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ORIGINAL PAPER

Quantifying the role of insurance in tornado-impacted community recovery: a survey and simulation-based approach

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Abstract
Insurance against disasters plays a critical role in community recovery by providing policyholders with reliable and timely payments for repairing or reconstructing damaged houses. By allowing homeowners to transfer risk, insurance enables homeowners to address house without experiencing significant financial burdens. Although historical events have highlighted the importance of insurance, its quantitative impact on community recovery, particularly in tornado-impacted communities, is understudied. This study focuses on advancing our understanding of whether sufficiently insured houses can have a positive impact on the recovery of tornado-impacted communities (i.e., the main research question). This paper proposes a two-stage simulation framework to quantitatively evaluate the effects of insurance on community recovery. In the first stage of the framework, we developed statistical models to estimate homeowners' insurance decisions prior to a tornado event. In the second stage, we examined the effects of insurance on various aspects of community recovery. To develop empirical and statistical models regarding insurance decisions and their impacts on housing recovery, we collected data through online surveys targeting residents whose properties were damaged by the tornadoes that occurred in May 2019 in the United States. Finally, the proposed simulation framework was applied to the City of Dayton, Ohio following those May 2019 tornado events to address the main research question. The results of the simulation concluded that sufficiently insured houses can have a positive impact on community recovery and highlighted the need for effective policies and economic incentives to encourage individuals to purchase insurance.

Keywords Tornado · Insurance · Housing recovery · Community resilience · Survey · Quantitative analysis

1 Introduction

Tornadoes are one of the most violent and costliest natural hazards in the United States, accounting for 40% of insured catastrophe losses between 1997 and 2016 (Insurance Information Institute 2021). On average, about 1000 tornadoes strike the United States every year and result in \$10 to \$36 billion dollars in direct and indirect economic losses

Extended author information available on the last page of the article

(Insurance Information Institute 2021). Although federal, state, and local governments are actively engaged in mitigating tornado risk for communities, individual responsibility also plays a significant role in reducing risk and facilitating the prompt recovery of housing. In general, individuals can take two types of proactive actions to reduce the potential impact of tornadoes: applying structural mitigation measures and purchasing insurance. Structural mitigation measures cannot reduce the probability of tornado occurrence but can affect its consequences (e.g., house damage and human/economic losses). On the other hand, although insurance does not reduce tornado risk, it transfers risk to another party (i.e., from homeowners to the insurance company) through an insurance policy. The effects of mitigation measures on tornado-induced property damage and community resilience can be quantified through tornado catastrophe modeling and simulation if sufficient data about tornadic wind and its effects on house damage and losses are available (Amini and van de Lindt 2014; Elsner et al. 2013; Eppelbaum 2013; Honerkamp et al. 2022a; Honerkamp et al. 2022b; Masoomi and van de Lindt 2016; Plaz 2018; Refan et al. 2020; Roueche et al. 2017). However, the investigation of the impact of insurance on community recovery through quantitative analysis has received relatively little attention, particularly in the context of communities affected by tornadoes.

Following a tornado event, insurance can serve as a means for homeowners to alleviate the substantial financial hardships that arise from damage to their homes and belongings (Lee and Li 2021; Lee et al. 2019, 2022; Zhao et al. 2020). Homeowners insurance and flood insurance are two types of insurance that can cover tornado-related damage. Homeowners insurance is a form of property insurance that covers dwelling and personal property, providing coverage for repairing, replacing, or rebuilding homes and belongings damaged by tornadic winds. If a tornado is accompanied by heavy rain, the resulting flood damage will often not be covered by homeowners insurance unless the rainwater enters through a tornado-damaged roof or wall. Thus, homeowners should purchase a separate flood insurance policy to insure homes and belongings in the event of floods. Although homeowners insurance is required for mortgaged homes, many homes are underinsured or uninsured. Approximately 4 million homes in the United States (i.e., 3% of housing units) are uninsured, and about 64% of American homes are underinsured by an average of 27% of the home's replacement value (CoreLogic 2022; Kin 2021). Additionally, since flood insurance is not federally required outside of high-risk flood areas, only 50% of American homes in the National Flood Insurance Program (NFIP) flood zones have flood insurance. This take-up rate for flood insurance is even much lower outside of NFIP flood zones (Altmaier et al. 2017). Uninsurance and underinsurance issues can create financial hardship for homeowners and leave them unable to repair or rebuild their homes, prolonging the housing and community recovery process.

There are various reasons for uninsurance and underinsurance. First, individuals tend to underestimate the potential risks associated with low-probability hazard events, despite the significant financial burden that these events may cause (Cutler et al. 2008; Jullien et al. 1999; Kunreuther and Pauly 2006). Second, the high cost of insurance premiums and deductibles is a significant obstacle to obtaining adequate insurance coverage (Corcos et al. 2017). For example, in seismic-prone areas, earthquake insurance is costly, and deductibles are typically high (ranging from 5 to 25% of the home's value), resulting in low take-up rates (between 10 and 17% of the total population) for earthquake insurance in California (Zhao et al. 2020). Finally, some homeowners may rely on government financial assistance rather than purchasing insurance (Picard 2008). Although the FEMA's Individuals and Households Program (IHP) provides financial assistance to eligible individuals and households affected by a disaster, this funding may be insufficient to cover all losses caused by a disaster, as stated explicitly in the program's Fact Sheet that "IHP is not a substitute for insurance and cannot compensate for all losses caused by a disaster" (FEMA 2020). Given that uninsurance and underinsurance are serious issues in tornado-impacted communities, it is imperative to understand the effects of these issues on housing and community recovery.

Recently, several studies have considered the effect of insurance on the housing recovery process as part of the community recovery simulation process (Lin and Wang 2017; Miles and Chang 2007). These studies have accounted for the reduced time for housing recovery due to reliable and timely payment provided by insurance companies. However, most of them have investigated the role of insurance in earthquake-impacted community recovery, and thus have considered only binary variables in their insurance demand models by assuming that there are only two states (i.e., insured or not). This assumption is reasonable for earthquake-impacted communities because purchasing earthquake insurance is completely voluntary, and insured states could significantly impact the recovery speed of damaged homes (Zhao et al. 2020). However, due to the requirement of homeowners insurance for mortgaged homes, which accounts for 63% of American homes, a significant portion of damaged homes in tornado-impacted communities are covered by homeowners insurance. In this case, the coverage limits play a more significant role in the housing recovery process than insured states do. Only a limited number of studies (e.g., Lee and Yan 2022; Paul and Che 2010; Shan et al. 2017; Steinglass and Gerrity 1990) have explored the role of insurance in tornado-impacted communities, and most of them have taken a qualitative approach to investigate this issue. Additionally, existing studies have primarily assessed the impact of insurance on housing repair time, whereas insurance also affects both the housing recovery process and the homeowner's financial stability.

In summary, the existing studies that have explored the effect of insurance on tornado-impacted community recovery have several research gaps. Firstly, the abilities to quantitatively model individual insurance purchase decisions and establish a link between insurance coverage and community recovery are currently limited. Secondly, the existing literature has not comprehensively examined various aspects of community recovery, such as repair decisions, financial hardship, and recovery delay. While the impact of insurance coverage on recovery time has been studied to some extent, other aspects of community recovery (e.g., homeowners' financial hardship and their repair decisions) have received less attention. Understanding these aspects is crucial for developing effective disaster management strategies that can mitigate the negative impacts of tornadoes and promote faster recovery. To address these gaps, this paper proposes a two-stage simulation framework for evaluating the role of insurance in tornado-impacted community recovery.

