Case Study

Preliminary Documented Recovery Patterns and Observations from Video Cataloged Data of the 2011 Joplin, Missouri, Tornado

Stephanie F. Pilkington, M.ASCE[1]; Andrew Curtis[2]; Hussam Mahmoud, M.ASCE[3]; John van de Lindt, F.ASCE[4]; Steve Smith[5]; and Jayakrishnan Ajayakumar[6]

Abstract: The 2011 Joplin, Missouri, tornado was one of the deadliest and costliest tornadoes in US history, damaging approximately 8,000 structures and causing more than $2 billion in economic damages. As with most extreme events, reports following the tornado documented the widespread damage, including complete destruction of one of the local hospitals along with various schools. However, recovery processes have not been documented and evaluated at the same level of spatial detail. Following the 2011 Joplin tornado, researchers periodically revisited neighborhoods at 6-month intervals for the first 2 years, then yearly for the following 3 years, with the goal of collecting spatial video data in order to document when structures were fully repaired or rebuilt. This case study documents the building repair time (time to reach full building functionality) patterns based on that data set for the first 2 years following the devastating Enhanced Fujita (EF) 5 tornado that struck Joplin, Missouri. The preliminary results comprehensively show a longer average building repair time for older (pre-1970) buildings and areas of lower population count, while rebuild times were quicker for areas where a relatively small amount of the population did not have access to a vehicle and the median age was lower. Within this Joplin recovery study, however, the year built for the structures was concluded to be a stronger factor in delaying recovery time than income, which is typically considered a primary contributor to repairing and rebuilding a structure following an extreme event. Overall, buildings ranging from minimal to severe damage were typically fully repaired within the first year, while buildings that were completely destroyed reached full functionality evenly across 6-month, 1-year, 1.5-year, 2-year, and greater than 2 years recovery times. **DOI: 10.1061/(ASCE)NH.1527-6996.0000425.** © *2020 American Society of Civil Engineers.*

Author keywords: Tornado; Recovery; Joplin, Missouri.

Introduction

A tornado is a violent wind hazard that commonly occurs within the United States and has the potential to drastically impact a community. The most common tornadoes are typically classified as EF1 or weaker on the Enhanced Fujita scale, which classifies tornadoes by wind speed based on the damage to building types (Dosewell et al. 2009; Edwards et al. 2013; Mehta 2013). However, heavy media focus tends toward large violent tornadoes that strike a populated area. For example, some recent disastrous tornado events of EF4 or higher ranking, including the 2013 Moore, Oklahoma, 2011 Tuscaloosa, Alabama, and 2011 Joplin, Missouri, tornadoes, which resulted in substantial damage of at least $2 billion (Burgess et al. 2014; Curtis and Mills 2012; Kuligowski et al. 2014; Marshall 2002; Rouche and Prevatt 2013; Storm Prediction Center 2015) and required years for each community to rebuild, with full recovery still in progress in some cases. Most studies following such events focus on that initial impact in terms of damage, but there is growing interest in the subsequent recovery process and time to recover for individual buildings and the overall community (e.g., McAllister 2016).

The EF5 tornado that struck Joplin, Missouri, on May 22, 2011, had a 1.6 km (1 mi)–wide path and resulted in approximately $2 billion in damage and the loss of 161 lives (Onstot 2016) with 158 attributed directly to the tornado (NIST 2011). On the morning of May 22, 2011, the Storm Prediction Center (SPC) indicated a moderate risk for severe weather in southwestern Missouri, "with at least 10% probability of a significant tornado within 25 miles of Joplin, MO" (Davies 2017). The environmental characteristics for this event have been associated with other violent tornado events across the Central Plains in recent years (May 20, 2013 in Moore, Oklahoma, and May 31, 2013 in El Reno, Oklahoma). In these cases, low-level moisture was able to deepen for several days ahead of a slow-moving upper-atmosphere system. In such scenarios, the cold front associated with the upper-level low pressure hangs back

[1]Assistant Professor, Dept. of Engineering Technology and Construction Management, Univ. of North Carolina at Charlotte, Charlotte, NC 28223 (corresponding author). ORCID: https://orcid.org/0000-0002-0218-4849. Email: spilking@uncc.edu

[2]Professor, Geographic Information System Health and Hazards Lab, Dept. of Population and Quantitative Health Sciences, Case Western Reserve Univ. School of Medicine, Cleveland, OH 44106. Email: ajc321@case.edu

[3]Professor of Infrastructure, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80523. Email: Hussam .Mahmoud@colostate.edu

[4]Harold H. Short Endowed Chair Professor and Co-Director, Center for Risk-Based Community Resilience Planning, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80523. Email: jwv@colostate.edu

[5]Professor of Geography, Dept. of Social Science, Missouri Southern State Univ., Joplin, MO 64801. Email: Smith-Steve@mssu.edu

[6]Research Associate, Geographic Information System Health and Hazards Lab, Dept. of Population and Quantitative Health Sciences, Case Western Reserve Univ. School of Medicine, Cleveland, OH 44106. Email: jxa421@case.edu

Note. This manuscript was submitted on September 19, 2019; approved on July 21, 2020; published online on November 19, 2020. Discussion period open until April 19, 2021; separate discussions must be submitted for individual papers. This paper is part of the ***Natural Hazards Review***, © ASCE, ISSN 1527-6988.

from the southwest of the upper-level primary low to a secondary low or dry-line cold front. This interaction forms what it termed a triple point and can result in favorable conditions for forming strong and violent tornadoes (Davies 2017).

This single event damaged nearly 7,500 residential structures along with 553 nonresidential buildings (Kuligowski et al. 2014), with the majority of structures completely damaged, or leveled. In addition to the many residential structures and commercial buildings, two fire stations, Joplin High School, and a major hospital [St. John's Regional Medical Center (SJRMC)] were also severely damaged. The findings following the National Institute of Standards and Technology (NIST) technical investigation indicate that 135 of 161 fatalities were a result of building failures (Kuligowski et al. 2014; NIST 2011). This event remains the single costliest and deadliest tornado in US record keeping since 1950.

During the first 2 years following the tornado, as with any major disaster, the City of Joplin coped with rehousing those who had lost their homes and began the process of rebuilding, especially in the commercial sector. Spatial video captured these different stages, with some local stores displaying remarkable resilience in their return (Ajayakumar et al. 2019). Larger projects, such as rebuilding the high school and hospital, took far longer because they involved considerable demolition projects, and in the case of the high school, a change in location. Local institutions as well as state and federal agencies played a key role in investing in the redevelopment of residential and commercial real estate. Addressing the repair and replacement of important elements of social and public health institutions, such as the hospital and local high school, were key to securing employment and educational opportunities for returning families. Also, in the year or so immediately following the tornado, various forms of governmental assistance and insurance helped citizens secure housing in and around the City of Joplin. All of these developments can be seen in video documentation over time (Ajayakumar et al. 2019; Curtis and Fagan 2013), including the hospital demolition and the construction efforts around the new high school and surrounding housing. These video data also provided an interesting gauge to how some of this recovery was more successful than others, with some business, as previously mentioned, returning to full operation within a few months, while in other examples new apartment complexes stalled in their construction. Finally, the importance of shelters was also documented, as evident by a suite of shelters that were placed outside the school, with students being drilled in evacuation strategies.

In this study, the repair time for individual buildings within the first 2 years, when the bulk of building permits were issued (Onstot 2016), will be presented along with statistical features similar to those commonly referred to for the initial impact. Furthermore, an evaluation for any potential patterns among quicker or slower repair times was conducted in the interest of contributing to the body of data currently being produced in monitoring overall community recovery times. This study focuses solely on the Joplin tornado and patterns derived from that event only; however, there may be commonalities with other events if similar evaluation methods were to be continued. Such patterns could primarily highlight potential contributions to repair time of buildings for future decision-making and/or modeling for community resilience planning.

Background

Assessment of building repair begins with cataloging the initial building impact and damage state, and then monitoring the buildings over time. These damage states are considered as a result of wind pressure acting on a building and exceeding the resistive capacity of the structural main wind force–resisting systems (MWFRSs) and components and cladding (C&C). The amount of pressure acting on the building can also change as debris punctures the building envelope. Additionally, such damage states describe building functionality (whether it can be occupied) and repair or rebuilding needs, as outlined in Table 1. If a building is considered occupiable, its primary load-bearing structure is intact, and people could safely enter the building. A repairable building may not necessarily be considered occupiable, but portions of it could be rebuilt without full demolition. A building that is not repairable is also typically not occupiable and will require a full rebuild.

Table 1. Building damage states resulting from tornadoes

Damage state	Descriptor	Description of physical damage
1	Slight	Slight damage to doors and windows/roof covering; occupiable and/or repairable
2	Moderate	Moderate damage to windows and doors/roof covering; occupiable and/or repairable
3	Extensive	Not occupiable but repairable
4	Complete	Not occupiable nor repairable

Source: Modified from Memari et al. (2018), ©ASCE.

