household disruptions. Many households took protective action to address potential household contamination in the absence of official warnings and PARS.

3.1. Community survey deployment

To understand the determinants of protective actions, we conducted a community survey ($n = 259$). To participate in the survey, people must have been 18 years or older and lived or worked in the counties in Fig. 1 as of February 3, 2023 (the day of the train derailment). The survey was conducted approximately six months after the crisis, with a two-month open period from July 20 to September 20, 2023. This timing was chosen to capture the acute post-disaster period (Norris, 2006), the key decision-making context relevant to our research questions.

Prior to deployment, the survey was reviewed by seven subject matter experts and the survey was pre-deployed to ten people, including community members and researchers. Feedback from the expert review and pre-deployment were included as revisions in the final survey instrument. Prior to implementation, the study was reviewed by university Human Subjects in Research Ethics Boards.

Considering the traumatic nature of the event (Madakasira & O'Brian, 1987) and the community challenges that it caused, we used a non-probability, cross-sectional sampling approach designed to minimize additional stress on respondents. Such an approach is common in disaster research (Norris, 2006; Stratton, 2019). First, we identified the counties that were likely to have impacts, based on reports from responding agencies, community partners, and the media (e.g., Cochrane, 2023; Hammond et al., 2023; Kekatos, 2023; Lenharo, 2023; Messenger, 2023; Sullivan, 2023). Within these communities, we used both convenience and purposive sampling (Palinkas et al., 2015), methods commonly used in disaster studies (Norris, 2006; Stratton et al., 2021). For example, we distributed survey materials via US Postal Service Every Door Direct Mail® mailers to all addresses in four zip codes (44413: East Palestine, OH; 44441: Negley, OH; 16115: Darlington, PA; 16120: Enon Valley, PA) with the highest reported impacts, including soot deposition and water quality impacts of streams (Coelho et al., 2024). Mailers were used to ensure populations with low-technology

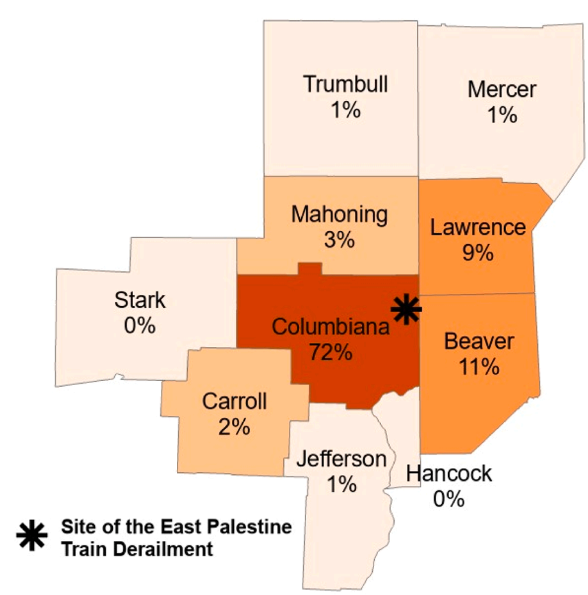

Fig. 1. Community survey study area. Percentages indicate the percent of respondents who resided or worked in each county.

access had the opportunity to participate. In addition to the mailers, we shared information about the study through local news media (Launtz, 2023), distributed flyers to local businesses, and through a weekly EPA newsletter that was sent to impacted residents (EPA, 2023b). Such convenience sampling approaches allowed us to increase response rates in the surrounding rural areas, for those with low-technology access, and the elderly (Dillman et al., 2014; Emmel, 2013; Nelson et al., 2023; Stratton et al., 2021). Survey materials were available through Qualtrics, LLC, a web-based survey software company, in-person canvasing efforts, and hard-copy mail (by request). To compensate for their time, survey participants were entered into a drawing for $100 gift cards.

Sample validation involved removing duplicates, Completely Automated Public Turing test to tell Computers and Humans Apart (CAPTCHA), discarding responses with minimal or no information, and other strategies outlined by Panesar and Mayo (2023). The survey took 23 min, on average, based on timestamps from the final valid samples, with the option to return to complete. This is a common strategy we adopted to minimize survey fatigue (Savage & Waldman, 2008).

Of particular interest to the current study are 23 survey questions pertaining to social and environmental cues, individual perceptions of risk and risk communication effectiveness, household protective actions taken, and sociodemographics. Several questions were developed to measure protective action response and associated information seeking behavior (the dependent variables in our study). First, two responses to questions were combined to measure the lower-cost actions of replacement of HVAC air filters and the purchase/use of new air purification systems. For example, we asked: *Which of the following have you done to clean your house and/or water, air, or land in response to the East Palestine chemical spill and fires? (Selected Choice: Used air purifiers). If you have a central heating and cooling system (HVAC) in your home, has the filter been changed since the chemical spill and fires?* To measure the rate of adoption of a costly, long-term protective action response, and to identify information seeking to support protective action response, we asked, respectively: *Have you relocated or are you trying to relocate from the community because of the chemical spill and fires? Have you requested air, water, or soil sampling from any organizations?*

Three questions were developed to measure environmental cues (Lindell & Perry, 2011), including: *Was there ever soot inside your house? Did it smell differently inside your home after the chemical spill and fires?* Social cues (Lindell & Perry, 2011) were measured through questions about community engagement, which capture meeting attendance, delivering oral or written comments, and helping to organize community meetings. Social cues were also measured in Likert-scaled questions on perceptions of equity, transparency, fairness, and resource access by average response, which yielded a measure with high internal consistency/reliability (Cronbach's $\alpha = 0.94$). Similarly, measures of information access frequency from media and social network sources were included as average of Likert-scaled questions (Cronbach's $\alpha = 0.77$). Risk perceptions were measured by proxy through Likert-scaled questions on expert knowledge (Cronbach's $\alpha = 0.85$) and trust (Cronbach's $\alpha = 0.9$), averaged over responses (Lindell, Huang, & Prater, 2017). Risk communication effectiveness and the receipt of warning and guidance messages on general home safety, water safety, or evacuation were measured using four questions. Perceptions of ineffective risk communication were measured by average responses to Likert-scaled questions, which rated reception of the elements of effective warning messages (Mileti & Sorensen, 1990; Wood et al., 2018) (Cronbach's $\alpha = 0.95$). Receipt of other warnings and guidance were captured through questions like: *Were you told by responding agencies that staying in your home or workplace was unsafe? Did you or any member of your household evacuate from your residence or workplace once the train derailment occurred?* The last question captures those respondents that were told to evacuate and complied. A list of all survey questions for the study is presented in the Supplemental Information (SI).