This study was designed to answer the main research question: will sufficiently insured houses have a positive impact on community recovery? To answer this question, we utilized the proposed simulation framework to examine whether sufficiently insured houses could encourage more homeowners to repair or rebuild their damaged homes, reduce their post-tornado financial hardship, and reduce the wait (or delay) time to initiate the housing recovery process. The proposed framework included both existing fragility, loss, and recovery models and newly developed insurance-related models that were formulated using the data collected from online surveys. In this study, two rounds of online surveys were conducted targeting residents whose properties were damaged by the tornadoes that occurred in May 2019 in the United States. More specifically, the first stage of the framework was designed to estimate homeowners' decisions on insurance prior to a tornado event. In the second stage, the framework investigated the effects of insurance on repair decisions made by homeowners, financial hardship experienced by individuals after a tornado event, and the delay time associated with the housing recovery process. This stage of the framework is crucial as it provides insights into the various factors that impact the recovery process in tornado-impacted communities. By examining the role of insurance in repair decisions and financial hardship, this study can identify strategies to promote faster recovery and enhance community resilience. Additionally, analyzing the delay time associated with the housing recovery process can provide valuable information for policymakers and disaster management agencies to improve pre- and post-tornado planning and resource allocation.

The remainder of this paper is organized as follows. Section 2 presents the simulation framework as well as the empirical and statistical models developed from the online survey data. It introduces the design and procedure of the online survey, followed by the statistical analyses performed to identify the factors influencing individuals' insurance purchase decisions and coverages. It also investigates the effects of insurance on community recovery, both quantitatively and qualitatively. In Sect. 3, the proposed framework is utilized to simulate the recovery process of the City of Dayton, Ohio, which was severely impacted by the May 2019 tornadoes, to address the research question. Finally, Sect. 4 provides a summary of the study's contributions and key findings.

2 Methodology

This paper proposes a two-stage simulation framework to quantitatively assess the effect of insurance on tornado-impacted community recovery. As presented in Fig. 1, the proposed framework is comprised of two interconnected stages, which are executed sequentially: Stage 1, the pre-tornado individual homeowners' decision model; and Stage 2, the post-tornado community-level recovery model. In Stage 1, individual homeowners decide on the purchase of insurance and determine the coverage limit based on a number of key independent variables. The key variables that influence these homeowners' decisions are identified statistically using online survey data. The insured states of individual residential buildings within a community, as determined in Stage 1,

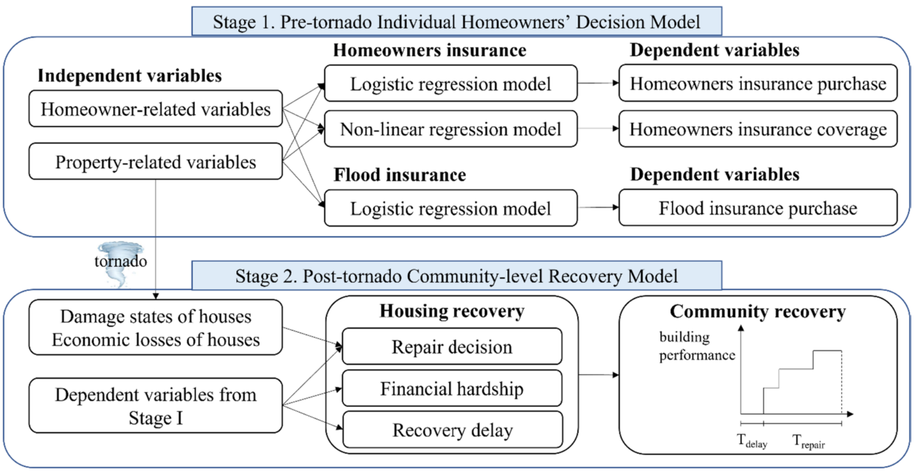

Fig. 1 A two-stage simulation framework for quantitatively assessing the impact of insurance on community recovery process

play a critical role in estimating the repair decisions of homeowners, the delay time of the housing recovery process, and the potential for financial hardship that homeowners experience in Stage 2. In Stage 2, following a tornado event, the damage state and associated economic losses of each building are evaluated through fragility and loss analyses. Subsequently, the total recovery time and process of each house are calculated using damage states, possible impeding factors, and the results from Stage 1. By aggregating the recovery states of individual houses at each time step, the time-varying recovery process of the entire residential community can be determined.

The simulation framework presented in Fig. 1 involves several empirical models that were developed based on statistical analyses of online survey data. These models include insurance demand models, as well as the empirical relationship between insurance and major recovery-related variables (i.e., repair decisions, delay time, and post-tornado financial hardship). This section illustrates a detailed explanation of the online survey design and data, the analysis procedure, and the empirical and statistical models that were developed as a result.

2.1 Online survey design and procedure

This study recruited residents in five communities that were severely affected by the May 2019 Tornado Outbreak—a series of destructive tornadoes that impacted a wide swath of the United States from May 17 to May 30, 2019. As shown in Fig. 2, the study sites include Jefferson City, Missouri (EF-3 tornado), Douglas and Leavenworth, Kansas (EF-4 tornado), and Dayton and Trotwood, Ohio (EF-4 tornado). The May 2019 Tornado Outbreak resulted in a total of $190 million in insured losses in Missouri (Missouri Department of Commerce and Insurance 2020) and the largest insured losses in state history in Ohio. Official data about insured losses in Kansas were not available.

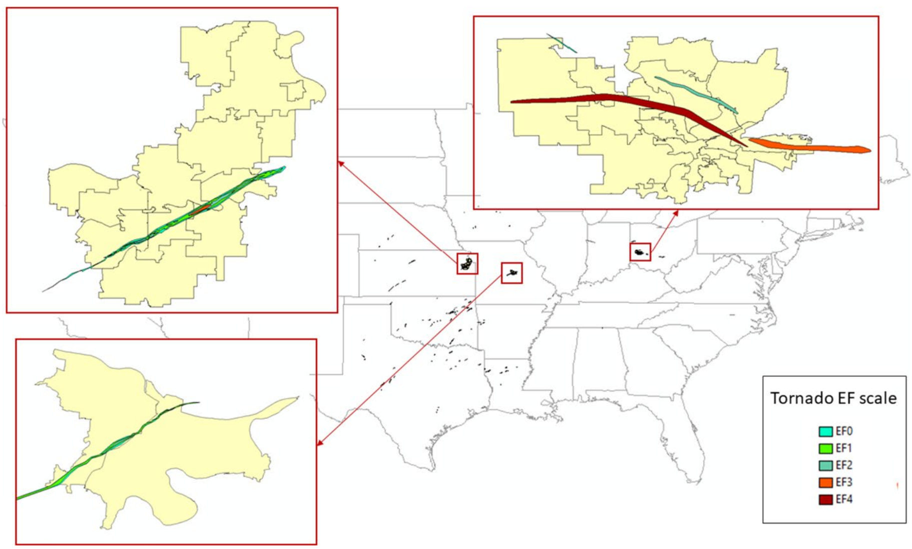

Fig. 2 Tracks and Enhanced Fujita (EF) scales of the May 2019 tornadoes in the study areas

Qualtrics professional panels recruited participants for two rounds of online surveys in May 2020 and February 2021, respectively. They primarily engage individuals registered with Qualtrics Panel, thus constituting online convenience sampling. However, despite using online convenience sampling, the samples collected by the Qualtrics professional panels can be representative of the population in terms of demographics, as evidenced by Boas et al. (2020). The inclusion criteria for participating in the survey were residents living in the study sites (i.e., one of the five communities) who were at least 18 years of age and whose houses sustained at least minor damage from the May 2019 tornadoes. A total of 133 participants responded to the survey, comprising 86 responses in the first round and 47 responses in the second round.