While building damage provides a baseline for repairs and rebuilds needed, the action of executing such repairs and rebuilds also depends on socioeconomic demographics. Resource availability in terms of household income may contribute to the ability to repair or rebuild a damaged home within a timely manner as noted in many previous studies. For example, the combination of socioeconomic status and demographics from US Census data were used at the University of South Carolina (Cutter et al. 2003) in order to create the Social Vulnerability Index (SoVI). The SoVI relates the two main components of location vulnerability: physical vulnerability (i.e., hurricane, tornado, and/or earthquake-prone area), and the various characteristics of a population that determine people's ability to cope and recover from natural hazards (Cutter and Emrich 2006). The main factors of social vulnerability that are widely accepted include age, race, gender, and socioeconomic status. The SoVI used 11 factors (listed in Table 2) in an additive model in order to produce a SoVI score for each US county. These same variables could then be considered as contributors to overall recovery time because, generally, a more vulnerable population (low income, for example) may be associated with a longer

Table 2. SoVI final variables

Concept	Dominant variable (census data)
Personal wealth	Per capita income
Age	Median age
Density of built environment	No. of commercial establishments/m^2
Single-sector economic dependence	% employed in extractive industries
Housing stock and tenancy	% housing units that are mobile homes
Race: African American	% African American
Ethnicity: Hispanic	% Hispanic
Ethnicity: Native American	% Native American
Race: Asian	% Asian
Occupation	% employed in service occupations
Infrastructure dependence	% employed in transportation, communication, and public utilities

Source: Data from Cutter et al. (2003).

Table 3. CDC social vulnerability variables

Domain	Variable	Additional descriptions
Socioeconomic status	% individuals below poverty	Individuals who would be classified as below the federally defined poverty line
	% civilian employed	—
	Per capita income	—
	% persons with no high school diploma	—
Household composition and disability	% persons 65 years of age or older	—
	% persons 17 years of age or younger	—
	% persons more than 5 years old with a disability	—
	% male or female householder, no spouse present, with children under 18	—
	% minority	White alone − (African American + Native American + Asian + Hispanic + Pacific Islander + two or more races + other)
	% persons 5 years of age or older who speak English less than well	—
Housing and transportation	% multiunit structure	>10 units
	% mobile homes	—
	Crowding	More people than rooms at household level
	No vehicle available	—
	% persons in group quarters	—

Source: Data from Flanagan et al. (2011).

recovery time. These variables have also been referenced for finer-scale social vulnerability analysis at the census block group (BG) level, resulting in the socioeconomic and demographic vulnerability index (SEDVI) (Strader and Ashley 2018).

While the SoVI focused on the county level, another study (Morrow 1999) focused on the neighborhood level and proposed that at-risk (vulnerable) groups involve concentrated areas of

- Residents in group housing,
- Elderly (high median age),
- Those on disability (physically or mentally disabled),
- Renters (housing tenure),
- Low-income households,
- Women-headed households [single female householder with children (SFHwC)],
- Ethnic minorities based on language spoken in the area,
- Recent residents,
- Larger households, and
- High concentrations of children/youths, homeless, and/or tourists and transients.

Ultimately, the conclusion of this study suggested that more disaster-resistant communities involve a level of grassroots activism (Geis 1997; Morrow 1999). While many of these neighborhood demographics overlapped with those on the county level from the SoVI, parameters such as group housing, disability, and women-headed households were not represented at the county-level analysis. The Centers for Disease Control and Prevention (CDC) established another social vulnerability index at the census tract level, which would be considered closer to the size of a neighborhood. This index included 15 census variables as outlined in Table 3.

The damage state conditions of a structure in conjunction with some of the previously identified social variables, including the building age, might be indicative of a time to repair or rebuild a home or structure. The interconnection of such parameters may be related to an individual requiring a building permit for rebuilding and the concept that some demographics may have a more difficult time managing the current system than others. In general, the repair process for a home needing rebuilding would follow the process as shown in Fig. 1, with social factors attributing to insurance claims, permitting, and hiring contractors, while the engineering components focused on the damage evaluations and the repair or rebuild process.

Currently, the focus within natural hazards research has been evaluating the potential tie between infrastructure engineering and socioeconomic variables within both the damage and recovery process. This interaction is still being evaluated and documented infrastructure repair data would help in filling this knowledge gap. A study conducted in 2006, 1 year following Hurricane Katrina, evaluated repair and recovery efforts made in the Lower and Upper Ninth Wards. This study found that the southern section of the

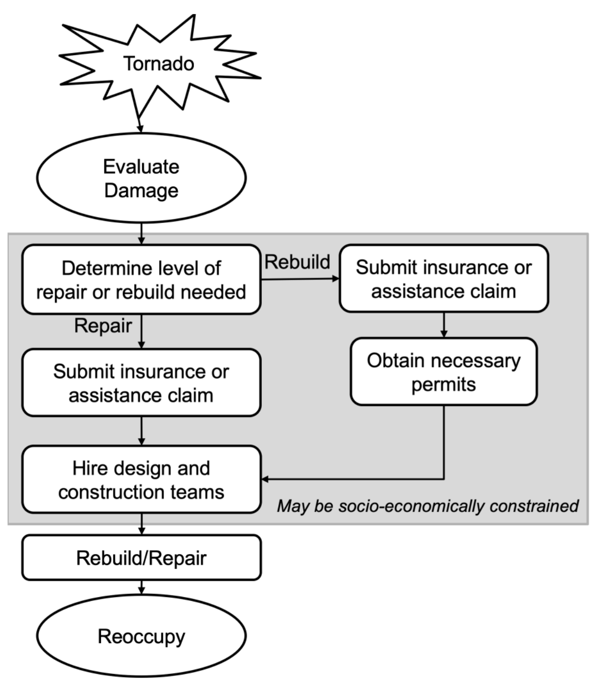

Fig. 1. General repair process for individual building.

Lower Ninth Ward and Holy Cross lagged behind the Upper Ninth Ward while having similar economic resources and sustaining similar damage. The authors of this study concluded that this disparity may have been due to the delay in restoring power and water by 14 months, as well as this region of the Lower Ninth Ward not being designated as a FEMA flood zone (Green et al. 2007). This contributed to a high number of residents without flood insurance to assist in starting repair or recovery efforts (Green et al. 2007). Another 1-year-later study, following the Carlton Complex Fire in north-central Washington, conducted in-person surveys of individuals impacted, approximately 61% of whom experienced some form of property damage. This study primarily highlighted the difficulties residents expressed in the FEMA recovery application process (Edgeley and Paveglio 2017). However, when conducting a similar recovery study for the April 27, 2011 Tuscaloosa, Alabama, tornado, results were found to be similar to those of the Hurricane Katrina recovery study: ample resources and full insurance coverage allowed those residing in well-off neighborhoods to recover more quickly than those without (Weber and Lichtenstein 2015). These studies primarily indicate a relationship between financial resources and ability to recover—a concept well accepted within the natural hazards topic area.

In this study, damage and video repaired data for select buildings are presented and assessed for potential patterns for the 2 years immediately following the 2011 Joplin, Missouri, tornado. These data were gathered by researchers at Kent State University using spatial video of buildings within the main tornado path in Joplin (Curtis and Fagan 2013). Spatial video, which has global positioning system coordinates embedded within the imagery, has been used in various postdisaster environments (Mills et al. 2010). The method can be thought of as an inexpensive version of Google Street View that places data collection (including location and time frame) at the control of the researcher (Ajayakumar et al. 2019). The resulting data recorded approximately 3,000 of the nearly 8,000 damaged buildings within the tornado wind swath at 1, 1.5, and 2 years post-tornado. Most of these 3,000 structures initially fell into the higher-damage categories. While the initial analysis focused on the damage, this study focuses on evaluating the subsequent pattern of building repair within the Joplin community.

Methods

Gathering Building Data

The spatial video refers to a geospatial technique that can capture fine-scale change in different environments, including assessing both damage and recovery following a disaster (Curtis and Mills 2012; Duval-Diop et al. 2010; McMillan et al. 2008; Mills et al. 2010), including post-tornadic landscapes (Curtis and Fagan 2013; Curtis and Mills 2012). The basic premise is that a video camera is synced to a GPS receiver, with the resulting image frames then being visualized with an associated coordinate. Using appropriate software, these synced images and maps can be used as a digitizing source for map making.

The first time a spatial video approach was used in Joplin was on June 14, 2011, to survey neighborhoods and create fine-scale damage maps (Curtis and Fagan 2013). On this first run, three Panasonic PV-GS500 video cameras (Osaka, Japan) were connected to a Red Hen Systems GPS receiver (Fort Collins, Colorado) using a roof aerial, with the location being attached to the tape as an audio signal. The resulting video, when processed through Red Hen's MediaMapper ArcGIS extension, displayed both images and location as a series of points in the geographic information system (GIS). This same setup was used to collect subsequent building repair data during 2011 and 2012. By 2013, a change in the technology had occurred with the team switching to the Contour +2 video camera (Curtis et al. 2015). These extreme-sports cameras were smaller, easier to use, and had an internal GPS receiver. For all subsequent data collection, the team followed the routes of the first 2011 damage mapping, using either a two- or four-camera system. Cameras would be placed on either side of a vehicle, which was driven at road speed. After data collection, the video was downloaded and viewed within Storyteller software (Ajayakumar et al. 2019; Curtis and Fagan 2013), and the GPS path was extracted. A metadata sheet was then completed for each ride including the route followed and the performance of each camera (Ajayakumar et al. 2019).

Analyzing Video Data

The video data collected by the methods described was subsequently processed by evaluating the condition of each building observed in the videos. The geolocated video allowed for these data to be moved from a visual format to a shapefile data format. The shapefile data subsequently consisted of individual features representative of each building with attributes relating their building archetype, initial damage state, and subsequent building repair states at 1, 1.5, and 2 years. The building archetypes were previously established by Memari et al. (2018) and are provided in Table 4. Each building within the tornado path had been previously identified by its archetype (Attary et al. 2018). The archetype shapefile and video catalog repair data were spatially aligned to translate the archetype attributes from the group of nearly 8,000 buildings (features) to the approximately 3,000 buildings with repair data.