3.2. Survey validation

We received 259 valid survey responses, mostly submitted online with about 5% of the sample returned via hardcopy. The majority of respondents were from Columbiana County, Ohio (72%), the county where the derailment occurred. 11% of respondents were from Beaver County, Pennsylvania and 9% were from Lawrence County, Pennsylvania. The remaining 9% of respondents were from the other counties in the study area. Among respondents, 80% were homeowners, 14% were renters, and 6% did not provide housing details. The median household income of respondents fell between $50,000-$74,999, consistent with the median income in Columbiana, Beaver, and Lawrence Counties (U.S. Census, 2023). The median age ranged from 45 to 55, similar to demographic trends in these areas (U.S. Census, 2023). Ethnicity aligned closely with county demographics, with 94% identifying as Caucasian, 2% as African American, 2% as Asian/Pacific Islander, and 2% as Native American. Regarding gender distribution, 68% identified as female, 31% as male, and 1% as non-binary. While responses from female respondents were proportionally higher than the average representation in Columbiana, Beaver, and Lawrence Counties (50.4%; U.S. Census, 2023), previous work has found that women are more likely to respond to surveys (Smith, 2008) and are more risk aware (Harris et al., 2006). Regarding education, over 50% reported achieving at least an associate's degree or higher, consistent with educational attainment data in Columbiana, Beaver, and Lawrence Counties (U.S. Census, 2023). About 62.4% of respondents indicated current workforce participation, in line with Bureau of Labor Statistics reports (BLS, 2023).

Of the 259 valid responses, 19% (49 responses) had incomplete response information (>25%) and were omitted. Of the remaining sample (210 responses) about 13.8% (29 responses) contained missing values in variables needed to conduct the analysis. In our validation, we performed Little's MCAR test to check if missing values are Missing Completely at Random (MCAR) (Little, 1988). The non-significant result provides evidence that missing values are MCAR ($p = 0.71$) and that analysis on the remaining responses would be unbiased ($n = 181$) if the missing records were excluded. To assess central tendency bias in Likert-scale responses (Cascio & Aguinis, 2004), we conducted one-sample t-tests to detect pseudo-attitudes towards the midpoint. Results indicate that 25% (two of eight) of responses on information access, 50% (four of eight) on expert knowledge, and 11% (two of nineteen) on trust were not significantly different from the midpoint ($L = 3$). However, testing for Within-Group Agreement (rWG) revealed low reliability (rWG = 0.14), suggesting little consensus (Dunlap et al., 2003). Thus, pseudo-attitudes likely have minimal impact on the data and subsequent statistical analysis. In summary, 181 validated survey responses were used for statistical analysis, showing no pseudo-attitudes or central tendency bias, with only minimal, expected demographic biases. We also found no evidence of class imbalance in the response variables, as measured by all variables exceeding a modest 10:1 threshold (Daskalaki et al., 2006). See the SI for more details.

3.3. Statistical analysis

As a first step, we explored associations between variables of interest to inform the modeling approach, see Toland et al. (2024) for more details. We examined the correlations between Likert-scale, ordinal variables using the Spearman's Rank Correlation Coefficient (ρ) and performed chi-square tests to validate the relationships between the chosen proxies for protective action. The Spearman's Rank Correlation formula quantifies the strength and direction of association between two ranked variables, as:

$$\rho = 1 - \frac{6\sum {d_i}^2}{n(n^2 - 1)} \tag{1}$$

ρ: Spearman's rank correlation coefficient, d_i: Difference between ranks of each observation, n: Number of observations, i: Observation, $1 \leq i \leq n$.

Logistic regression was chosen as the baseline modeling approach for its simplicity and interpretability (Hosmer & Lemeshow, 2000; James et al., 2023). It is a standard choice for binary classification problems and provides clear insights into the explanatory relationships between predictor variables and the outcome. We also explored XGBoost (Jian et al., 2020; Lundberg, 2018) to determine if a more sophisticated gradient boosting model could enhance predictive accuracy. However, we found that the models had comparable Area Under the Curve (AUC) values but were less interpretable than logistic regression results. See the SI for more details. The logistic regression equation models the probability of a binary outcome, where "1″ is the suggested outcome of Y, as:

$$P(Y=1|X) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k)}} \tag{2}$$

$P(Y = 1|X)$: Probability of the positive response ($Y = 1$) given X predictors, $\beta_0, \beta_1, \beta_2, \ldots \beta_k$: Model coefficients, for k predictors, $X_1, X_2, \ldots X_k$: Independent variables ($k = 23$ predictors).

We performed variable selection based on backward selection in iterative removal of variables with p-values below the threshold of marginal significance ($p = 0.1$) (Bursac et al., 2008; Derksen & Keselman, 1992). Using this threshold allows for a wider range of predictors to be retained throughout each step of the iterative removal process, where interpretation of the explanatory power of the predictors can be performed from the final model (Bursac et al., 2008). The optimal model was selected based on the Akaike Information Criterion (AIC). AIC quantifies the information loss associated with a particular model, where the lower AIC values indicate superior model fit (Bozdogan, 1987). To test for multicollinearity, we used the Variance Inflation Factor (VIF) with a threshold of five, consistent with previous literature (Kim, 2019). If a predictor variable's VIF exceeds five, it suggests a higher level of multicollinearity with other variables in the regression model, potentially affecting the reliability of the regression coefficients. We found no evidence of multicollinearity in the final models—see the SI for more details about these results. We evaluated the model performance using the Receiver Operating Characteristic (ROC) curves and the corresponding AUC metric, which show the trade-off between sensitivity and the false positive rate (Bradley, 1997). We include additional metrics for accuracy, specificity, and sensitivity following 10-fold cross-validation (James et al., 2023) of the logistic regression models, which provides more insight into their robustness.

3.4. Limitations

As with any research, our study has its own set of limitations that need to be considered. One such limitation is that the survey was designed through the lens of the PADM, around investigation of risk perceptions and experiences of social and environmental cues in the built environment. Therefore, it does not include health related perceptions and experiences (e.g., Haynes, 2023; Haynes et al., 2024). However, it is important to separate the sociotechnical interactions that drive protective action decision making from the health-related impacts, as policy measures to address each will differ.

Limitations arise due to the cross-sectional nature of this research. However, many disaster research studies use a cross-sectional design (e.g., Balluz et al., 1997; Cannon et al., 2023; Ifdil et al., 2023; Norris, 2006) due to challenges related to the ephemeral nature of data in disasters (Wu, 2020), displacement (Araya et al., 2019), and recall accuracy after traumatic events (Madakasira & O'Brian, 1987), which complicate longitudinal research. Additionally, a longitudinal design may not accurately capture the decision-making context of the acute post-disaster period, especially if participants are contacted long after those decisions were made. Given that a large portion of the population was relocated or planned to relocate after the East Palestine crisis, a cross-sectional design was the most appropriate way to understand household protective actions.