The first online survey consisted of both closed-ended qualitative and quantitative questions that covered a range of topics, including demographic information; property type; major construction material of the home; property and personal belonging values; mortgage/rental status; structural damage and economic losses caused by the May 2019 tornadoes; pre- and post-tornado financial status; homeowners and flood insurance coverages, deductibles, and premiums; time to receive insurance payment and government disaster assistance; repair decisions; and home recovery duration. The second online survey contained a series of open-ended questions about respondents' experiences during the insurance claim process and the building repair/reconstruction process, in addition to the questionnaires similar to the first online survey. These questions are categorized and presented in Appendix 1.

To participate in the survey, respondents were required to have their insurance policies they held in May 2019 accessible to answer questions related to the documents. Given the necessity for accurate reporting of insurance policy and property information, ensuring data quality through rigorous validation checks was important. To address these concerns, initially, the test–retest reliability was examined. We strategically included an identical set of questions in the survey randomly at different points in time and compared their responses to determine the degree of consistency or reliability in their answers. Following the collection of responses, additional layers of validation checks were implemented. These checks encompassed a comprehensive evaluation of various aspects, including but not limited to: (a) the mortgage amount should not exceed the property value; (b) the dwelling coverage limit should not exceed the property value; and (c) the premium and deductible should be within a reasonable range given the dwelling and content coverage limits. Out of the 133 responses received, 33 were considered invalid as they failed to meet one or more of these validation checks. Although implementing validation checks helps ensure data quality and reliability to a certain degree, conducting an in-person experiment would be preferable. This approach would allow participants to receive additional information and clarification throughout the experiment, thereby potentially improving the accuracy and completeness of their responses.

The 100 valid responses were collected from five distinct communities spanning three different states, as shown in Fig. 2. It was because of the spatial compactness of tornadoes, resulting in a limited number of affected houses. However, different states may offer varying contexts for homeowners' decisions on insurance and distinct experiences with past tornado events. Thus, ensuring that there were no significant differences between the samples from each state was crucial. Several factors affecting homeowners' decisions on insurance purchase were examined, including (a) site-specific tornado hazards, (b) available homeowners insurance policies, and (c) the affordability of insurance. First, as these three states are situated in Tornado Alley characterized by a high annual frequency of tornadoes (Dixon et al. 2011), homeowners in these areas are presumed to face similar tornado hazards. Second, while homeowner insurance policies may vary by state, the standard policies in Missouri, Kansas, and Ohio share substantial coverage similarities (Kansas Insurance Department 2023; ODI 2019; Missouri DCI 2024): more specifically, home insurance is not legally required in these three states, except for mortgage purposes; homeowners insurance in these states typically covers windstorm and hail damage caused by tornadoes and hurricanes; and standard home insurance does not cover damage from flooding. Third, the average homeowners insurance premiums were compared with the median household incomes in 2019 among these three states, reflecting the affordability of insurance. The slight differences in the Insurance Premiums-to-Income ratio for Missouri, Kansas, and Ohio (2.26%, 2.73%, and 1.46%, respectively) were observed but could be negligible when considering these factors collectively (United States Census Bureau 2019; RMIIA 2019). Examining these three factors supported our assumption that there were no significant differences between the samples from each state. To further justify this assumption, we performed a set of chi-square tests to compare the distributions of decision variables between the states and found that there were no statistically significant differences.

During the May 2019 Tornado Outbreak, approximately 1000 houses suffered damage at the study sites. The minimum required sample size for a population of around 1000 was determined to be 97 based on a desired confidence interval of 95% and a margin of error of 10%. Thus, for practical purposes, our sample size of 100 would provide a reasonable level of accuracy in estimating population parameters with the desired level of confidence. In the final sample of 100 participants, 60% of the respondents were female, and 40% of the respondents were male. At the time of the tornadoes, the majority of the respondents (75%) had homeowners insurance, while only 29% of the total respondents had flood insurance. Through a comparison of sample demographics with those of the respective communities, we determined that the sample reflected population characteristics well, thus negating the need for sample weighting.

2.2 Survey data analyses

This study places emphasis on the behavior of "homeowners" as they possess greater power and control over the repair of their damaged homes, as compared to renters who often face difficulties in initiating repairs due to lease agreements and property ownership issues. This study specifically seeks to understand the decision-making processes of homeowners with regard to insurance and the extent to which this decision affects the overall housing and community recovery in the aftermath of a tornado event. Given the distinct characteristics of homeowners insurance and flood insurance, they may have varying effects on communities impacted by tornadoes. Therefore, the quantitative analyses in this study consider these two types of insurance separately to better understand their respective effects.

To determine the factors that affect homeowners' decisions regarding insurance purchases, a logistic regression analysis was first conducted using survey data. The independent variables used in estimating the regression models are summarized in Appendix 2 Homeowners had already made a decision on whether or not to purchase insurance before their properties were damaged. This decision variable was binary, with the values of 1 indicating purchasing insurance and 0 indicating not purchasing insurance. The probability (p) of purchasing insurance was determined by the logistic regression equation:

$$p = \frac{e\beta X}{1 + e\beta X} \tag{1}$$

in which β = the vector of coefficients for independent variables; and X = the vector of independent variables. A backward stepwise regression approach was used to estimate the regression model (Lee et al. 2022; Lee and Ma 2023). At the initial step of the process, all independent variables were included in the analysis. Subsequently, the least statistically significant variables were eliminated in a stepwise manner using the Wald Chi-Square test with a predetermined significance level of 5%.

This study also investigated an insurance demand model focusing on the coverage limit of homeowners insurance. To account for the nonlinear and complex relationship between variables, this study employed a two-step approach. The first step involved a simple linear regression analysis to identify the most significant factors that affected a decision on the coverage limit. In the second step, polynomial features were gradually introduced to capture more complex patterns in the data and improve its predictive power until the R-squared value reached a stable level. All independent variables listed in Appendix 2 were utilized in the analysis, where the dependent variable was defined as the dwelling coverage ratio (i.e., the ratio of coverage to property values, which is generally between 0 and 1).