The video data also provided a means by which to categorize each building's damage state. This was originally done by Curtis and Fagan (2013) when gathering the spatial data. However, within this study it was considered preferable to work using damage states

Table 4. Generalized community building archetypes

Archetype	Building description
T1	Residential wood building—small rectangular plan, gable roof, 1 story
T2	Residential wood building—small square plan, gable roof, 2 stories
T3	Residential wood building—medium rectangular plan, gable roof, 1 story
T4	Residential wood building—medium rectangular plan, hip roof, 2 stories
T5	Residential wood building—large rectangular plan, gable roof, 2 stories
T6	Business and retail building (strip mall)
T7	Light industrial building
T8	Heavy industrial building
T9	Elementary/middle school (unreinforced masonry)
T10	High school (reinforced masonry)
T11	Fire/police station
T12	Hospital
T13	Community center/church
T14	Government building
T15	Large big-box store
T16	Small big-box store
T17	Mobile home
T18	Shopping center
T19	Office building

Source: Reprinted from Memari et al. (2018), ©ASCE.

Table 5. Converting TIS ranking to DS for wood and steel buildings

TIS description	TIS	DS	DS description
No visible damage	1	0	No damage
Minor visible damage (usually loss of roof tiles, guttering, etc.)	2	1	Slight damage to doors and windows/roof covering; able to be occupied and repaired
More substantial roof loss and/or boarded windows, and doors	3		
Large sections of roof material are lost, as are less rigid sections of the house such as the collapse of carports	4	2	Moderate damage to windows and/or doors/roof covering; not able to be occupied but repairable
Building has shifted on its foundation or sizable holes have been knocked through walls or the roof	5	3	Not able to be occupied but repairable
Roof has been removed	6		
Exterior walls have collapsed	7	4	Not able to be occupied and not repairable
All exterior walls have collapsed, leaving just a few inner walls standing	8		
Entire structure has been reduced to rubble	9		
Even the debris has blown away, leaving just dirt or concrete slab	10		

Source: Data from Curtis and Fagan (2013); Memari et al. (2018).

Table 6. Converting TIS ranking to DS for masonry and concrete buildings

TIS description	TIS	DS	DS description
No visible damage	1	0	No damage
Minor visible damage (usually loss of roof tiles, guttering, etc.)	2	1	Slight damage to doors and windows/roof covering; able to be occupied and repaired
More substantial roof loss and/or boarded windows, and doors	3	2	Moderate damage to windows and/or doors/roof covering; not able to be occupied but repairable
Large sections of roof material are lost, as are less rigid sections of the house such as the collapse of carports	4	3	Not able to be occupied but repairable
Building has shifted on its foundation or sizable holes have been knocked through walls or the roof	5	4	Not able to be occupied and not repairable
Roof has been removed	6		
Exterior walls have collapsed	7		
All exterior walls have collapsed, leaving just a few inner walls standing	8		
Entire structure has been reduced to rubble	9		
Even the debris has blown away, leaving just dirt or concrete slab	10		

Source: Data from Curtis and Fagan (2013); Memari et al. (2018).

Table 7. Building repair states

Repair state	Description	Subcategory	Elaboration
0	No rebuild/new structure	—	Abandoned lot
1	Uninhabited	2	Livable: unoccupied
		5	Blighted
		10	Nonlivable: extreme
2	Cleared	—	Lot empty due to destroyed home or clear for rebuilding
3	Rebuilding	1	Frame skeleton is up; this would only appear for homes needing a complete rebuild
		2	Walls are enclosed
		3	Nonstructural components have been added; likely that DS2 and DS3 would not require more than this level of construction
		4	Cosmetic finishes being applied
4	Rebuilt and occupied	—	Good as new
5	New archetype built	—	New structure of different zoning designation

(DSs) instead of the tornado injury scale (TIS) previously defined by Curtis and Fagan (2013) in the interest of overall community resilience and its relationship to possible building repair times (1, 1.5, 2, and >2 years). The conversion from TIS to DS by structure types is described in Tables 5 and 6.

Once the building damage states were converted from their already identified TIS, the video data were evaluated for each building's condition over time. At each time interval, the buildings were given a repair state designation, outlined in Table 7. These repair states (RSs) are intended to indicate the progress toward a full building repair or rebuild, with RS4 indicating the building is completely rebuilt and reoccupied. RS5 and RS6 were added to illustrate when a lot has either been abandoned or rezoned for a different usage. Additionally, RS3 was expanded to document at what stage a structure was in the construction (rebuilding) process. An example of one of these rebuilding states is shown in Fig. 2 with graphics from the video player used to analyze the data. In Fig. 2, a repair state of 3.2 is assigned to the building, indicating that it was being rebuilt at the time and the walls have enclosed the building per the designations in Table 7.

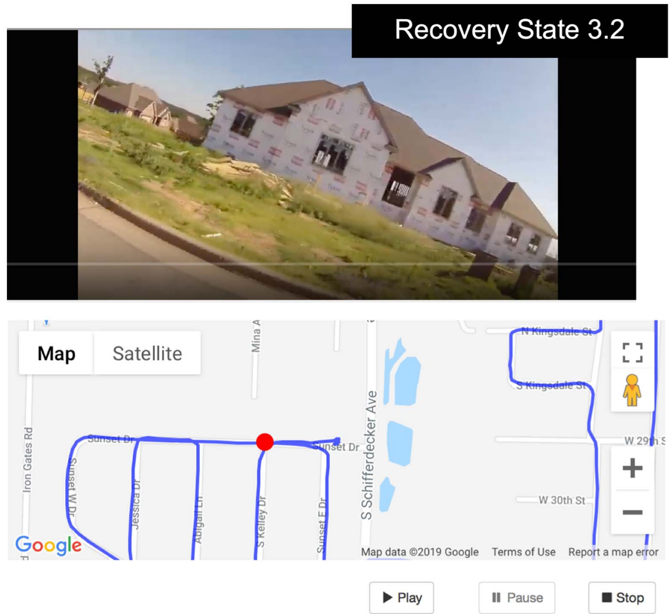

Fig. 2. Example image of an RS3.2 building as seen when using the video player with dot indicating location within Google Maps. (Map data ©2019 Google.)

Once the building repair states were identified for each feature (building), the time to repair or rebuild that feature was determined by evaluating when RS4 was reached. Following this process, the number of buildings in each DS and each repair or rebuild time were summed and subsequently evaluated for how many of those buildings in a specified DS were repaired or rebuilt by 1, 1.5, or 2 years, or took more than 2 years to return a building to its original functionality. For example, what percentage of buildings that were classified as DS4 were repaired or rebuilt by 1 year? Repair time of each archetype was then summarized for evaluation as well.

Following this generalized analysis were specific spatial analyses. The first spatial analysis was to see if buildings within a parcel recovered at the same rates. For the purposes of this research, these parcels were defined as areas of land containing multiple buildings and bounded by roads, similar to city blocks (these are outlined in the "Data Results" section). To evaluate each parcel, individual layers were created from the RS data shapefile such that all buildings with 1-year repair time were on one layer, all buildings with 1.5-year repair time were on another layer, and so on. Each of these layers was then spatially joined with the defined parcels, so that each parcel would take on an RS for the buildings residing within it. This smaller parcel-level analysis was meant to investigate whether a building was fully repaired or rebuilt at the same pace as its neighbor.

The next analysis was conducted to determine whether or not certain census block groups contained buildings that reached functionality in a similar time frame or consisted of a variety of repair time patterns. This analysis was conducted in the interest of comparing the overall pattern of damage state distribution and relative repair times, as described previously for the whole data set, at the block group level. These block groups were also associated with specific demographic data from the 2010 US Census American Community Survey (ACS) (US Census Bureau 2018). American Community Survey (ACS) available through TIGER/Line shapefiles. Select demographic options were evaluated based on previous social science studies (outlined in the "Background" section), the availability in the 2010 ACS, and their relevance to Joplin. For example, a large majority of the population of Joplin (>87%) is classified as white alone (US Census Bureau 2019), which leads to minimal variation in race and ethnicity across census block groups. Therefore, demographics related to race and languages spoken were not analyzed in the present study. The association of damage state and repair time patterns with the social demographics mentioned in the "Background" section allowed for insight as to whether a correlation existed between quicker or slower repair time patterns and certain demographics within the Joplin region. More specifically, this data analysis allowed for potential explanation as to why one block group may have recovered its DS4 buildings faster than another block group.

Finally, the block groups were associated with their relevant school attendance zones in the interest of evaluating the potential impact of school repair time (restored functionality) to housing repair time. Because schools are central to a community, both under normal operations and during an emergency (Butler and Diaz 2016; US Department of Education 2007), this was considered a potential contributor to when nearby buildings may also become fully repaired or recovered. A final matrix of fast, slow, or standard (for this specific event) repair time and the corresponding socioeconomic and school district–related variables was created to determine how one variable may impact building repair time. For example, were slower building repair times by block group associated with a population of elderly or younger individuals and families? These patterns and findings were specific to 2011 Joplin, Missouri, and this singular event.

Data Results

The total number of buildings within the tornado path, as defined in Attary et. al. (2018), was 7,912. However, of those 7,912 buildings, only 2,771 had repair or rebuild data recorded for the first 2 years, which lead to approximately 35% of affected buildings being considered within this study. These buildings did, however, cover an array of neighborhoods, damage states, and wind speeds, which led to a relatively diverse data set.

Fig. 3 shows each building data point and how long it took that building to reach RS4 and be considered fully functional again. The magnified area in this figure illustrates that these building repair times were not specifically bounded by the wind speed, with some buildings in the EF2 region not yet fully repaired or rebuilt by the 2-year mark. Table 8 lists how these repair times break down by the represented building archetypes. The majority of the buildings analyzed were residential, specifically, T1 and T5 archetypes, with some business and retail buildings (T6), a hospital (T12), and some office buildings (T19). Building archetypes without corresponding building counts in Table 8 were not captured in the video data used in this study. Approximately 38% of residential buildings reached full functionality within the first year, while most retail buildings took longer.