Non-probability sampling limits the generalizability of findings to the broader population. However, random samples and full census approaches often show weaker effects, as general populations typically experience less severe impacts in disasters compared to those directly affected (Norris, 2006). To address these challenges, we considered both of these factors in our sampling methods, consistent with broader literature on disaster research design (Norris, 2006; Stratton, 2019). We acknowledge that non-probability sampling methods come with limitations, including self-selection and motivational bias. However, many outlying communities were underserved by the official government response, where impacts went unaddressed (Buckley & Meyer, 2023; Gay et al., 2024; Messenger, 2023; PDEP, 2024). Such trends can bias respondents in these areas to those who have had some household impacts from the East Palestine crisis, and were likely underserved, to seek out participation. Hence, this motivational bias may be aligned with our research objectives (Palinkas et al., 2015; Stratton, 2019). Similarly, convenience samples may include disproportionately distressed individuals through self-selection bias (Norris, 2006). However, we found no evidence of self-selection bias through class imbalance in protective action response variables in these areas. See the SI for more details.

The sample size ($n = 181$ survey responses) in our study is relatively small. However, small sample sizes are the norm in the disaster response literature (Norris, 2006), often due to the difficulty in reaching participants (e.g., Nelson et al., 2023) and the need to provide data back to the community rapidly. For example, recent disaster studies have had sample sizes in a similar range (e.g., Fletcher et al., 2022, $n = 139$; Von Behren et al., 2022; $n = 136$; Aranda et al., 2023, $n = 103$; Nelson et al., 2023, $n = 154$; and Balluz et al., 1997, $n = 146$). Additionally, the small sample size reflects the size of the rural populations in the affected areas from which our sample is drawn. For example, East Palestine, Ohio had a population of only 4,650 people in 2023.

A final limitation of the study arises from assumptions made in merging "no-opinion" or non-responses in categorical predictor variables. However, multiple studies (Fowler & Cannell, 1996; Krosnick et al., 2002; Krosnick et al., 2005) indicate that including "no-opinion" options does not enhance data quality. Similarly, measuring income presents challenges due to reluctance in disclosure, with some studies showing non-response rates to income-related question ranging from 10% to 26.2% (Bais et al., 2020; Moore & Loomis, 2001; Moore et al., 2000). Questions on educational attainment have shown up to 19% non-responsiveness (Bais et al., 2020). Our survey revealed similar patterns of non-responsiveness, with a combined 29% decrease in responses to questions regarding income and education. Consequently, these non-responses were merged with the reference category, along with other 'no-opinion' option selections in creating categorical predictor variables (Table 1). This prevents a significant reduction in sample size and ensures inclusion of participants who chose not to disclose this information, but otherwise provided a complete response.

4. Results

Table 1 presents the descriptive statistics for the independent and dependent variables used in the statistical models. The table includes the minimum and maximum values, as well as the average and standard deviation across the survey sample pool for each dependent response and independent predictor variable.

Table 1
Descriptive statistics of predictor and response variables.

Group	Variable	Type	Min/ Max	Average	Std. Dev.	Categories
Protective Action Response	Requested sampling and testing	Categorical	0/1	0.52	0.50	Yes, No
	Relocation	Categorical	0/1	0.15	0.36	Yes, No
	Change in HVAC and air purification	Categorical	0/1	0.81	0.40	Yes, No
Environmental Cues	Told there may be contamination inside home	Categorical	0/1	0.11	0.31	Yes, No
	Noticed a new smell inside home	Categorical	0/1	0.63	0.48	Yes, No
	Noticed soot inside home	Categorical	0/1	0.19	0.40	Yes, No
Social Cues	Perceptions of equity and fairness	Ordinal	1/5	2.41	1.25	Likert (average): Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
	Community engagement	Categorical	0/1	0.71	0.46	Yes, No
	Information access frequency	Ordinal	1/5	2.87	0.90	Likert (average): Never, A few times a month, Weekly, A few times a week, Daily
Risk Perceptions	Perceptions of trust (e.g., in agencies, media, or community groups)	Ordinal	1/5	2.43	0.74	Likert (average): Very Low, Low, Medium, High, Very High
	Perceptions about expert knowledge	Ordinal	1/5	2.96	0.90	Likert (average): Not at all, Very little, Neutral, Somewhat, To a great extent
Risk Communication	Evacuation	Categorical	0/1	0.54	0.50	Yes, No
	Perceptions of risk communication effectiveness	Ordinal	1/5	2.24	1.18	Likert (average): Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree
	Told that staying in home was unsafe	Categorical	0/1	0.40	0.49	Yes, No
	Told drinking water was unsafe	Categorical	0/1	0.09	0.28	Yes, No
Demographics[a]	Lived in Columbiana County	Categorical	0/1	0.74	0.44	Yes, No
	Owns home	Categorical	0/1	0.81	0.40	Yes, No
	Education (Bachelor's degree or higher)	Categorical	0/1	0.32	0.47	Yes, No
	Income (< $50,000 a year)	Categorical	0/1	0.36	0.48	Yes, No
	Financial impacts	Categorical	0/1	0.18	0.38	Yes, No
	Gender (Female)	Categorical	0/1	0.67	0.47	Yes, No
	Age (< 34)	Categorical	0/1	0.14	0.35	Yes, No
	Age (44–65)	Categorical	0/1	0.39	0.49	Yes, No
	Age (> 65)	Categorical	0/1	0.24	0.43	Yes, No
	Employment (Working full or part time)	Categorical	0/1	0.59	0.49	Yes, No
	Employment (Retired)	Categorical	0/1	0.23	0.42	Yes, No

[a] Background and demographic questions are based on Qualtrics, LLC, certified demographic questions and the U.S. Census American Community Survey questionnaire. Some questions from the survey are omitted. Descriptive statistics are for the final data used in analysis ($n = 181$).

4.1. Survey descriptive statistics

The results of the community survey show that half (50%) of the respondents requested air, water, or soil sampling. However, only 62% of those who requested sampling actually received these services. Of those who received results, the vast majority found them hard to understand (73%) and did not trust the accuracy of the results (75%). About 14% of respondents employed independent contractors for environmental sampling and testing, where 18% reported that paying for these services financially impacted their household. As expected, requests for air, water, or soil sampling services originated mostly from the zip code that included East Palestine, Ohio (44413; 73%). Sampling and testing were mostly performed by the US Environmental Protection Agency (US EPA; 24%) and through Norfolk Southern's contractors (21%). Of those surveyed, 15% had relocated or were trying to relocate after the incident, including 11% who had already moved or been displaced. Meanwhile, many households throughout the area took lower-cost actions compared to relocation, like using air purifiers (15%) or changing HVAC filters (65%).

Regarding environmental cues (Table 1), after the vent and burn, the majority of respondents (82%) did not find soot or ash inside their homes following the crisis. Nevertheless, a significant portion (61%) noted the presence of a new odor within their home in the weeks following. Further, about 10% were told they may have contamination in their home. Regarding social cues, half of the respondents (50%) attended community meetings, where about 15% gave public comments. Surprisingly, 78% of respondents rated equity, transparency, and fairness in the government response as neutral or lower.