The effect of insurance on housing/community recovery following tornado events was quantitatively assessed using three variables, including (a) the repair decisions of homeowners, (b) post-tornado financial hardship, and (c) the delay time of the housing recovery process. More specifically, the repair decisions of homeowners were modeled as a binary decision variable indicating whether to repair their damaged houses or not because it could simplify the modeling process and make it easier to communicate findings to stakeholders. This paper assessed the individual effects of homeowners insurance and flood insurance on the community recovery process following the May 2019 tornadoes. To evaluate if sufficiently insured houses have a positive impact on community recovery (i.e., the main research question of this study), the participants who provided valid responses were divided into three groups: uninsured (Group A), underinsured (Group B), and fully insured (Group C). Respondents who purchased insurance coverage at least 80% of their replacement cost values were assumed to be fully insured and assigned to Group C. It was based on the 80% rule for homeowners insurance that insurers would reimburse the expenses for damage to a house or property if the homeowner has obtained insurance coverage equivalent to at least 80% of the total replacement value of the house. Homeowners who had insurance but whose coverage was less than 80% of the replacement cost value were categorized as Group B. Among the 100 valid responses, 16.67%, 47.62%, and 35.71% of respondents belonged to Groups A, B, and C, respectively. These numbers were consistent with the findings that "about 64 percent of homeowners don't have enough insurance" (CoreLogic 2022). A two-proportion Z-test was used to evaluate the significance of the differences in proportions between the groups. For example, the proportion of uninsured homeowners who experienced post-tornado financial hardship was compared to the proportion of fully insured homeowners experiencing post-tornado financial hardship in order to assess the effect of insurance (especially full coverage insurance) on financial stability. Similar tests were conducted for different combinations among the three groups, as well as for housing repair decisions. The Kruskal–Wallis H test was used to assess the effect of insurance coverage on the delay time to initiate the housing recovery process, as it is a non-parametric test that relaxes the assumption of normality in the Analysis of Variance (ANOVA).

Table 1 Logistic regression results of individual's decision about purchasing homeowner insurance (95% confidence interval)

Variable	Estimated coefficient	Wald chi-square	*p*-value
Intercept	− 1.2628	− 2.4520	0.0142
Household income	0.4040	2.7949	0.0052
Mortgage conditions	1.3195	2.4976	0.0125

Table 2 Logistic regression results of individual's decisions about purchasing flood insurance (95% confidence interval)

Variable	Estimated coefficient	Wald chi-square	*p*-value
Intercept	− 3.3330	− 3.6563	0.0003
Construction year	0.3964	2.7014	0.0069
Building material	− 1.3080	− 2.2243	0.0261
Personal belonging value	0.5940	2.3256	0.0200

2.3 Statistical analysis results and discussions

2.3.1 Homeowners' decisions on insurance

In this subsection, a set of statistical models is proposed based on the survey data that can be used to simulate homeowners' decisions on insurance. Table 1 presents the key independent variables that influenced a decision about purchasing homeowners insurance. Two key independent variables identified through the backward stepwise regression approach were household income and mortgage conditions. As per regulations in the United States, mortgage holders are required to have homeowners insurance, hence a positive coefficient for the mortgage conditions was well supported. A similar finding was observed by Lee et al. (2022). Table 2 summarizes the logistic regression results for the decision of homeowners regarding purchasing flood insurance. The significant independent variables included in the model were the construction year of the property, the building material used, and the value of personal belonging. Since flood insurance mostly covers damage to personal belongings due to water-related damage, a positive coefficient for the value of personal belongings was well explained. The results indicated a positive coefficient value for the construction year, implying that individuals owning the recently constructed properties were more likely to purchase flood insurance. One possible explanation for the positive coefficient is that newer properties may have higher property values, which would make the cost of repairing or rebuilding the property after a flood more expensive. In this case, homeowners who own newer properties may be more likely to purchase flood insurance to protect their investments. Conversely, a negative coefficient value was observed for the building materials, indicating that homeowners with non-timber constructed properties were more likely to purchase flood insurance. It may be because non-timber constructed properties may be more expensive to repair or replace in the event of a flood. Another possible explanation could be that non-timber constructed properties are prevalent in flood-prone areas, where flood insurance is either required or strongly recommended. However, it is important to note that these are merely possible explanations and there could be other factors to play (such as statistical noise or random variation). Moreover, no statistical relationship was found between homeowners' decisions to purchase homeowners insurance and flood insurance. One plausible explanation for this finding is that the motivations for purchasing these two types of insurance are different. Homeowners insurance is typically required for homeowners with mortgages, whereas homeowners often purchase flood insurance voluntarily to safeguard against flood damage.

In Sect. 1, the significance of coverage limits in the housing recovery process, particularly for homeowners insurance, was highlighted. Therefore, this study examined the key variables that impacted an individual's decision regarding homeowners insurance coverage. All independent variables listed in Appendix 2 were initially considered, and utilized in the analysis, and a backward stepwise regression approach was used to gradually remove the least statistically significant variables. Table 3 presents the most significant factors that influenced a homeowner's choice of dwelling coverage ratio (i.e., the ratio of dwelling coverage limit to property value, which is between 0 and 1). The findings revealed that the construction year and household income were the most statistically significant factors in determining the dwelling coverage ratio. However, the estimation had an 85% confidence level and an R-squared value of 0.1, which indicated that the linear regression model was unable to capture non-linear relationships. To improve the predictive power of the model, polynomial features were progressively introduced by adding high-order terms, with the R-squared value improvement being evaluated at each step. The process continued until the increment in the R-squared value became significantly smaller than that achieved in the previous step. Finally, the polynomial features of degree 6 were selected as the prediction model for the coverage ratio to strike a balance between capturing the nonlinear relationships in the data and avoiding overfitting, which can occur when using too many polynomial features.

The six-degree polynomial function that can be utilized to predict the dwelling coverage ratio (γ) is shown below:

$$\begin{aligned}\gamma = {} & 2.58554 * 10^{-7} + 337.2023x_0 + 43.4240x_1 - 196.7021x_0^2 - 95.3419x_0x_1 \\ & + 10.6692x_1^2 + 46.6021x_0^3 + 63.0114x_0^2x_1 - 4.3636x_0x_1^2 - 4.9759x_1^3 - 3.8950x_0^4 \\ & - 16.1415x_0^3x_1 - 2.2099x_0^2x_1^2 + 2.7090x_0x_1^3 + 0.8603x_1^4 - 0.1009x_0^5 + 1.6947x_0^4x_1 \\ & + 0.9289x_0^3x_1^2 - 0.5177x_0^2x_1^3 - 0.1641x_0x_1^4 - 0.0893x_1^5 + 0.0217x_0^6 - 0.0587x_0^5x_1 \\ & - 0.0768x_0^4x_1^2 + 0.0225x_0^3x_1^3 + 0.0194x_0^2x_1^4 + 0.0027x_0x_1^5 + 0.0040x_1^6\end{aligned} \tag{2}$$

where x_0 = the construction year; and x_1 = the household income. The R-squared value of this model was 0.673, implying that homeowners' decisions regarding coverage limits were complex and hardly predictable. Its complexity and relatively low R-squared value suggest that the proposed six-degree polynomial function may not be suitable for practical use. Rather, this model serves as a demonstration of the potential factors that may

Table 3 Linear regression results of homeowner's decision about dwelling coverage ratio (85% confidence interval)

Variable	Estimated coefficient	t-value	*p*-value
Intercept	0.6851	5.395	< 0.001
Construction year	0.0500	2.040	0.047
Household income	– 0.0398	– 1.560	0.125

be statistically significant in modeling this choice. More data collection and analysis are needed to develop a more accurate and practical model for predicting homeowners' choice of dwelling coverage ratio.

2.3.2 Effect of insurance on community recovery

Repair decisions of homeowners The effects of homeowners insurance on the repair decisions of three respondent groups are presented in Fig. 3a. As expected, uninsured homeowners were the least likely to repair their damaged homes mainly due to a lack of funds, while higher levels of insurance coverage enabled more homeowners to repair homes. However, based on the two-proportion Z-test results, at the 10% level of significance, there was not sufficient evidence to conclude that the proportion of uninsured homeowners who repaired their houses (Group A) was significantly less than the proportion of underinsured or fully insured homeowners who did the same. This might be explained by the fact that after dividing the collected valid responses into three groups, the sample size of each group became too small to detect a significant statistical difference between the proportions.