Thus far, the repair data do not show much of a pattern to recovery, specifically as a function of wind speed. Spatially speaking, if wind did not strictly bind the various building repair times, buildings possibly were influenced by the repairs of neighboring buildings or some other factor(s). When these repair times were distributed spatially by parcels (areas of land with multiple buildings and bounded by streets), the majority of parcels were found to contain buildings that took various time frames between 6 months to more than 2 years to reach full functionality. The spatial distribution by parcels and their neighbors is shown in Fig. 4. Fig. 4(a) shows parcels containing buildings that reached full functionality by 1 year, Fig. 4(b) shows parcels containing buildings that reached full functionality by 1.5 years, and so on for Figs. 4(c and d).

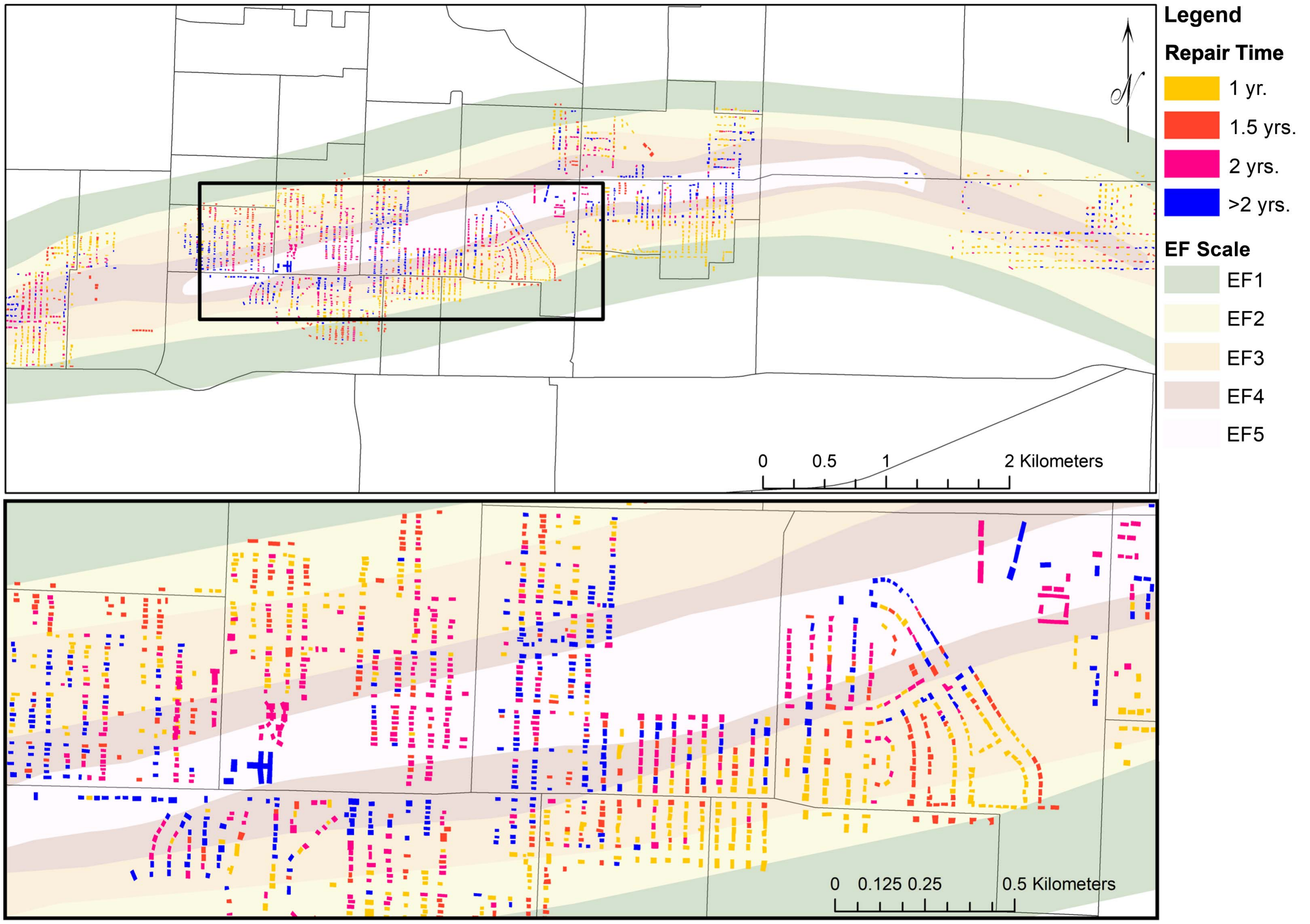

Fig. 3. Building repair (and rebuilding) of the Joplin community's building stock in a 2-year period.

A single parcel may be highlighted in the 1-, 1.5-, 2-, or longer than 2-year repair time, which indicates that this area contains buildings recovering at different rates. Therefore, the results of this distribution indicate that neighbor repair time did not necessarily contribute to an individual building's recovery time. In other words, if a building's neighboring structures all reached full functionality by 1 year, that does not necessarily correlate to that building also recovering within 1 year. The repair time of structures within a parcel was not found to influence other structures within that parcel.

Table 8. Building repair times by archetype listed in Table 5

	Building count				
Archetype	Total	1 year	1.5 years	2 years	>2 years
T1	2,708	1,037	476	605	590
T2	—	—	—	—	—
T3	—	—	—	—	—
T4	—	—	—	—	—
T5	14	0	8	4	2
T6	18	4	1	6	7
T7	—	—	—	—	—
T8	—	—	—	—	—
T9	—	—	—	—	—
T10	—	—	—	—	—
T11	—	—	—	—	—
T12	1	0	0	1	0
T13	—	—	—	—	—
T14	—	—	—	—	—
T15	—	—	—	—	—
T16	—	—	—	—	—
T17	—	—	—	—	—
T18	—	—	—	—	—
T19	30	11	4	6	9

Most of the buildings within this data set were categorized as DS4 and would need to have been fully rebuilt; however, most buildings reached full functionality again within the first year. The average recovery time for all buildings assessed and recovered within 2 years was approximately 1.4 years. At first assessment, this would indicate a correlation between high damage states and quick recovery times. However, by evaluating each DS group individually, as shown in Fig. 5, most DS1, DS2, and DS3 buildings were fully repaired or rebuilt within the first year, with DS1 buildings sometimes needing additional repair time through 1.5 years. The DS4 buildings were relatively evenly spread out across the 1-year, 1.5-year, 2-year, and longer time frames. Of the more than 600 buildings still not yet recovered, only 53 were noted as in the rebuilding phase, or RS3, at the 2-year mark.

Fig. 5 represents the overall building repair time pattern for Joplin and deviation from this pattern may suggest quicker or slower repair times. From here, buildings were nested into their associated census BGs so as to evaluate correlations between spatial location, demographics, and repair times. These BGs are designated Blocks A through N as shown in Fig. 6(a). Fig. 6(b) shows which elementary school contains attendance from each BG.

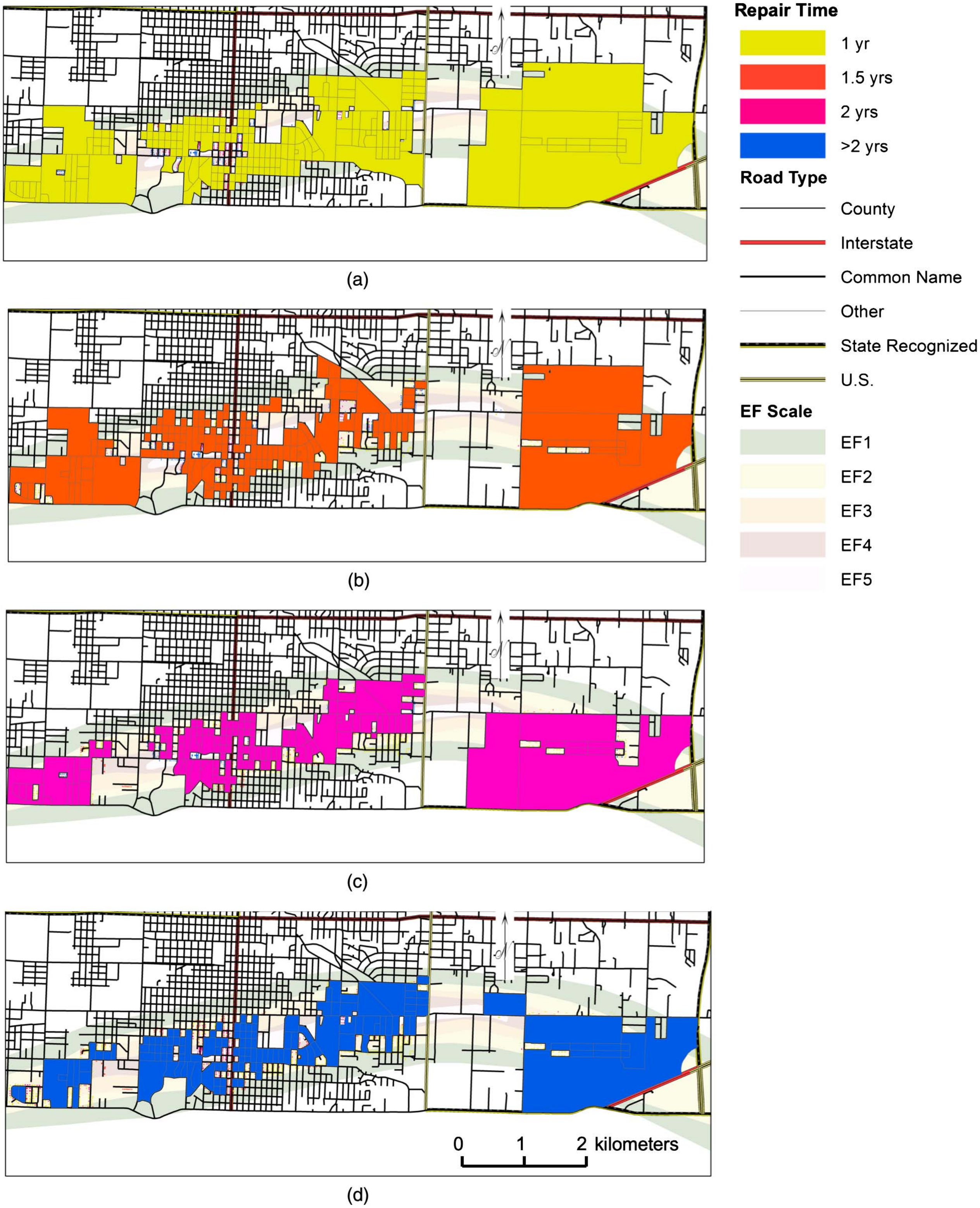

Fig. 4. Neighborhoods containing structures that reached full functionality by (a) 1 year; (b) 1.5 years; and (c) 2 years; and (d) structures that had not yet reached full functionality by 2 years.