Regarding information access, 65% of respondents reported using social media to get information about the incident and response, with about 46% of respondents using it daily. Respondents mostly received information about the crisis from word of mouth (66% of respondents) with 29% of respondents reporting daily interactions. In terms of risk perceptions (Table 1), most people did not trust information provided by the government and media. While social media played a large role in transmitting information, more than 50% of respondents reported a very low to low perception of trust in that information. In contrast, the most trusted sources of information were provided by personal physicians, community groups, and academic researchers. The least trusted source of information (where 75% of respondents reported at most a low level of trust) was information provided by Norfolk Southern and its contractors.

More than 50% of respondents disagreed that risk communications were effective, but they rated expert knowledge higher than average. This suggests that respondents may believe the issue lies not solely in a lack of knowledge, but rather in effectively utilizing that knowledge to identify and communicate the risks. About half of the respondents (53%) reported evacuating on or after February 3, 2023. Further, 41% were warned at some stage of the crisis that staying in their home was unsafe or that their drinking water was unsafe (8%). A full report and summary of the survey was shared with the community and responders—see the SI for this report.

4.2. Tests for association in response variables

We conducted chi-square tests to examine the associations among protective action response variables (Table 1). Our findings indicated a statistically significant association between requests for testing and relocation ($p = 0.04$), and requests for testing and changing air filters (p

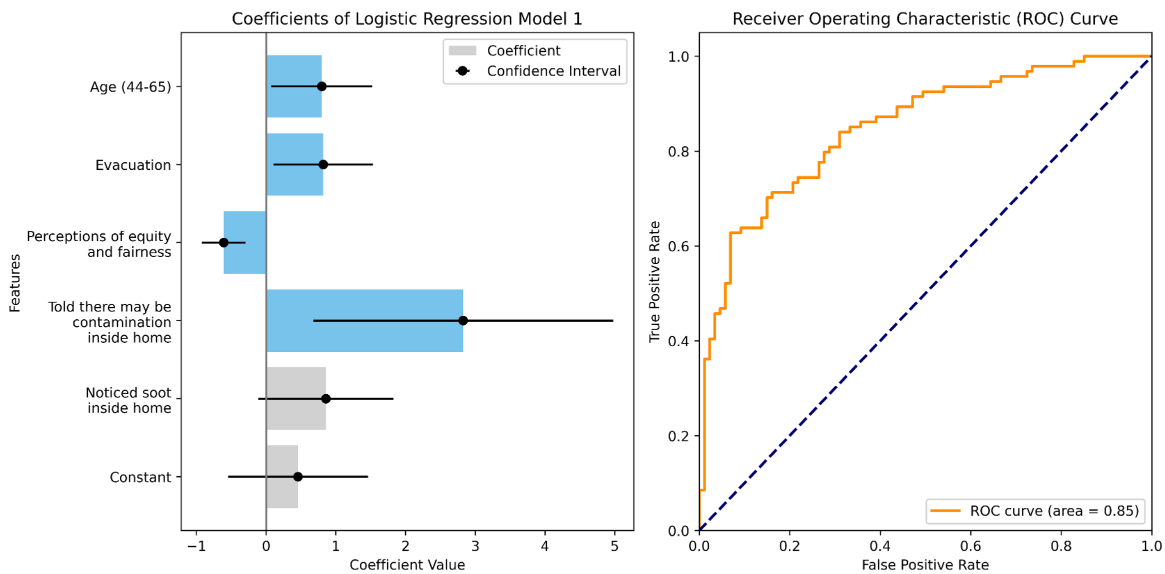

Fig. 2. Coefficients and ROC curve for the logistic regression model predicting requests for sampling and testing (Model 1). (Left: Predictor importance by coefficient values and confidence intervals; Right: ROC Curve and AUC). Cross-validation (average) metrics for Model 1 performance result in Accuracy = 0.71 (±0.02), Specificity = 0.68 (±0.02), and Sensitivity = 0.73 (±0.03).

Table 2
Logistic regression results showing the explanatory variables for requests for sampling and testing (Model 1).

Group	Predictor (Variable)	Coefficient[a]	Standard Error	Lower bound (95% Confidence Interval)	Upper bound (95% Confidence Interval)	Z-Score	P > |Z|
Environmental Cues	Told there may be contamination inside home	2.826	1.098	0.675	4.978	2.575	0.010
	Noticed soot inside home	0.858	0.495	-0.112	1.828	1.734	0.083
Social Cues	Perceptions of equity and fairness	-0.608	0.160	-0.923	-0.294	-3.792	0.000
Risk Communication	Evacuation	0.820	0.364	0.106	1.533	2.251	0.024
Demographics	Age (44-65)	0.798	0.369	0.074	1.522	2.161	0.031
	Constant[b]	0.457	0.512	-0.547	1.461	0.892	0.372

[a] Change in the log-odds of the outcome variable for a one-unit increase in the predictor variable, positive (+) implies increase in log-odds and negative (-) implies decrease in log-odds of protective action response relative to predictor.
[b] Constant represents the log-odds of the outcome variable when all predictor variables are set to zero from logistic regression results.

= 0.00). However, relocation and changing air filters showed no statistically significant association with each other ($p = 0.96$). This validates both our assumption that these proxies can represent independent extremes of decision-making and our characterization of requests for testing as information seeking behaviors to inform those decisions. Additional chi-squared results can be found in the SI.

4.3. Logistic regression results

In this section, we present the results of our logistic regressions. The first model predicted the decision to request sampling and testing based on the predictor variables from Table 1. Backward selection proceeded over 18 iterations, until all remaining variables were at least marginally significant ($p < 0.1$). Validating our approach, AIC monotonically decreased until the last step, ranging from 221.3 to 200.2 in the final model, with all remaining predictor variables showing a VIF < 2. The Receiver Operating Characteristic (ROC) summarized model performance, with the Area Under the Curve (AUC = 0.85) indicating a very good model result (Fig. 2). Results are presented in Table 2.

Here, lower perceptions of equity and fairness were statistically significant in explaining the choice for testing and sampling ($p = 0.000$). Among environmental cues, noticing soot ($p = 0.083$) was marginally significant, while being told there may be contamination inside their home ($p = 0.010$) was statistically significant. Experiences of evacuation also impacted the decision to pursue testing upon return ($p = 0.024$). Middle-aged respondents emerged as the only statistically significant demographic predictor of requests for sampling and testing ($p = 0.031$). Other demographic factors, risk communication, and perceptions of trust and expert knowledge did not show any explanatory power.