Since a regression model for flood insurance coverage was not developed due to the insufficient number of survey respondents who purchased flood insurance (only 29%), the participants who provided valid responses were divided into only two groups: uninsured (Group A) and insured (Groups B&C) homeowners. In contrast to the finding that only 16.67% of respondents did not purchase homeowners insurance, a significant portion of respondents appeared to lack awareness regarding the necessity of obtaining flood insurance. This could be primarily attributed to the mandatory requirement of homeowners insurance for mortgaged houses, whereas flood insurance remains an optimal purchase. Figure 3b suggests that the insured group had a lower proportion of repair decisions than the uninsured group, which was contrary to the expectation that insured homeowners are more likely to repair their tornado-damaged homes (as shown in Fig. 3a). One possible explanation could be the limited sample size for the flood insurance case. Another potential factor is the nature of flood insurance coverage. Following tornadoes, flood insurance policies typically cover damage to personal belongings due to water-related damage rather than structural damage to homes, which is mostly caused by high winds. Therefore, the presence of flood insurance may not have a significant impact on the home repair decisions of homeowners who have experienced tornado damage. In conclusion, homeowners insurance may be a more relevant factor to consider in predicting the repair decisions of homeowners

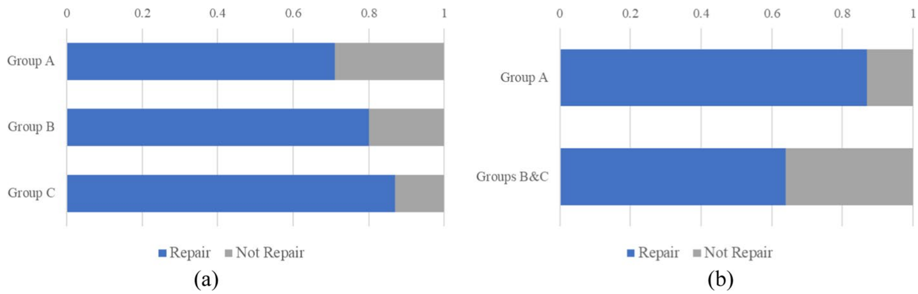

Fig. 3 Effects of insurance on the repair decisions of homeowners: **a** homeowners insurance and **b** flood insurance

following tornadoes. In Sect. 3, homeowners insurance states will be used as input in the simulation models.

Post-tornado financial hardship The effects of homeowners and flood insurance on post-tornado financial hardship were assessed by asking about the levels and types of financial hardships respondents experienced due to tornado-induced damage, including falling into mortgage default or forbearance, being forced to sell properties, or incurring large amounts of loan or debt. Figure 4a presents a comparison of financial hardship experienced by three groups with varying levels of coverage for homeowners insurance. As shown in Fig. 4a, the majority of fully insured homeowners (69%) indicated that they did not have any financial hardship after the May 2019 tornadoes because most of the house repair or reconstruction costs were covered by insurance claim payments. The proportions of Groups A and B homeowners who experienced financial hardship are also summarized in Fig. 4a. As expected, uninsured homeowners were more likely to experience post-tornado financial hardship compared to their insured counterparts. Similar to the repair decisions, however, differences in the proportions of homeowners who experienced financial hardship were not statistically supported by the two-proportion Z-tests because of small sample sizes. While increasing sample size could potentially resolve this issue in future research, large sample size can be difficult to achieve because tornado touchdowns are geographically small and limit the number of houses damaged.

Figure 4b illustrates a comparison of the financial hardship experienced by the respondents who didn't have flood insurance (Group A) and had flood insurance (Groups B&C). The proportion of insured homeowners who faced financial hardship after the May 2019 tornadoes was much higher than the proportion of uninsured homeowners. This observation was consistent with the findings in Fig. 3b. Similar to Fig. 3b, this unexpected result could be attributed to the small number of respondents who had flood insurance at the time of the May 2019 tornadoes (only 29%), which may have limited the ability to directly capture the relationship between flood insurance and financial hardship. Moreover, this result may suggest that the May 2019 tornadoes did not cause significant flood damage, and the presence of flood insurance did not have a significant impact on the repair decisions or financial hardship experienced by homeowners. Instead, homeowners insurance may have played a much more significant role in determining post-tornado repair decisions and associated financial hardship. However, it should be noted that this conclusion cannot be generalized to all tornadoes as they can sometimes result in significant flood damage.

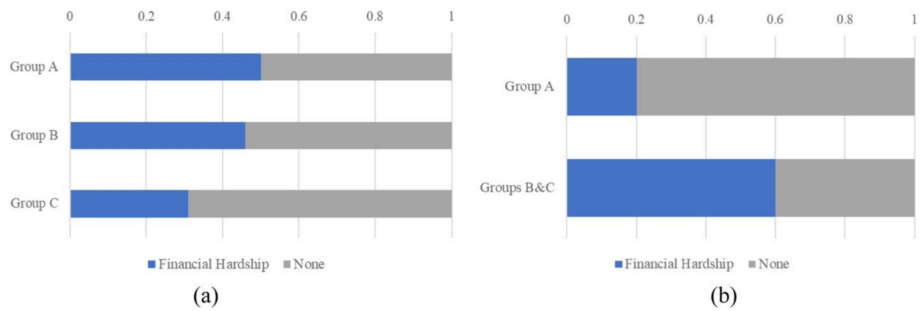

Fig. 4 Effects of insurance on post-tornado financial hardship: **a** homeowners insurance and **b** flood insurance

The delay time associated with the housing recovery process The survey question asked participants about the delay time, which was defined as the time between the date when their houses were damaged by the May 2019 tornadoes and the initiation of repair or reconstruction. Delay time could have been induced by a variety of factors, including post-tornado inspection; engineering mobilization and review/redesign; financing; contractor mobilization and bid process; and permitting (Almufti and Willford 2013; Zhao et al. 2020). By assuming that all these factors except financing had the same statistical properties (e.g., mean and standard deviation) for the three groups, the differences in the recovery delay between groups could be explained solely by financing delay. The mean delay times were 194 days, 144 days, and 113 days for uninsured, underinsured, and fully insured homeowners, respectively. This was consistent with our expectation that homeowners with sufficient insurance coverage might receive timely claim payments from insurance companies that could cover most of the repair cost and ultimately speed up the housing recovery processes. A set of Kruskal–Wallis H tests were also performed to determine if there were statistically significant differences between the three groups in the recovery delay time. Table 4 summarizes the test results for various combinations. At the 10% level of significance, there was a significant difference between uninsured and fully insured homeowners. Similarly, the *p*-value (0.0927) indicated that, at the 10% level of significance, the median delay times for uninsured homeowners were different from insured homeowners. A Kruskal–Wallis H test was also performed to compare the recovery delay time between the insured and uninsured groups in flood insurance, as only these two groups were included in the analysis. However, similar to Figs. 3b and 4b, the limited sample size prevented the identification of statistically significant differences between these two groups.