There are numerous elementary schools, but Joplin High School serves the entire city. The BGs are evaluated and subsequently matched with their school district, as well as social demographics, in the interest of evaluating if a specific BG *or* school district may have had slower or quicker building repair times when compared to the overall pattern in Fig. 5.

The damage and building repair time patterns were assessed for each BG using the data in Figs. 7 and 8. Each BG's damage state distribution and corresponding division by repair state (Fig. 8) allowed for evaluation of which areas deviated from the overall pattern previously found in Fig. 4. Blocks C, D, E, and F showed patterns that indicated slower repair times with a distribution of

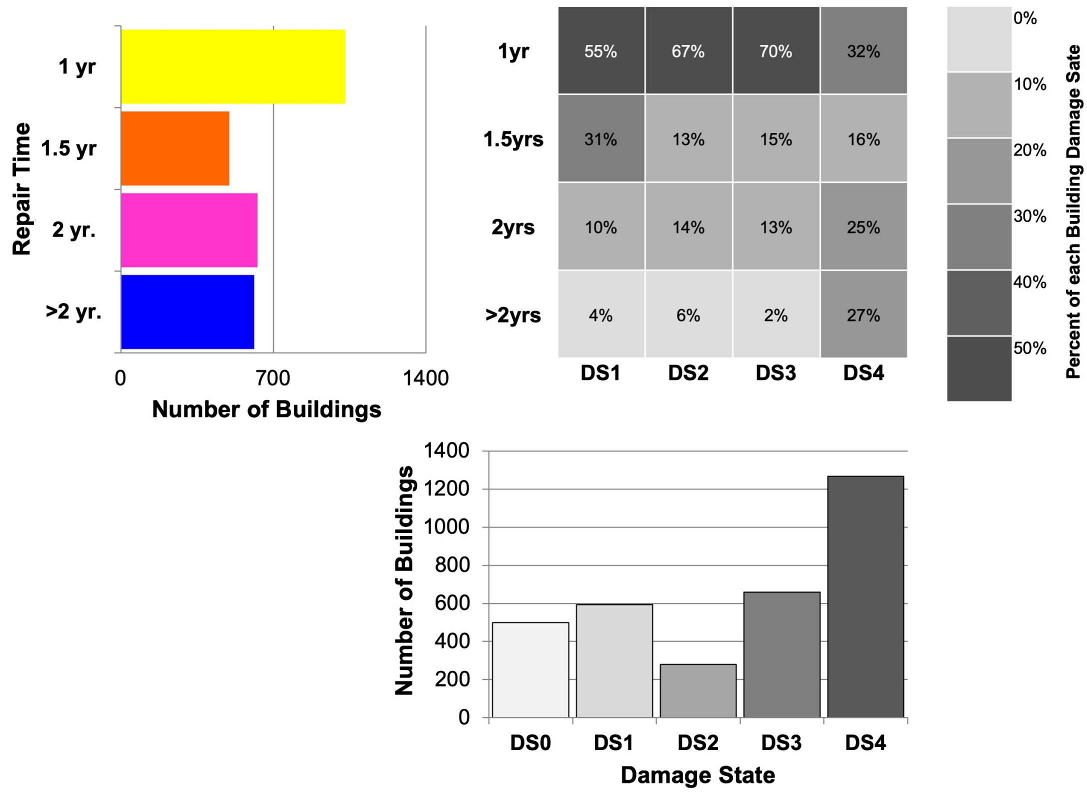

Fig. 5. Histogram of buildings categorized as being in Damage States 0–4, recovery time, and how many buildings in each damage state corresponded to each recovery time.

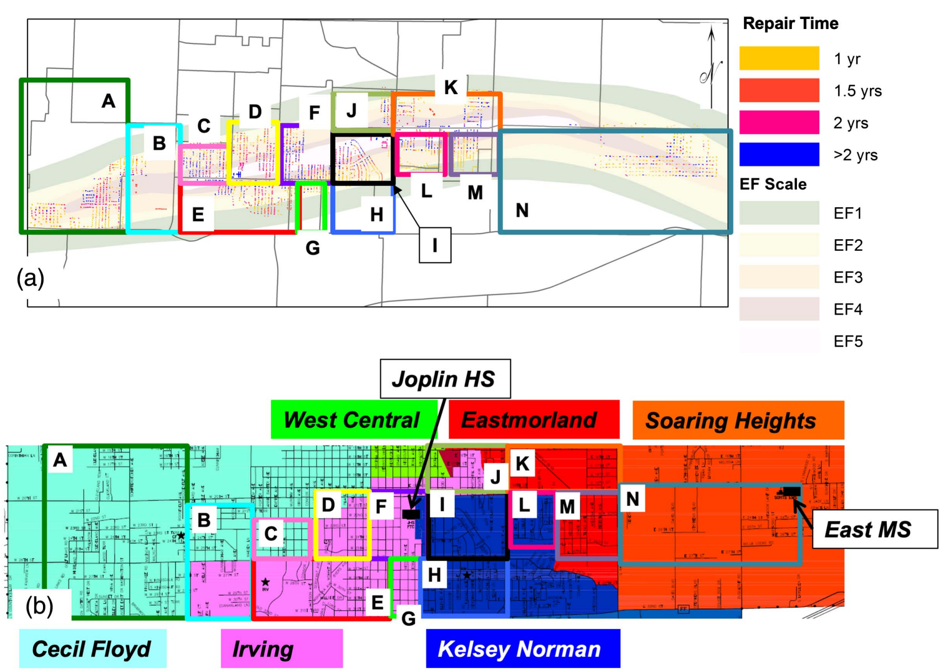

Fig. 6. Census block group designation (a) for structures with repair and rebuild data (data from Curtis and Fagan 2013; US Census Bureau 2018); and (b) by school district (adapted from Joplin Schools Transportation Department 2019).

longer repair times across each damage state. In Block C, DS1 buildings were more spread out across the possible repair times and a larger percent of structures had not yet reached full functionality by the 2-year mark. This was similar for Blocks D and F, with most DS4 buildings taking at least 2 years to be repaired or rebuilt, instead of being evenly spread out across the multiple repair time frames. Block E had the most DS3 structures that had not yet reached a fully functional status by 2 years, but the DS4 structures

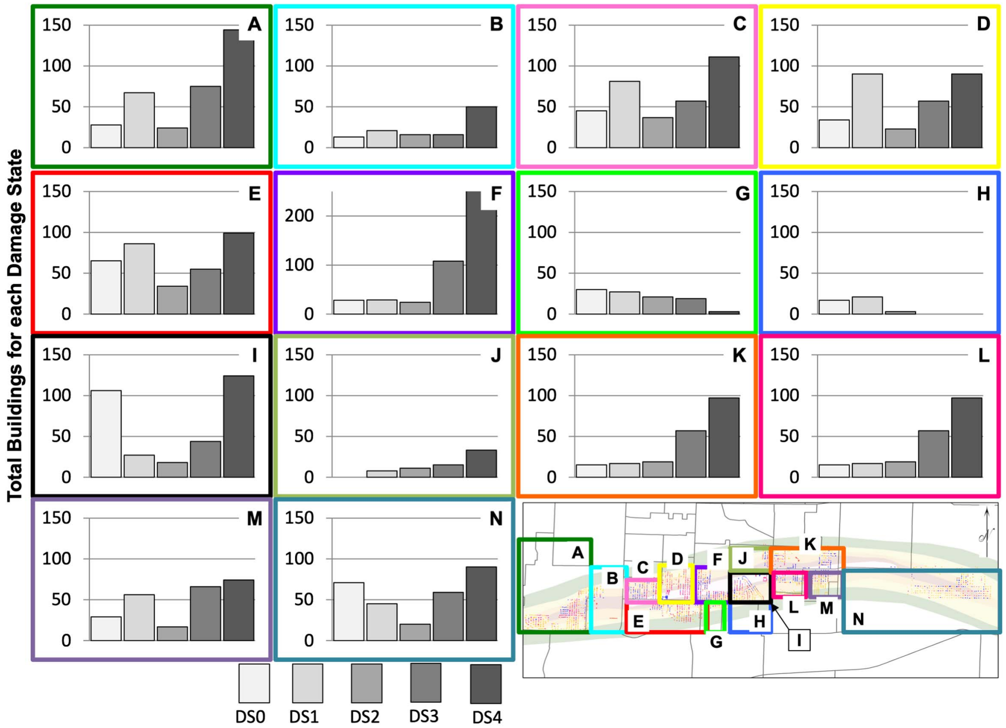

Fig. 7. Building damage state distribution by census block group [inset panel is a thumbnail of Fig. 6(a) schematic].