The second model predicted the likelihood of choosing the lower-cost protective action of changing filters or using air purifiers. In the second model, backward selection proceeded over 15 iterations with (p

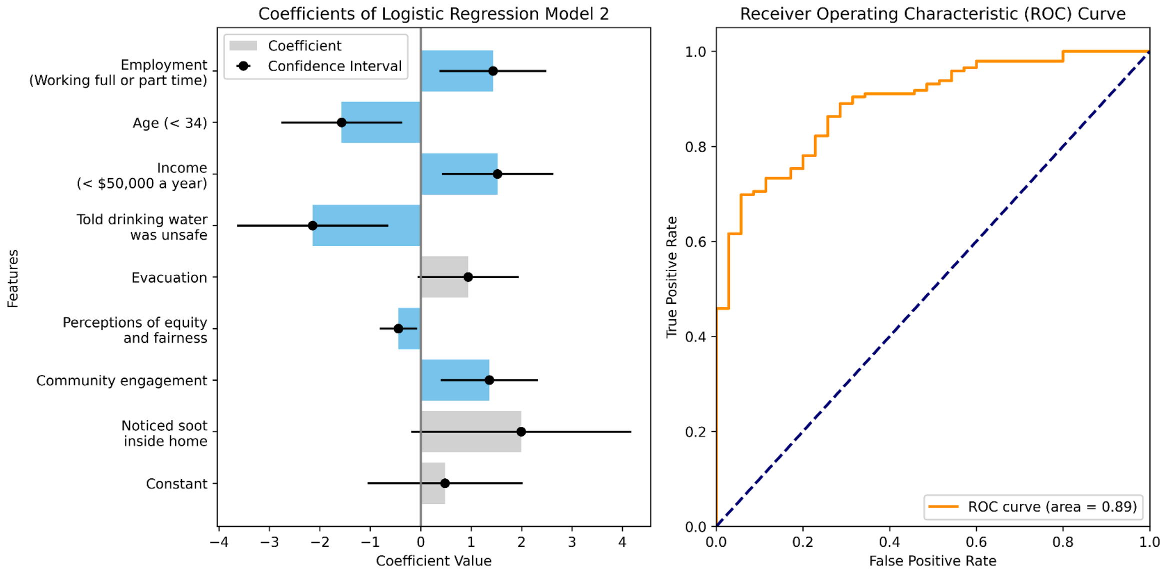

Fig. 3. Coefficients and ROC curve for logistic regression model predicting the use of air purifiers or changing HVAC filters (Model 2). (Left: Predictor importance by coefficient values and confidence intervals; Right: ROC Curve and AUC). Cross-validation (average) metrics for Model 2 performance result in Accuracy = 0.81 (±0.01), Specificity = 0.36 (±0.03), and Sensitivity = 0.92 (±0.01).

< 0.1). Again, AIC was monotonically decreasing until the last step, ranging from 157.7 to 139.0 in the final model, with most remaining predictor variables showing a VIF < 3. The AUC = 0.89 indicated a near excellent model result (Fig. 3). Results are presented in Table 3.

In predicting the use of air purifiers or changing HVAC filters (Model 2), lower perceptions of equity and fairness ($p = 0.020$) were statistically significant. Additionally, community engagement activities like meeting attendance, delivering oral or written comments, and helping to organize community meetings show a statistically significant relationship with the decision to change HVAC filters or use air purifiers ($p = 0.006$). Again, environmental cues like soot were marginally significant ($p = 0.073$). The absence of water safety warnings ($p = 0.005$), along with transparency concerns ($p = 0.020$), may have prompted people to change their HVAC filters or use air purifiers. Regarding demographics, lower-income individuals were more likely to change HVAC filters or use air purifiers ($p = 0.007$), despite potentially allocating a larger proportion of their income. Employment status influenced action-taking, with unemployed individuals less likely to engage in changing HVAC filters or using air purifiers ($p = 0.008$). Younger respondents (< 34 years old) tended not to take action ($p = 0.010$) (Fig. 3).

The third model predicted the high-cost protective action of relocation based on the predictor variables from Table 1. In Model 3, backward

Table 3
Logistic regression results showing the explanatory variables for using air purifiers or changing HVAC filters (Model 2).

Group	Predictor (Variable)	Coefficient[a]	Standard Error	Lower bound (95% Confidence Interval)	Upper bound (95% Confidence Interval)	Z-Score	P > |Z|
Environmental Cues	Noticed soot inside home	1.992	1.112	-0.187	4.170	1.791	0.073
Social Cues	Community engagement	1.361	0.492	0.397	2.324	2.767	0.006
	Perceptions of equity and fairness	-0.442	0.190	-0.814	-0.069	-2.326	0.020
Risk Communication	Told drinking water was unsafe	-2.142	0.765	-3.642	-0.643	-2.800	0.005
	Evacuation	0.941	0.510	-0.059	1.941	1.844	0.065
Demographics	Income (< $50,000 a year)	1.522	0.564	0.418	2.626	2.701	0.007
	Employment (Working full or part time)	1.433	0.540	0.375	2.492	2.654	0.008
	Age (< 34)	-1.567	0.612	-2.766	-0.369	-2.563	0.010
	Constant[b]	0.483	0.785	-1.057	2.022	0.615	0.539

[a] Change in the log-odds of the outcome variable for a one-unit increase in the predictor variable, positive (+) implies increase in log-odds and negative (-) implies decrease in log-odds of protective action response relative to predictor.
[b] Constant represents the log odds of the outcome variable when all predictor variables are set to zero from logistic regression results.

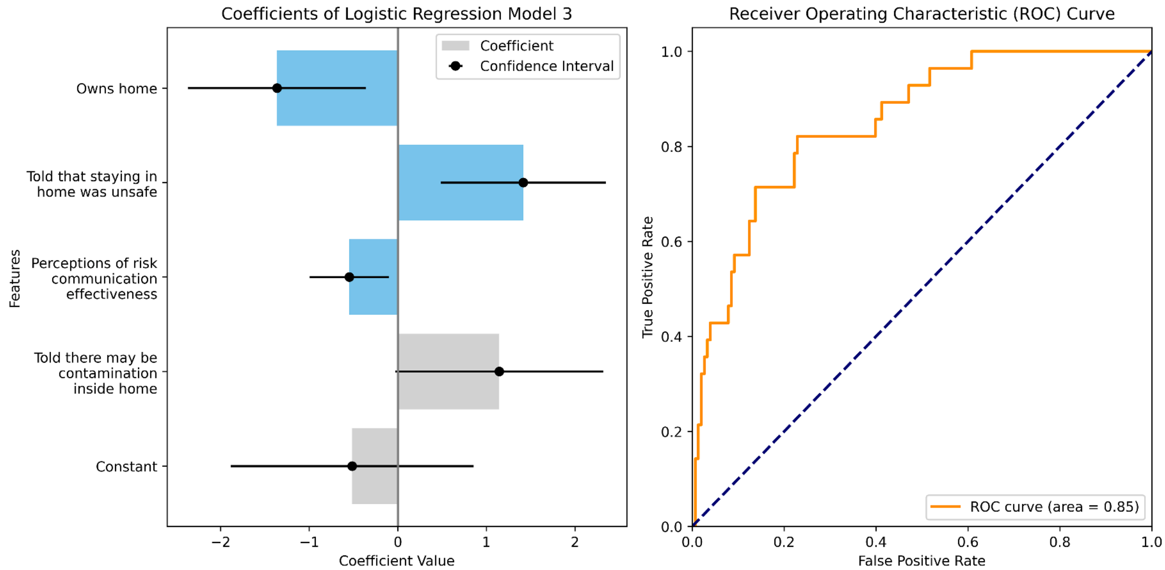

Fig. 4. Coefficients and ROC curve for logistic regression predicting relocation (Model 3). (Left: Predictor importance by coefficient and confidence intervals; Right: ROC Curve and AUC). Cross-validation (average) metrics for Model 3 performance result in Accuracy = 0.83 (±0.01), Specificity = 0.96 (±0.01), and Sensitivity = 0.14 (±0.01).