2.3.3 In-depth analysis results and discussions

A large portion of respondents indicated that they benefited from insurance during the recovery process after the May 2019 tornadoes, as a result of the prompt and adequate payments. However, some respondents provided negative feedback regarding insurance policies, mainly focusing on unaffordable premiums, high levels of deductible, or unforeseeable payment delays. Despite these negative responses, 61% of respondents expressed their willingness to purchase insurance in the future to protect their properties against tornadoes, highlighting the efficiency of insurance in post-tornado recovery processes. Effective government policies and economic incentives can play a significant role in further encouraging individuals to purchase insurance and reducing the excessive financial burden caused by tornadoes. Such incentives can eventually enhance the community recovery process and resilience.

Table 4 Comparison of the housing recovery delay among three groups

Comparison	Null hypothesis	Alternative hypothesis	*p*-value (homeowners insurance)	*p*-value (flood insurance)
Group A vs. Group B	$m_A = m_B$	$m_A \neq m_B$	0.234	NA
Group A vs. Group C	$m_A = m_C$	$m_A \neq m_C$	0.070	NA
Group B vs. Group C	$m_B = m_C$	$m_B \neq m_C$	0.391	NA
Group A vs. Groups B&C	$m_A = m_{B+C}$	$m_A \neq m_{B+C}$	0.093	0.265

During the online survey, respondents identified various financial sources that were utilized to fund the repair or reconstruction of their damaged houses. These included insurance, savings, retirement accounts, inheritances, assistance or loans from nonprofit or government agencies, a second loan, home equity loan, gift from family or friends, proceeds from the sale of another property, etc. About 46.4% of the respondents considered insurance as the most helpful source among these financial sources. Many individuals found that their savings, retirement accounts, inheritances, or other assets were the most useful funds to implement restorative activities. Moreover, the majority of individuals received financial aid from the federal or local government following the May 2019 tornadoes. While the financial aid provided by the government to homeowners following a disaster can be beneficial during the post-disaster recovery processes, it may also discourage individuals from purchasing insurance, as they may feel that they can rely on government aid in the event of a disaster. Therefore, it is important to consider the balance between government assistance and insurance purchases when developing effective policies to facilitate community recovery following tornado events. Encouraging individuals to purchase insurance through economic incentives and education may reduce the excessive financial burdens caused by hazard events, while also promoting self-reliance and decreasing reliance on government aid.

3 An illustrative example: simulating the proposed framework in the city of Dayton, Ohio following the May 2019 tornadoes

3.1 Simulation procedure

To test if sufficiently insured houses can have a positive impact on the recovery of tornado-impacted communities, this section applies the proposed simulation framework to the City of Dayton, Ohio following multiple tornado events in May 2019. The City of Dayton, Ohio was chosen for the case study site because the majority of survey respondents were located in this area, and one of the two EF4 tornadoes occurred in Dayton during the May 2019 Tornado Outbreak. The case study community is illustrated in Fig. 5, which presents the tornado-impacted areas in Dayton, Ohio. The total number of residential buildings in those areas is 1835 (OSM Building 2021). The study focused on residential buildings, and the simulation considered only the damage and associated restorations for these buildings caused by wind loads, while content damage due to rain entering the building was not considered. As indicated in Sect. 2.3.2, homeowners insurance is likely to be a more pertinent factor in predicting the repair decisions of homeowners following tornadoes. Therefore, in this section, the simulation models incorporated only the homeowners insurance states as input variables.

As shown in Fig. 1, the simulation process was comprised of two stages. The first stage aimed to estimate the decisions of individuals on homeowners insurance purchase and dwelling coverage limit. Statistical properties of the independent variables of these two models were obtained from HAZUS-MH (FEMA 2009) and Census data. As both HAZUS-MH and Census provided aggregated data on these variables at the census level, Monte Carlo simulation was utilized in this study to assign building and demographic parameters to individual houses and homeowners/households. Then, the input variables were employed in the logistic regression models for homeowners insurance purchase (as presented in Table 1) and in the regression model for dwelling coverage ratio (Eq. 2).

In the second stage, the tornado events that occurred on May 28th, 2019 in the City of Dayton were simulated in this study, as depicted in Fig. 5. To determine the hazard intensities,

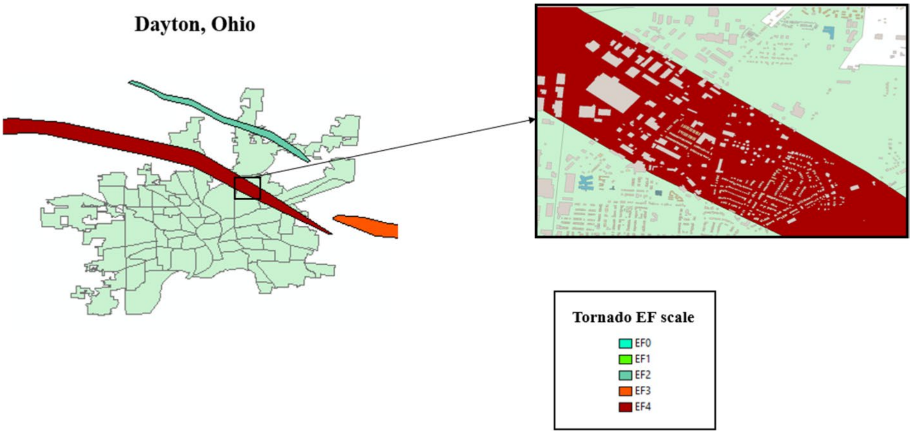

Fig. 5 The May 2019 tornadoes in the case study region: the City of Dayton, Ohio

Table 5 Wind speeds in the EF scale (adapted from WSEC 2006)

EF scale	Weed speeds (mph)
0	65–85
1	86–110
2	111–135
3	136–165
4	166–200
5	Over 200

Table 5 was used to establish the relationship between EF scales and wind speeds (WSEC 2006), and the median value of wind speed at each EF scale was considered. To estimate community recovery processes following the tornado events, the assessment of damage state probability for each residential building and the subsequent estimation of its damage state were key steps. These steps were achieved through a combination of the tornado wind intensity (i.e., wind speed) and the fragility function of the buildings, which was assumed to follow a lognormal distribution with parameters depending on building type and damage state. The tornado fragility function was obtained from Masoomi et al. (2018). In this study, damage states were classified into five categories ranging from no damage to destruction, and five residential building types were considered in the simulation. Monto Carlo simulation was then utilized to estimate the damage state of each residential building following the tornado events and the corresponding economic losses (Koliou and van de Lindt 2020). The economic losses sustained by each residential building were partially or fully covered depending on the homeowners insurance coverage limit predicted in the first stage of the simulation model.