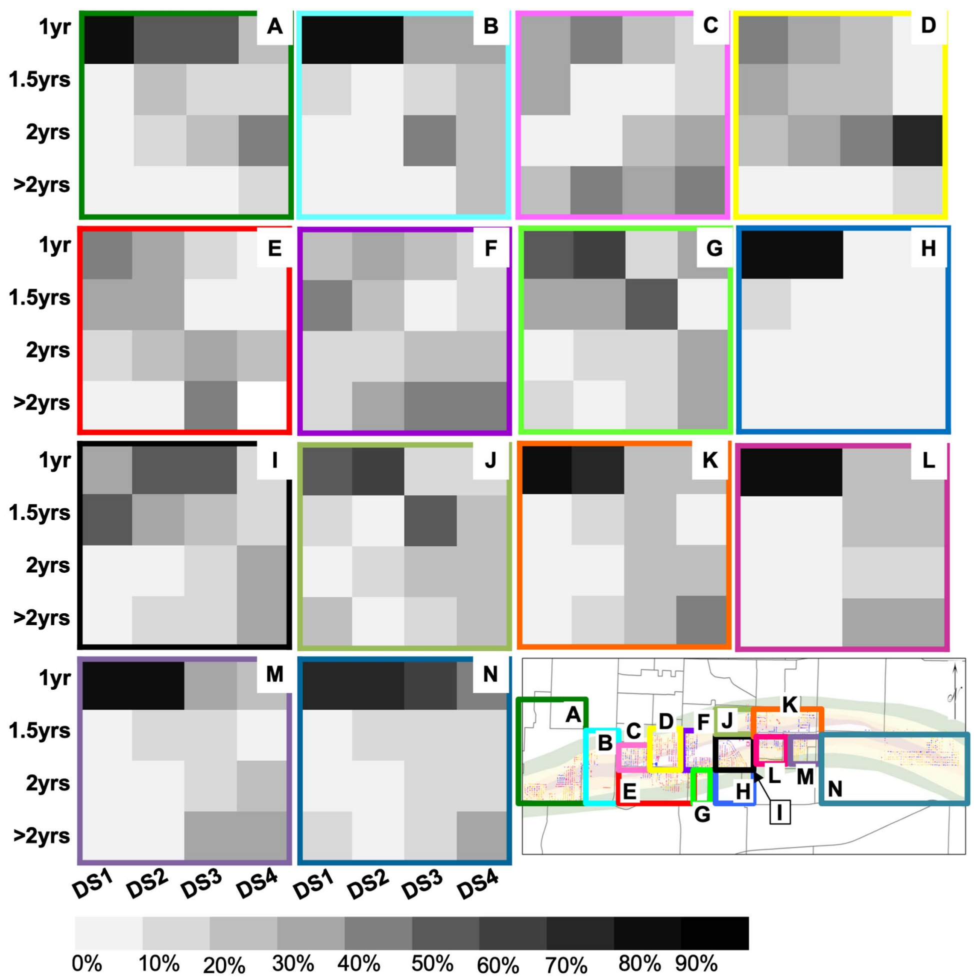

Fig. 8. Percent of each damage state's buildings corresponding to each repair or rebuild time by census block group [inset panel is a thumbnail of Fig. 6(a) schematic].

were mostly rebuilt by the 2-year mark. The BGs with some quicker repair indicators were Blocks B and N, with Block N showing most buildings repaired or rebuilt within the first year across all damage states, and Block B had a larger percentage of DS1 and DS2 buildings repaired by 1 year when compared to the overall community pattern. Blocks K, L, and M showed a mix of quicker building repair times for DS1 and DS2 (similar to Blocks B and N) but a slower building repair or rebuild time for DS3 and DS4 as indicated by the percent of buildings in each damage state recovered by each time step. This assessment allowed for the overall identification of groups of buildings, on a spatial level, that had differing building repair time patterns, which leads to explaining the potential reasons as to why these variances occurred.

Discussion of Correlations

The preceding results prompted an assessment of the BG demographics to identify which of the previously studied vulnerability factors correlated to changes in building repair time distributions by building damage state. However, not all of the social characteristics are discussed herein because some did not show much correlation and/or were not available in the 2010 ACS for the state of Missouri.

For example, one of the most commonly discussed demographics in association with recovery from natural hazard is income. However, as can be seen in Fig. 9, the per capita income is not particularly diverse across the Joplin area. Blocks B, C, E, and N all have per capita incomes of less than $25,000, even though these blocks also showed differing building repair time patterns. Additionally, Block A, which had the highest income, consisted of repair time patterns by damage state similar to the overall pattern for Joplin as a whole, further indicating a lacking correlation between repair time and income for this specific event. However, a stronger positive correlation was found between the median year built (YB) of the structures in a BG and slower building repair times. In terms of building damage, the year built for a structure is often an important factor to consider because building codes were not developed until around 1970. Along with aging deterioration, this indicates that such structures would be vulnerable to higher damage states for a specified wind speed. However, in rebuilding structures from the 2011 Joplin tornado, most were considered fully functional again within the first year. The same BGs that showed slower building repair time (C, D, E, and F) also contained structures of a median YB prior to 1970. Overall, Fig. 9 shows correlation between older structures and slower repair and rebuild times, but not a correlation with income.

The BGs that showed some tendencies toward quicker repair times were Blocks B, K, L, M, N, with Blocks K, L, and M containing a higher percentage of DS3 and DS4 structures that conversely took longer to reach full functionality again. There were multiple demographics that were correlated to these areas. Block B, which showed the majority of DS1 and DS2 buildings being repaired within the first year, was also one of the lowest median age BGs. Blocks K, M, and N, which all showed quicker repair times for DS1 and DS2, had a low percentage of individuals within the BG without access to a vehicle. While renters are commonly considered when looking at social vulnerability and tenure, these same three BGs actually had a *low* percentage of housing units that were classified as *neither* rented nor owned, which correlated to

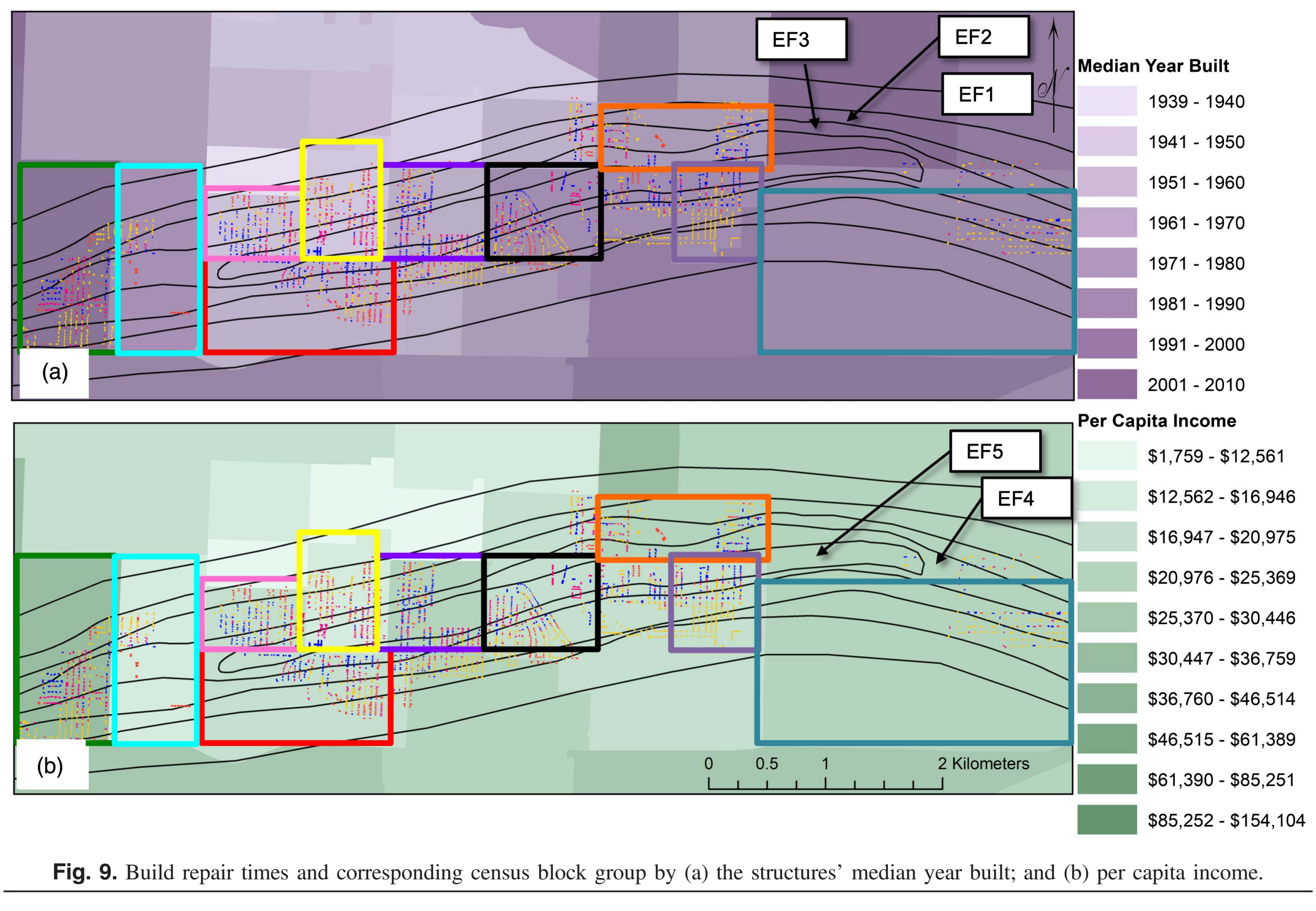

Fig. 9. Build repair times and corresponding census block group by (a) the structures' median year built; and (b) per capita income.