Table 4
Logistic regression results showing the explanatory variables for relocation (Model 3).

Group	Predictor (Variable)	Coefficient[a]	Standard Error	Lower bound (95% Confidence Interval)	Upper bound (95% Confidence Interval)	Z-Score	P > |Z|
Environmental Cues	Told there may be contamination inside home	1.146	0.598	-0.026	2.318	1.916	0.055
Risk Communication	Told that staying in home was unsafe	1.417	0.476	0.485	2.349	2.979	0.003
	Perceptions of risk communication effectiveness	-0.548	0.228	-0.996	-0.100	-2.400	0.016
Demographics	Owns home	-1.364	0.513	-2.368	-0.359	-2.660	0.008
	Constant[b]	-0.516	0.700	-1.887	0.855	-0.738	0.461

[a] Change in the log-odds of the outcome variable for a one-unit increase in the predictor variable, positive (+) implies increase in log-odds and negative (-) implies decrease in log-odds of protective action response relative to predictor.
[b] Constant represents the log odds of the outcome variable when all predictor variables are set to zero from logistic regression results.

selection proceeded over 19 iterations with ($p < 0.1$). Again, AIC monotonically decreased until the last step, ranging from 158.7 to 137.0, with all remaining variables showing a VIF < 3 and an AUC = 0.85, which indicated a very good model result, despite a lower average sensitivity (Fig. 4). Results are presented in Table 4.

In Model 3, the perception of ineffective risk communication ($p = 0.016$) was a statistically significant predictor of relocation. Lower sensitivity in the model may be explained by negative directionality in most explanatory factors, where higher perceptions of risk communication effectiveness and home ownership, for example, are associated with taking no protective action. Consequently, renters were more likely to relocate, which could be attributed to the lack of financial ties to home ownership ($p = 0.008$). As one may expect, a warning that staying in the home was unsafe ($p = 0.003$) at some stage of the crisis was a statistically significant predictor of relocation.

5. Discussion

We discuss the results of our models in relation to the six hypotheses proposed in Section 2. Additionally, we examine the implications of our findings within the broader context of public warning systems and PADM literature, with a focus on theoretical advancements and contributions to the study of underdeveloped warning systems in industrial disasters.

5.1. Hypothesis 1: There is a statistically significant predictive relationship between environmental cues and decisions to take protective action

Results from all three models suggest protective actions are marginally explained by physical experiences of the hazard, based on environmental cues, like soot in the home (Model 1, requests for sampling and testing and Model 2, use of purifiers or changing HVAC filters) or being told there may be contamination in the home (Model 3, relocation). Furthermore, being told that there may be contamination inside the home was the only statistically significant predictor ($p < 0.010$) in the environmental cues group explaining requests for sampling and testing (Model 1). Previous studies shows that people may be more likely to take protective action as evidence of an environmental hazard increases (Grothmann & Reusswig, 2006; Hou et al., 2024; Johnson & Scicchitano, 2000; McGuire, 1995). However, our marginally significant results do not provide strong support for this conclusion. This suggests that protective action decision-making processes may be more complex in industrial disasters. A lack of information, or conflicting information, may lead some respondents to delay protective action, even when strong environmental cues are present. Sampling and testing results, with interpretation of those results to guide household decision-making, are critical in these cases. Yet, our survey shows that only 62% of those that requested sampling and testing received it. Consequently, inconsistent sampling and testing methods (see Coelho et al., 2024) may have impacted hazard detection—the core issue highlighted by Miletti & Sorensen (1990) that determines the effectiveness of the public warning system in an industrial disaster.

5.2. *Hypothesis 2: There is a statistically significant predictive relationship between social cues and decisions to take protective action*

We found confirmation of Hypothesis 2 in the models predicting both requests for sampling and testing (Model 1) and changing HVAC filters or using air purifiers (Model 2). However, social cues were not found in the model predicting relocation (Model 3). It may be that requesting sampling and testing, as well as changing HVAC filters or using air purifiers, have a lower barrier to action, and that decisions for high-cost protective actions like relocation may require more substantive evidence than social cues. Reports indicate that eligibility for reimbursement may have been a consideration (Buckley & Meyer, 2023), where some households could not afford to relocate unassisted. Our results finding social cues significant are consistent with previous work on community engagement as a determinant of household protective action response in other disasters (Reynolds, 2011). Some findings suggest that information from community organizations and public forums helps build consensus on interpreting environmental cues and encourages collective willingness to take protective action (Reynolds, 2011; Chavez et al., 2017). Our results confirm these findings in predicting lower-cost protective actions like use of air purifiers or changing HVAC filters (Barber, 2023; Johnson, 2023).

Surprisingly, our results did not reveal connections between community engagement and requests for sampling and testing. Additionally, the variable representing frequency of information access was absent from all models. Instead, we found that perceptions of equity were statistically significant in both predicting requests for sampling and testing (Model 1) and the use of air purifiers or changing HVAC filters (Model 2). Such concerns may have arisen due to the lack of clarity and consistency in decision-making and policies regarding access to crucial services, such as reimbursement for expenses and allocation of resources for air, water, or soil testing (Buckley & Meyer, 2023). Recent research has identified risk communication inequities in access and response to warning messages (e.g., FEMA, 2021; Hansson et al., 2020) and identified the absence of equity considerations in risk assessments (e.g., Finucane et al., 2023; Soden et al., 2023). Our findings represent new connections between hazard identification, which directly impacted the effectiveness of risk communication in this industrial crisis, and perceptions of equity, transparency, and fairness.

5.3. *Hypothesis 3: Perceptions of inadequate risk communication will have a statistically significant predictive relationship with protective action response*

Most research on the public warning system has focused on the effectiveness of risk communication, particularly the message channel, message content, and public reception of the warning message (e.g., Hansson et al., 2020; Hyman et al., 2022; Lindell & Perry, 2004; Lindell et al., 2017). These studies rarely mention the challenges of hazard identification. Instead, it is often assumed that hazards have been thoroughly identified, guided by scientific or technical experts who assess risk, and that emergency managers and public officials have been informed about that risk. However, in complex industrial crises this may not be the case. Instead, the public warning system may be undermined if hazards are not first identified.