The repair decisions of homeowners were estimated based on the results from the first stage, which was insurance status. The empirical relationships, shown in Fig. 3, were used to estimate these repair decisions of homeowners whose houses were damaged by the tornado events. For the homeowners who opted to repair their houses, the total recovery time ($T_{recovery}$) was calculated by summing the delay time (T_{delay}) and the repair time (T_{repair}). The delay time (T_{delay}) represents the delay in restorative activities of damaged buildings following the tornado events due to several impeding factors (Almufti and Willford 2013), which typically include post-disaster inspection ($T_{inspection}$), engineering mobilization and review/re-design ($T_{engineering}$), financing ($T_{financing}$), contractor mobilization and bid process ($T_{mobilization}$), and permitting ($T_{permitting}$). A detailed description of each impeding factor can be found in Almufti and Willford (2013). Due to a lack of empirical data on these factors in the context of tornadoes, it was assumed that each impeding factor followed a lognormal distribution, with the median and coefficient of variation (COV) values recommended in the REDi™ framework (Almufti and Willford 2013). However, financing delays due to insurance payments and government assistance were specifically modeled based on the survey data. According to the online survey, the mean delay times associated with homeowners insurance payment and government assistance were 4.58 and 5.12 months, respectively. There were three delay sequences of a damaged building due to these impeding factors, and the longest one governed the total delay time, which can be expressed using the following equations (Zhao et al. 2020):

$$T_{delay} = \max\left(T_{delay,i}\right), \quad i = 1, 2, 3 \tag{3}$$

$$T_{delay,1} = T_{inspection} + T_{financing} \tag{4}$$

$$T_{delay,2} = T_{inspection} + T_{engineering} + T_{permitting} \tag{5}$$

$$T_{delay,3} = T_{inspection} + T_{mobilization} \tag{6}$$

The repair time (T_{repair}) for a damaged building was dependent on its building type and damage state, which was obtained from Koliou and van de Lindt (2020). The model proposed by Zhao et al. (2020) was utilized to estimate the households that were at risk of insolvency or experienced financial instability. By repeating this procedure for every damaged house, a collection of total recovery curves for all damaged properties within the community was obtained. Finally, the post-tornado recovery of the community was assessed by aggregating the recovery states of individual houses at each time step. Here, the full recovery of the community was defined as the condition wherein all houses chosen for repair by homeowners have indeed been restored.

3.2 Simulation results

In the first stage of the simulation framework, the homeowner insurance states and dwelling coverage limits selected by individual homeowners in the study region were simulated. The outcomes of this stage revealed that 24.0%, 64.7%, and 11.3% of the properties were uninsured (Group A), underinsured (Group B), and fully insured (Group C), respectively. The estimated proportion of the population who purchased homeowners insurance (i.e., 76%, which is the sum of Groups B and C) aligned closely with the result obtained from the online survey (75%). This consistency suggests that the logistic regression and linear regression models derived from the online survey captured the underlying patterns and factors driving insurance purchase decisions appropriately. After simulating the tornado events, it was found that 34.3% of the residential buildings remained undamaged after the tornado events. Meanwhile, 38.7% (710 buildings), 15.2% (279 buildings), 5.3% (98 buildings), and 1.5% (28 buildings) of the residential buildings located in the tornado-impacted

Table 6 Comparison of repair decisions among three groups: simulation results

Insured status	Repair decision	Group A	Group B	Group C
Homeowners insurance	Repair	0.67	0.80	0.83
	Not repair	0.33	0.20	0.17

Table 7 Comparison of financial hardship among three groups: simulation results

Insured status	Financial hardship	Group A	Group B	Group C
Homeowners insurance	Hardship	0.55	0.41	0.00
	None	0.45	0.59	1.00

areas were categorized into the damage states of *DS1*, *DS2*, *DS3*, and *DS4*, respectively. It should be noted that the simulation results exhibited a slight deviation from the actual number of damaged houses that occurred after the May 28th, 2019 tornadoes in the City of Dayton, Ohio. Although precise figures for the number of homes categorized in minor and moderate damage states were unavailable, the data revealed that 95 buildings experienced severe damage, and 39 houses were completely destroyed (Government Technology 2021). This deviation was mainly due to uncertainties in property-related parameters and fragility analysis. Nonetheless, the results are still considered reasonable.

The repair decisions of the homeowners whose houses were damaged by the tornadoes were simulated by using the empirical relationship determined based on the survey data (see Fig. 3a). Table 6 presents the simulation results regarding the repair decisions made by homeowners in three distinct groups, which were categorized based on their insured status. Similar to the survey data depicted in Fig. 3a, the simulation results also showed that insured homeowners (Groups B and C) were more likely to repair their damaged houses compared to uninsured homeowners (Group A). A two-proportion Z-test was performed to compare the repair decisions between uninsured individuals (Group A) and insured individuals (Groups B&C). The p-value obtained from the test was found to be less than 0.05, which indicates statistical significance at the 5% level of significance. In other words, based on the simulation results, the hypothesis that the impact of homeowners insurance on repair decisions was significant was accepted. This finding can provide an answer to the main research question of the study, which is whether having a sufficient number of insured houses can positively affect community recovery.

The financial hardship experienced by homeowners in the aftermath of tornadoes was also simulated. According to Zhao et al. (2020), in cases where the financial burden of repair or reconstruction costs exceeds the wealth possessed by homeowners, it is assumed that they may be at risk of insolvency or be likely to experience financial instability. Based on this assumption and the model described by Zhao et al. (2020), the number of homeowners having post-tornado financial hardship in this community was simulated and presented in Table 7. Similar to the data collected through the online surveys (depicted in Fig. 4a), it was evident that homeowners who had comprehensive insurance coverage (Group C) were less likely to face financial hardship. While the proportions of financial hardship in Groups A and B aligned closely between the simulation results and the actual data collected, an extreme scenario emerged in the simulated result of Group C, where none of the homeowners in Group C experienced financial hardship. This anomaly might stem from the underlying assumption that insurance coverage could fully address all economic losses incurred as a result of tornado-induced

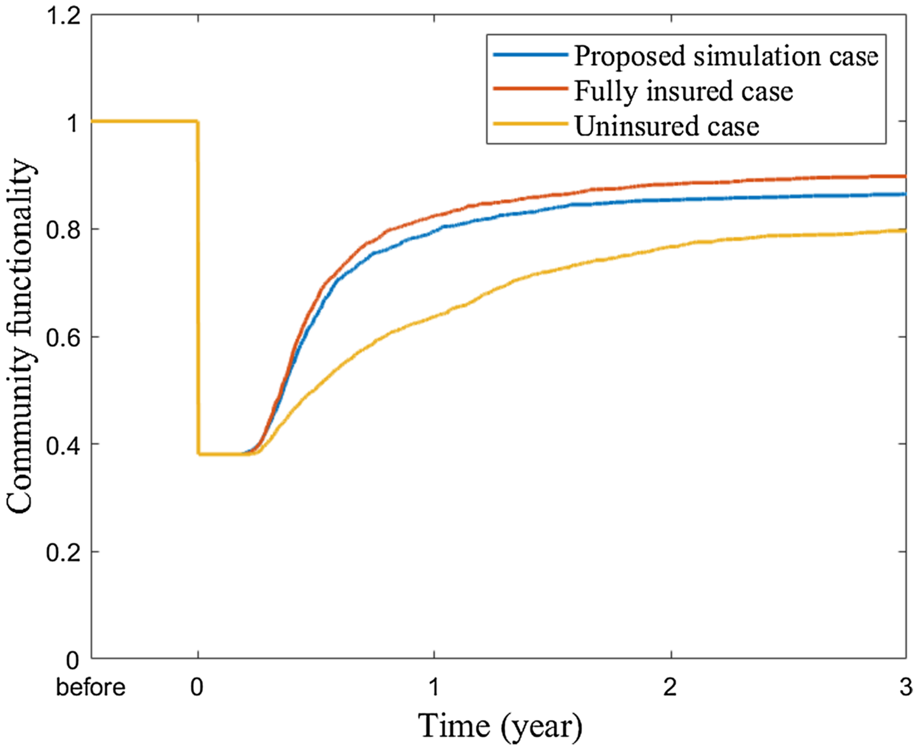

Fig. 6 Comparison of community recovery curves for three different cases under different insurance take-up rates

damage. However, the reality deviates from this assumption, as even homeowners with full insurance coverage are confronted with additional financial obligations, such as deductibles and removal fees. This reality was reflected in the survey data, wherein 31% of the homeowners with full insurance coverage were shown to experience financial hardship.