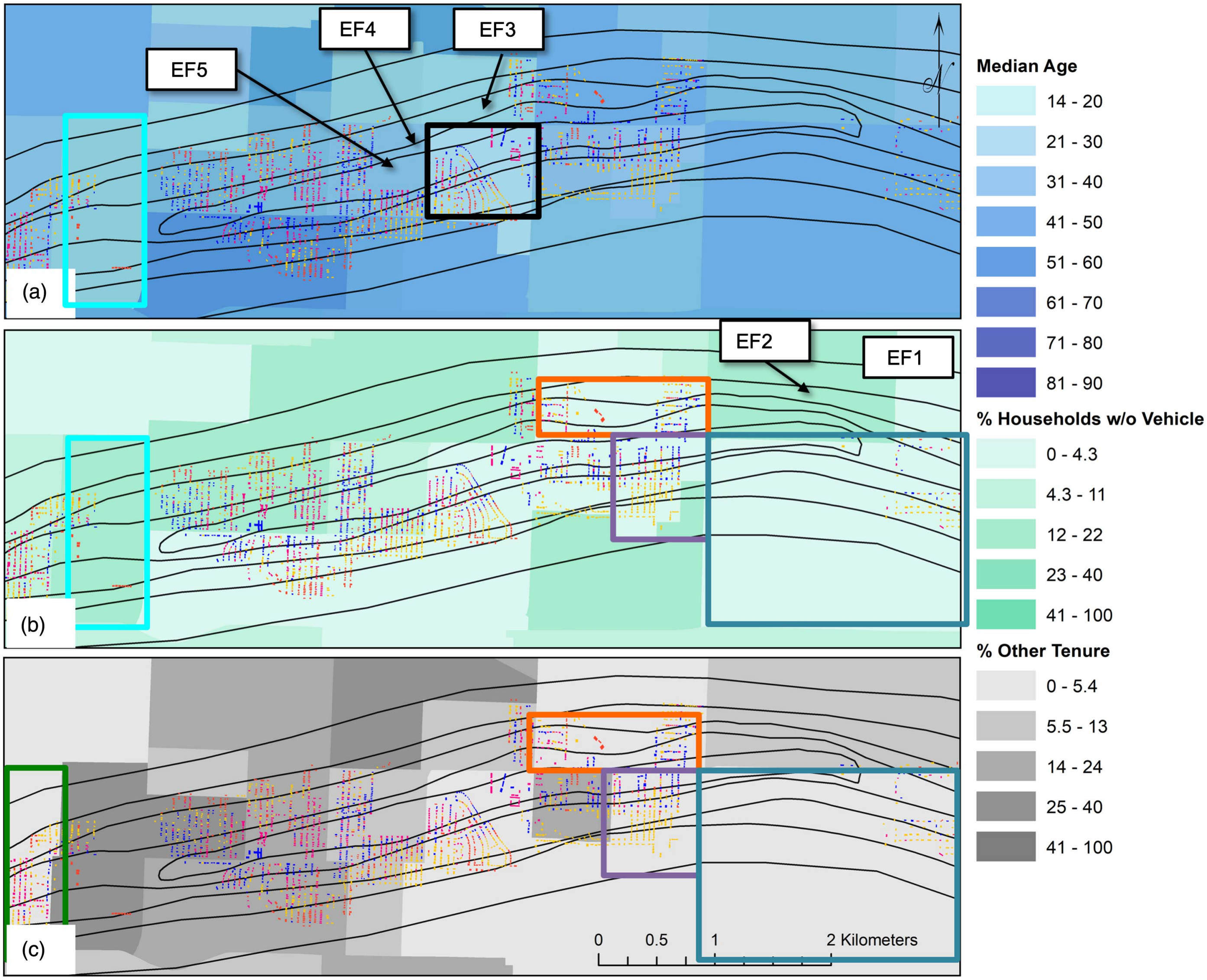

Fig. 10. Block groups that tended toward quicker building repair times by (a) median age; (b) percentage of individuals who do not have access to a vehicle; and (c) percentage of individuals who neither rent nor own.

quicker recovery times. These correlations within the Joplin community are shown in Fig. 10. These results suggest that individuals who have more resources available to them, in the form of transportation and living arrangements, are better able to recover than those without, which is consistent with previous demographic vulnerability studies (Fothergill and Peek 2015).

A summary of these and other select demographics is provided in Table 9. In addition to older structures being tied to slower repair times, a low population count was also found to correlate buildings of more severe damage states (DS3 and DS4) mostly requiring at least 2 years to reach full functionality again. The longer repair time for older buildings may suggest a difficulty in obtaining permits and repairing older structures that may not have originally been built to code, while the longer repair time for low population count areas may be attributed to a sense of community and help from neighbors.

In addition to census demographics, the BGs and their respective attendance zones, specifically for elementary and middle schools, were compared in light of the possibility that delays in sending kids back to school could cause decisional delays in rebuilding homes. One school that showed a potential correlation was Irving Elementary School, with Blocks D, E, and F in its attendance zone. Irving Elementary School suffered severe damage and was not recovered until 2013 (NIST 2011). This could suggest a dependence on schools being rebuilt and recovered in the area because these BGs consisted of higher percentages of severely damaged buildings taking at least 2 years to reach full functionality, which was the time it took this elementary school to also be rebuilt. Cecil Floyd and Kelsey Norman Elementary Schools were damaged less severely and were less significantly correlated to attendance zone and BG overlaps where some level of quicker repair time was observed. However, such a correlation was not necessarily consistent across all school zones (part of Cecil Floyd's attendance zone overlapped with a BG that was comparatively slow to recover), and this tornado event actually resulted in the City of Joplin reevaluating its education strategy, such that there may be other factors contributing to the length of time it took the schools themselves to fully recover. Outside support from Webb City and Carl Junction was also provided in terms of taking on additional elementary school students, which could have had a positive influence and

Table 9. Summary of BG recovery by certain demographics (approximated values) in different census blocks

	Census block designation													
Correlating demographics and school districts	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Low housing density	—	—	—	—	—	—	—	—	—	—	X	—	—	X
Pre-1970 buildings	—	—	X	X	X	X	—	—	—	—	—	—	—	—
Population <1,000	—	—	X	—	—	X	X	—	—	X	X	X	—	—
Per capita income <$25,000	—	X	X	—	X	—	—	—	—	—	—	—	—	X
<5% other tenure	X	—	—	—	—	—	—	X	X	—	X	—	X	X
>50% renters	—	X	—	X	—	—	—	—	X	—	—	—	—	—
<1% without vehicle	—	—	—	—	—	—	—	—	—	—	X	X	X	X
>5% SFHwC	—	—	X	X	X	—	—	X	—	X	—	X	X	—
<2% employed extractive industries	—	X	—	—	X	X	—	—	X	—	—	—	—	—
Median age <20 years	—	X	—	—	—	—	—	—	X	—	—	—	—	—
Median age >50 years	—	—	—	—	X	—	—	—	—	—	—	—	—	—
Irving Elementary (2013)	—	X	—	X	X	X	X	—	—	X	—	—	—	—
Cecil Floyd Elementary	X	X	X	—	—	—	—	—	—	—	—	—	—	—
Kelsey Norman Elementary	—	—	—	—	—	—	—	X	X	—	—	X	—	—
Soaring Heights Elementary (2013)	—	—	—	—	—	—	—	—	—	—	—	—	—	X
East Middle (2013)	—	—	—	—	—	—	—	—	—	X	X	—	X	X

allowed for residents to recover quicker. Ultimately, this study served to only evaluate potential correlation between repair time patterns of a zone's buildings and the relevant local school repair time, but did not look specifically at variables, such as policy and practice, that may more closely tie to causation.

Conclusions

The data and subsequent analyses presented herein for the 2011 Joplin, Missouri, tornado illustrate spatial correlations related to building recovery to full functionality within the initial 2 years following the event. Not only do these data serve to add to natural hazards recovery case study data and literature, they also highlight important factors to consider and further evaluate their contribution to speeding up or delaying repair or rebuild time of structures.

Preliminary findings through this study suggest a correlation between an earlier median year built of the census BG in which a damaged structure resides and slower building repair times. Future case studies could elaborate on whether this may have been a one-off instance for Joplin or is a consistent pattern for tornadic events. If this pattern does reemerge in other events, further studies into permitting and rebuilding or repairing structures over 40 years of age would be required to provide a causation explanation.

Another finding of this study was the lack of correlation between income and building repair. This could be due to the narrow income range across Joplin as a whole or possibly due to the extreme nature of this event, in which assistance was heavily provided and virtually all residents had wind-related homeowners insurance. This study's correlation to the social demographics of access to a vehicle and housing tenure status of neither renting nor owning may also suggest that, when referring to resources, income may not be a core driver, but access to tools and assistance may. While people with such access may typically have higher incomes, the focus on income may begin to break down in a less economically diverse community. In other words, income may be vital when wide discrepancies exist, but the actual resources related to the ability to move around and availability of assistance in rebuilding or repairing may be more vital in more homogenous communities.

Finally, while the rebuilding or repairing of a neighboring structure was not initially found to contribute to the rebuilding or repairing time of another structure, the restoration of an attendance zone's elementary school to full functionality status appears to have had a contribution to the repair and rebuild time in Joplin. However, the analysis herein focused on the BG level for building repairs, and multiple block groups may have contributed to an attendance zone, which may skew these results. Findings suggest that future events be monitored to evaluate if access to the local school contributed to the decision for families in rebuilding their homes.