In this context, perceptions of ineffective risk communication emerge as a statistically significant predictor of relocation in Model 3. This influence may stem from inconsistent messaging due to gaps in hazard identification, where respondents were told at some point that staying in their home was unsafe but did not receive any subsequent long-term, home safety assessment. While there is confirmation of Hypothesis 3 in the model that predicts relocation, in the other two models connections are less clear. In our survey results, low perceptions of equity have strong correlations to perceptions of ineffective risk communication, with a Spearman's Rank Correlation Coefficient value of $|\rho| \geq 0.70$. See the SI for more details. Of respondents that requested sampling and testing, 77% also "disagreed" or "strongly disagreed" that risk communication was effective (Toland et al., 2024). Similarly, of the respondents that requested sampling and testing, 77% "disagreed" or "strongly disagreed" that the government response was fair and equitable. Further, of the respondents that changed their HVAC filters or started using air purifiers, 64% "disagreed" or "strongly disagreed" that the government response was fair and equitable. In this respect, issues of ineffective risk communication may underpin broader issues of equity, transparency, and fairness, or vice versa. We find support for Hypothesis 3 in this regard.

5.4. *Hypothesis 4: There are statistically significant predictive relationships between receiving warnings about general home safety, water safety, or evacuation and protective action response*

As expected from previous work on the PADM and other frameworks (e.g., Gladwin et al., 2001; Hyman et al., 2022; Lindell et al., 2015; Lindell, Huang, & Prater, 2017), we find confirmation of Hypothesis 4 in all three models. In Model 1, evacuation emerged as a statistically significant predictor of requesting sampling and testing. In Model 2, the absence of water safety warnings cued people to take action. In Model 3, being told at some stage of the crisis that staying in their home was unsafe was a statistically significant predictor of relocation.

Results show that for those respondents that received some form of warning or guidance on general home safety, water safety, or evacuation, about 83% took at least one of the three protective actions under study. This response is consistent with Lindell, Huang, and Prater (2017), which shows about 77% took alternative protective action (drinking bottled water) in the 2010 Boston Water Crisis. Interestingly, our results also show that for respondents who did not receive any form of other warning, 64% still took at least one of the protective actions under study. We find support for Hypothesis 4 but recommend further research to explore the influence of warnings or guidance about general home safety, water safety, or evacuation on other protective actions within the context of underdeveloped warning systems.

5.5. Hypothesis 5: Risk perceptions about trust and expert knowledge have a statistically significant predictive relationship with decisions to take protective action

Risk perceptions about trust and expert knowledge were not found significant in any of the models, in line with findings from Heath et al. (2018). However, from the survey, many respondents found testing results hard to understand (73%) and lacked trust in the results (75%). Similarly, perceptions of trust and expert knowledge were moderately correlated ($|\rho| \geq 0.57$), again providing no clear determination about the relationship between trust and expert knowledge. However, descriptive statistics from the survey are consistent with previous work showing that inconsistent messages and unclear information contribute to mistrust (Quinn et al., 2005; Reynolds, 2011). For example, of those respondents that found testing results hard to understand, 87% also lacked trust in their results. Consequently, the availability of information might influence how much trust people place in authorities and experts in industrial disasters (Johnson & Scicchitano, 2000). However, the impacts of perceptions about trust and expert knowledge on household decision-making remain unclear, as these relationships are likely only found if sampling and testing have occurred. Therefore, support for Hypothesis 5 is indeterminant.

5.6. Hypothesis 6: Sociodemographic factors have no statistically significant predictive relationship with decisions to take protective action

In contrast with Hypothesis 6, we found statistically significant sociodemographic predictors of protective action. In Model 1, middle aged populations (44–65) emerged as the only statistically significant predictor of requests for sampling and testing, possibly due to a higher level of community engagement and home ownership. Younger residents (< 34 years old) tended not to take the low-cost protective actions like changing HVAC filters and using air purifiers ($p = 0.010$). Lower-income individuals were more likely to change HVAC filters or use air purifiers, even though they might spend a larger part of their income on these items ($p = 0.007$). Unemployed respondents were less likely to do so ($p = 0.008$). Yet, these findings are not consistent with the broader literature. For example, Hyman et al. (2022) found that age had a negative correlation with taking alternative protective action, and income had a positive correlation. Similarly, Lindell, Huang, & Prater (2017) found that any statistically significant correlations of demographic attributes with warning reception were only slightly greater than chance. Although our findings identify some sociodemographic factors relevant to industrial disasters in the absence of official warnings and PARS, broader literature suggests that sociodemographic connections are likely influenced by the specific context and nature of the hazard. Therefore, support for Hypothesis 6 is indeterminant.

5.7. Theoretical contributions

We outline three theoretical contributions based on our results:

1. Our research advances the PADM (Lindell & Perry, 2011) by exploring its application in industrial disasters. Industrial disasters often have underdeveloped warning systems (e.g., transportation incidents, hazardous material disasters; Mileti & Sorensen, 1990) given unknown impacts immediately post-event. Our study departs from existing research by examining the determinants of protective actions taken to address potential household contamination in the absence of official warnings and PARS. These findings are critical to understanding household decision-making, revealing how perceptions of social equity and fairness strongly influence protective actions, in contrast to the environmental cues typically found in most natural disasters. For instance, research has shown that environmental cues could be used instead of warnings for evacuation (Hou et al., 2024). However, we found that this may not always be the case. We observed that environmental cues like observation of soot or smell had little to no explanatory power in modeling household protective action decisions. This may have been the result of external influences, where response organizations minimized the importance of these cues without first identifying the hazards (e.g., CDC, 2017; Funk, 2024).
2. Our findings revealed the importance of hazard identification, which is often assumed to occur in previous research focused on the PADM (e.g., Lazo et al., 2015; Lindell et al., 2017; Nagele & Trainor, 2012; Strahan & Watson, 2019). Failures in hazard identification impacted risk communication effectiveness after the East Palestine crisis, influencing protective action. Further, low perceptions of risk communication effectiveness were found to be a key explanatory factor in relocation decisions. Similar issues have been observed in developed warning systems, such as when shifting pre-event evacuation zones in response to hurricane forecasts (Lazo et al., 2015). However, industrial disasters often involve greater uncertainty post-disaster compared to natural disasters. Future research on risk communication should critically examine the assumptions of hazard identification within this context of underdeveloped warning systems.
3. Our study revealed new connections between the effectiveness of risk communication in an industrial crisis and perceptions of equity, transparency, and fairness (e.g., Hansson et al., 2020). We found that disparities in information access may be rooted in systemic inequities, where failure to identify hazards disproportionately affects the most vulnerable populations (Emrich et al., 2022; Tierney, 2014). For example, we found that risk communication effectiveness and relocations are closely linked to social equity, as relocation without some form of reimbursement is costly and may not be feasible for low-income households. In turn, effective risk communication helps ensure that decisions are aligned with the risks, especially when resources are limited.

6. Practical and policy recommendations

Here, we propose specific policy changes aimed at strengthening industrial disaster response. While we argue that all disasters are unique, the frameworks through which they are managed are standardized. Strengthening the hazard identification subsystem of the public warning system and improving incident management policies are key recommendations from this study, which could broadly impact disasters response practices.