To confirm the statistical significance of the difference, a two-proportion Z-test was conducted to compare the proportions of financial hardship between uninsured individuals (Group A) and insured individuals (Groups B&C). The resulting p-value from the test was found to be 0.0035, which was less than the standard significance level of 0.05, indicating that this difference was statistically significant. In other words, the test result supported the main hypothesis that sufficiently insured houses have a positive impact on community recovery (i.e., a smaller number of homeowners experiencing financial hardship in this case).

To test the hypothesis that homeowners insurance affects housing recovery time, a Kruskal–Wallis H test was conducted. The results showed significant differences between the uninsured group (Group A) and insured groups (Groups B and C) for homeowners insurance, with a 10% level of significance. This result indicated that homeowners insurance was effective in reducing the delay time and expediting the recovery process. The research question of whether having a sufficient number of insured houses can positively affect community recovery was answered affirmatively by this result.

The blue line in Fig. 6 illustrates the post-tornado community recovery curve obtained from the proposed simulation framework. Based on the simulation results, the community did not achieve the pre-tornado performance level even after reaching full recovery due to 13.5% of the homeowners opting not to repair their damaged houses. To further investigate the impact of insurance on community recovery (i.e., the research question of this study), two additional cases were analyzed: the community was simulated under the scenario that all houses were insured and under the scenario that no houses were insured. The corresponding results are displayed as the red and yellow lines, respectively, in Fig. 6. The percentage of homeowners who decided not to repair their houses under the “fully insured case” was 10.3%, whereas under the “uninsured case”, it was 20.4%. Similar to the hypothesis test result results, the phenomenon observed in Fig. 6 underscores the significance of homeowners insurance in fostering post-disaster repair efforts and emphasizes the potential for bolstering overall community resilience by increasing the number of homeowners with insurance.

4 Summary and conclusions

This paper aimed to determine whether sufficiently insured houses have a positive impact on the recovery of a tornado-impacted community. A simulation framework was proposed to address this research question. The framework was composed of two stages: the first stage estimated individual decisions on insurance prior to a tornado event, while the second stage investigated the effects of insurance on repair decisions made by homeowners, the delay time associated with the housing recovery process, and the level of financial hardship experienced by individuals after the tornado event. To construct these insurance-related models, data were collected from two rounds of online surveys targeting residents whose properties were damaged by the tornadoes that occurred in May 2019 in the United States. Then, the simulation framework was applied to the City of Dayton, Ohio to address the research question. The quantitative results of the simulation concluded that sufficiently insured houses could have a positive impact on community recovery.

The practical applications of this study are multifaceted. First, the study can provide valuable insights for homeowners on the importance of having adequate insurance coverage to facilitate the repair process, reduce financial hardship, and shorten the delay time associated with the recovery process following a tornado event. The study can also be useful for policymakers and disaster management agencies to improve pre- and post-tornado planning and resource allocation, by highlighting the need for effective policies and economic incentives to encourage individuals to purchase insurance. Finally, the study can aid in developing community resilience strategies to mitigate the adverse impacts of future tornado events by achieving faster recovery.

Appendix 1: Categories and questions included in the online surveys

Questionnaires	Categories	Questions
Closed-ended	Homeowner characteristics	Location (Zip code)
		Age (years)
		Gender
		Education
		Employment
		Ethnicity

Questionnaires	Categories	Questions
	House condition at the time of the 2019 May tornado	Construction year
		Construction material
		Property type and ownership
		Personal belonging value
		Property value
		Property mortgage status and balance
	Homeowners insurance information at the time of the 2019 May tornado	Homeowners insurance purchase
		Dwelling coverage limit
		Dwelling deductible
		Annual insurance premium
		Additional Living Expenses (ALE) coverage
		Insurance claim application
		Total claim payment
		Percentage of reconstruction cost covered by insurance
		Time to receive an insurance claim payment
	Flood insurance information at the time of the 2019 May tornado	Flood insurance purchase
		Flood insurance type
		Content coverage limit
		Content deductible
		Annual insurance premium
		Insurance claim application
		Total claim payment
		Percentage of reconstruction cost covered by insurance
		Time to receive insurance claim payment
	Reconstruction following the 2019 May tornado	House damaged by windstorm due to the 2019 May tornado
		House damaged by rainwater due to the 2019 May tornado
		Repair actions
		Date of initial recovery
		Date of completed recovery
		Total wealth prior to the 2019 May tornado
		Total wealth following the 2019 May tornado
		Total combined economic losses resulting from the 2019 May tornado
		Financial aid from the federal or local government
		Time to receive government financial aid claim payment
		Financial hardship type due to 2019 May tornado

Questionnaires	Categories	Questions
Open-ended	Insurance-related experience	Reason for purchasing insurance or not
		Insurance claim experience
		Pros and cons of your insurance policy
		Willingness to purchase the insurance in the future
	Financial condition and aid	Other sources of funds to reconstruct property resulting from the 2019 May tornado
		Most helpful sources of funds to reconstruct property resulting from the 2019 May tornado
		Experience during structural (building) damage repair/reconstruction process

Appendix 2: Independent variables for regression models

Variables	Options
Location (Zip code)	Hazard-prone area
	Non-hazard-prone area
Age (years)	18–29
	30–39
	40–49
	50–59
	60–69
Gender	Male
	Female
Education	High school degree
	Some college but no degree
	Associate degree
	Bachelor's degree
	Master's degree
	PhD degree
Employment	Employed, working 1–39 h per week
	Employed, working 40 or more hours per week
	Not employed
Ethnicity	Caucasian
	Latino or Hispanic
	Asian
	African-American
	Native American
House constructed year	Before 1970
	1970–1979
	1980–1989
	1990–1999

Variables	Options
	2000–2007
	2008–2013
	2014–2019
	Do not know
House construction material	Wood
	Concrete
	Steel
	Other
	Do not know
Property type and ownership	House or condominium rented
	House or condominium owned or being bought by you or someone in your household
	Apartment
	Mobile or manufactured home owned or being bought by you or someone in your household
Personal belonging value	< $1000
	$1000–$4999
	$5000–$9999
	$10,000–$49,999
	$50,000–$99,999
	$100,000–$199,999
	$200,000–$299,999
	$300,000–$399,999
	$400,000–$499,999
	$500,000–$749,999
	$750,000–$999,999
	$1,000,000–$1,499,999
	> $1,500,000
	Do not know
Property (house) value	< $50,000
	$50,000–$99,999
	$100,000–$199,999
	$200,000–$299,999
	$300,000–$399,999
	$400,000–$499,999
	$500,000–$749,999
	$750,000–$999,999
	$1,000,000–$1,499,999
	> $1,500,000
	Do not know
Property (house) mortgage balance	< $10,000
	$10,000–$49,999
	$50,000–$99,999
	$100,000–$199,999
	$200,000–$299,999
	$300,000–$399,999

Variables	Options
	$400,000–$499,999
	$500,000–$749,999
	$750,000–$999,999
	$1,000,000–$1,499,999
	> $1,500,000
	Do not know

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Declarations

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