Community recovery modeling for natural hazards is still in the early stages of development due to a lack of available models. In the interest of preparing and calibrating models and decision-making tools for a community's moving forward, the socioeconomic contributions to, specifically, building repair and rebuild times could be critical. Studies like these, done over time, assist in building that knowledge base for the variables of community-wide recovery. The authors primarily suggest continued studies to monitor various communities for various types (at varying levels of intensity) of events in order to further corroborate the findings discussed herein attributing to slower or quicker building repair and rebuild times, ultimately contributing to a community's overall recovery time.

Data Availability Statement

All data used during the study are available from the corresponding author by request.

Acknowledgments

This research was conducted as part of the National Institute of Standards and Technology (NIST) Center of Excellence for Risk-Based Community Resilience Planning under Cooperative Agreement No. 70NANB15H044 between the NIST and Colorado State University. The content expressed in this paper are the views of the authors and do not necessarily represent the opinions or views of NIST or the US Department of Commerce.

References

Ajayakumar, J., A. Curtis, S. Smith, and J. Curtis. 2019. "The use of geonarratives to add context to fine scale geospatial research." *Int. J. Environ. Res. Publ. Health* 16 (3): 515. https://doi.org/10.3390/ijerph16030515.

Attary, N., J. W. van de Lindt, H. N. Mahmoud, S. Smith, C. M. Navarro, Y. W. Kim, and J. S. Lee. 2018. "Hindcasting community-level building damage for the 2011 Joplin EF5 tornado." *Nat. Hazard.* 93 (3): 1295–1316. https://doi.org/10.1007/s11069-018-3353-5.

Burgess, D., K. Ortega, G. Stumpf, G. Garfield, C. Karstens, T. Meyer, and B. Smith. 2014. "20 May 2013 Moore, Oklahoma tornado damage survey and analysis." *Weather Forecasting* 29 (5): 1229–1237. https://doi.org/10.1175/WAF-D-14-00039.1.

Butler, S., and C. Diaz. 2016. *Hospitals and schools as hubs for building healthy communities*. Washington, DC: Brookings Institution.

Curtis, A., J. W. Curtis, E. Shook, S. Smith, E. Jefferis, L. Porter, L. Schuch, C. Felix, and P. R. Kerndt. 2015. "Spatial video geonarratives and health: Case studies in post-disaster recovery, crime, mosquito control and tuberculosis in the homeless." *Int. J. Health Geogr.* 14 (1): 1–15. https://doi.org/10.1186/s12942-015-0014-8.

Curtis, A., and W. F. Fagan. 2013. "Capturing damage assessment with a spatial video: An example of a building and street-scale analysis of tornado-related mortality in Joplin, Missouri, 2011." *Ann. Assoc. Am. Geographers* 103 (6): 1522–1538. https://doi.org/10.1080/00045608.2013.784098.

Curtis, A., and J. W. Mills. 2012. "Spatial video data collection in a post disaster landscape: The Tuscaloosa tornado of April 27th 2011." *Appl. Geogr.* 32 (2): 393–400. https://doi.org/10.1016/j.apgeog.2011.06.002.

Cutter, S. L., B. J. Boruff, and W. L. Shirley. 2003. "Social vulnerability to environmental hazards." *Soc. Sci. Q.* 84 (2): 242–261. https://doi.org/10.1111/1540-6237.8402002.

Cutter, S. L., and C. T. Emrich. 2006. "Moral hazard, social catastrophe: The changing face of vulnerability along the hurricane coasts." *Ann. Am. Acad. Political Soc. Sci.* 604 (1): 102–112. https://doi.org/10.1177/0002716205285515.

Davies, J. 2017. "Meteorological setting for a catastrophic event: The deadly Joplin tornado of 22 May 2011." *Electron. J. Severe Storms Meteorol.* 12 (3): 1–23.

Dosewell, C. A. I., H. E. Brooks, and N. Doztek. 2009. "On the implementation of the enhanced Fujita scale in the USA." *Atmos. Res.* 93 (1–3): 554–563. https://doi.org/10.1016/j.atmosres.2008.11.003.

Duval-Diop, D., A. Curtis, and A. Clark. 2010. "Enhancing equity with public participatory GIS in hurricane rebuilding: Faith based organizations, community mapping, and policy advocacy." *J. Commun. Dev. Soc.* 41 (1): 32–49. https://doi.org/10.1080/15575330903288854.

Edgeley, C. M., and T. B. Paveglio. 2017. "Community recovery and assistance following large wildfires: The case of the Carlton Complex Fire." *Int. J. Disaster Risk Reduct.* 25 (Oct): 137–146. https://doi.org/10.1016/j.ijdrr.2017.09.009.

Edwards, R., J. G. LaDue, J. T. Ferre, K. Scharfenberg, C. Maier, and W. L. Coulbourne. 2013. "Tornado intensity estimation: Past, present and future." *Bull. Am. Meteorol. Soc.* 94 (5): 641–653. https://doi.org/10.1175/BAMS-D-11-00006.1.

Flanagan, B. E., E. W. Gregory, E. J. Hallisey, J. L. Heitgerd, and B. Lewis. 2011. "A social vulnerability index for disaster management." *J. Homeland Secur. Emergency Manage.* 8 (1). https://doi.org/10.2202/1547-7355.1792.

Fothergill, A., and L. Peek. 2015. *Children of Katrina.* Austin, TX: University of Texas Press.

Geis, D. 1997. "Disaster resistant communities: A community-based approach to hazard mitigation." *CUSEC J.* 4 (1): 1–2.

Green, R., L. K. Bates, and A. Smyth. 2007. "Impediments to recovery in New Orleans' upper and lower ninth ward: One year after hurricane Katrina." *Disasters* 31 (4): 311–335. https://doi.org/10.1111/j.1467-7717.2007.01011.x.

Joplin Schools Transportation Department. 2019. "Attendance zones." Accessed September 1, 2019. http://www.joplinschools.org/departments/transportation/attendance_zones.

Kuligowski, E. D., F. T. Lombardo, L. T. Phan, M. L. Levitan, and D. P. Jorgensen. 2014. *Technical investigation of the May 22, 2011 tornado in Joplin, Missouri*. Gaithersburg, MD: National Institute of Standards and Technology.

Marshall, T. P. 2002. "Tornado damage survey at Moore, Oklahoma." *Weather Forecasting* 17 (3): 582–598. https://doi.org/10.1175/1520-0434(2002)017<0582:TDSAMO>2.0.CO;2.

McAllister, T. 2016. "Research needs for developing a risk-informed methodology for community resilience." *J. Struct. Eng.* 142 (8): C4015008. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001379.

McMillan, A., B. J. Adams, A. Reynolds, T. Brown, D. Liang, and J. A. Womble. 2008. "Advanced technology for rapid tornado damage assessment following the 'super Tuesday' tornado outbreak of February 2008." Accessed October 6, 2009. http://mceer.buffalo.edu/research/Reconnaissance/tornado02-08/08-SP01.pdf.

Mehta, K. C. 2013. "Development of the EF-scale for tornado intensity." *J. Disaster Res.* 8 (6): 1034–1041. https://doi.org/10.20965/jdr.2013.p1034.

Memari, M., N. Attary, H. Masoomi, H. Mahmoud, J. W. van de Lindt, S. F. Pilkington, and M. R. Ameri. 2018. "Minimal building fragility portfolio for damage assessment of communities subject to tornadoes." *J. Struct. Eng.* 144 (7): 04018072. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002047.

Mills, J. W., A. Curtis, B. Kennedy, S. W. Kennedy, and J. Edwards. 2010. "Geospatial video for field data collection." *Appl. Geogr.* 30 (4): 533–547. https://doi.org/10.1016/j.apgeog.2010.03.008.

Morrow, B. H. 1999. "Identifying and mapping community vulnerability." *Disasters* 23 (1): 1–18. https://doi.org/10.1111/1467-7717.00102.

NIST (National Institute of Standards and Technology). 2011. *May 22, 2011 Joplin, MO tornado study.* Gaithersburg, MD: National Institute of Standards and Technology.

Onstot, L. I. 2016. *Joplin, Missouri hit by EF-5 tornado on May 22, 2011*. Joplin, MO: City of Joplin Public Information Office.

Rouche, D. B., and D. O. Prevatt. 2013. "Residential damage patterns following the 2011 Tuscaloosa, AL and Joplin, MO tornadoes." *J. Disaster Res.* 8 (6): 1061–1067.

Storm Prediction Center. 2015. *10 costliest US tornadoes since 1950*. Norman, Oklahoma: Storm Prediction Center.

Strader, S. M., and W. Ashley. 2018. "Fine-scale assessment of mobile home tornado vulnerability in the central and southeast US." *Weather Clim. Soc.* 10 (4): 797–812. https://doi.org/10.1175/WCAS-D-18-0060.1.

US Census Bureau. 2018. "TIGER/Line shapefiles and TIGER/Line files." Accessed May 1, 2018. https://www.census.gov/geo/maps-data/data/tiger-line.html.

US Census Bureau. 2019. "Joplin city, Missouri." http://www.joplinschools.org/departments/transportation/attendance_zones.

US Department of Education. 2007. "Recovering from natural disasters: Preparation is key." *Lessons Learned School Crises Emergencies* 2 (5): 1–13.

Weber, J., and B. Lichtenstein. 2015. "Building back: Stratified recovery after an EF-4 tornado in Tuscaloosa, Alabama." *City Commun.* 14 (2): 186–205. https://doi.org/10.1111/cico.12105.