6.1. Strengthen hazard identification within the public warning system by developing adaptive emergency sampling and testing guidelines for industrial disasters

Hazard identification underpins the entire public warning system (Fig. 5). Strengthening hazard identification in industrial disasters

Fig. 5. Hazard identification underpins the public warning system in industrial disasters.

requires rapid and complex sampling and testing procedures, based on adaptive emergency guidelines. Opportunities to adapt emergency guidelines, for example, on indoor air quality, like those developed in collaboration with the Environmental Protection Agency (EPA) for wildfire smoke (Stone et al., 2019) were generally overlooked in the East Palestine environmental crisis.

These guidelines could serve as a framework for conducting indoor air quality testing, communicating risks to the public, and establishing recommendations for protective actions. Protective actions might include surface cleaning and procedures for utilizing air filters or purifiers, for application in industrial disasters with similar contaminant and exposure pathways. Similarly, other studies (e.g., Laguerre & Gall, 2024; Li et al., 2023; Stinson et al., 2024; NEHA, 2023) provide technical guidance on indoor air quality and cleaning that could be adapted for future disasters. Further, community members have voiced concerns about the long-term impact of groundwater contamination to private wells (e.g., Bottar, 2024; PDEP, 2024). While some long-term testing and sampling have been funded, little to no guidance on conducting a hydrogeological study of hydraulic conductivity and groundwater flow to steer that testing, has been provided.

Adaptive protocols for environmental sample collection, data management, and test result dissemination for industrial incidents should align with established National Incident Management System (NIMS) policies (FEMA, 2017). These policies could support coordination between federal, state, local, and tribal agencies, leveraging their expertise and resources to manage and respond to industrial incidents effectively under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) authorities. For example, protocols and collected data could be available to responding agencies through a clearinghouse for interagency data sharing, in compliance with the Foundations for Evidence-Based Policymaking Act of 2018 (Public Law 115–435), given that complex jurisdictions and interagency efforts may require a coordinated response to support hazard identification. Implementing new guidelines in accordance with NIMS policies would significantly impact disaster response practices in complex industrial disasters under CERCLA and Stafford Act authorities within the United States and provide a roadmap for other countries facing similar challenges.

6.2. *Instill equity as a foundation of environmental disaster response*

We found connections between equity and risk communication, which may lead to disparities in information access. In the East Palestine crisis, certain subpopulations exhibited varying propensities to take action, influenced by factors such as age, income, and housing tenure, as shown in our model results. Implementing broader policies that guarantee equitable treatment for all community members can ensure access to information, resources, and targeted communication of risk. These measures could improve perceptions of equity, fairness, and transparency in future disasters. From a community standpoint, we found that timely sampling and clear pathways for households to request testing were essential. We recommend clarifying eligibility criteria and procedures for determining who receives services like sampling and testing (e.g., Buckley & Meyer, 2023) and establishing an appeals process that ensures federal civil rights and due process. Equitable treatment of individuals with safety concerns, along with transparent communication about data collection processes, limitations, and test results, could ensure understanding and trust in public safety measures, bolstering confidence in the overall response effort.

Connections between protective action and perceptions of social equity revealed here can motivate new avenues for advancing the PADM. One limitation of the PADM is that it does not explore broader cultural contexts, as framed under social cues (McBride et al., 2021), and that there are no feedback loops within the model (McBride et al., 2019). By integrating perceptions of social equity into the PADM, this study uncovers how these perceptions may influence protective action in industrial crises. Our exploration of the PADM within the context of underdeveloped public warning systems revealed how gaps in policies lead to disparities in information access. For example, our findings on risk communication effectiveness and relocation are closely linked to social equity, as relocation is a costly measure. In turn, effective risk communication helps ensure that decisions are aligned with the risks, especially when resources are limited.

To practically address these disparities, recent work under the Federal Emergency Management Agency (FEMA) Equity Act (H.R. 5775 / S. 2961) may serve as a guide to develop disaster equity policies (117th Congress, 2022; FEMA, 2023). New policies can be mirrored in environmental disaster response under the CERCLA authorities—making equity a pillar of environmental disaster response under CERCLA, as it is in natural disasters managed by FEMA. Moreover, redefining the role of the "responsible party", in the current case Norfolk Southern, during environmental crisis response is essential. A neutral, third-party agency like the US Department of Health and Human Services (DHHS) or FEMA could be tasked to coordinate household eligibility determination for access to emergency resources when the capabilities of the responsible party or lead agency to deliver human services have been exceeded. These improvements could have a broad impact towards instilling equity in industrial disaster response practices under CERCLA, as they have had in natural disasters managed under Stafford Act authorities (FEMA, 2023, 2024).

7. Conclusion

The East Palestine train derailment, chemical spill, and fires illustrate the challenges posed by underdeveloped public warning systems in industrial disasters, exposing gaps in identifying hazardous materials and assessing their threats. Our study advances the theoretical literature on the PADM by exploring its application in underdeveloped warning systems. We examine factors within the PADM influencing household protective action response from a community survey across Ohio, Pennsylvania, and West Virginia ($n = 259$). We found that, while environmental cues played a limited role, social cues such as community engagement and perceptions of equity, fairness, and transparency significantly influenced protective action decision-making in response to potential household contamination in the absence of official warnings and PARS.

Additionally, our study challenges theoretical assumptions about public warning systems often made in previous research, revealing how failures in hazard identification can impact the effectiveness of risk communication in an industrial crisis, thereby influencing protective action. Based on our findings, gaps in sampling and testing may have impacted the detection of hazards, undermining the effectiveness of an already underdeveloped public warning system. Strengthening these public warning systems will require the implementation of new policies and guidelines for responding agencies in designing and conducting emergency sampling and testing plans, communicating risks to the public, and establishing recommendations for protective actions.

Moreover, our work contributes to the growing body of literature on disaster equity, identifying new connections in the PADM that may drive household protective action. Vulnerable communities often bear the disproportionate impacts of failed policies in disasters, emphasizing the need for further study, with integration of these findings to ensure equity in environmental disaster response. Future work should use interviews and qualitative research methods to understand relationships between protective actions, information access, and social equity that cannot be captured with a survey alone.

Notes

The authors declare no competing financial interests.

Associated Content

The following files are available in the Supplemental Information (SI).
Supplemental Document 1: Survey Instrument
Supplemental Document 2: Community Survey Report
Supplemental Table 1: Selected Survey Questions in Study
Supplemental Table 2: Model Selection Metrics from Backward Selection
Supplemental Table 3: Chi-Squared Results and Spearman Rank Results
Supplemental Analysis 1: XGBoost Model Results
Supplemental Analysis 2: Validation Results
Supplemental Media 1: Community Survey Recruitment

CRediT authorship contribution statement

Joseph Toland: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Andrew Whelton:** Writing – review & editing, Conceptualization. **Clayton Wukich:** Writing – review & editing, Conceptualization. **Lauryn A. Spearing:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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.

Data availability

Due to the sensitive nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared. *Data not available / The data that has been used is confidential*.

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Supplementary materials

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