Digital Reconnaissance and Performance Assessment of Rural Infrastructure for 2018 Natural Hazards

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Abstract: The goal of this investigation is to assess the performance of rural structures in natural hazard events in 2018. Digital reconnaissance was implemented to retrieve data on damage-inflicting events, where collected data included a general summary of the event, the severity of damage inflicted, and the types of structures affected. To better understand the benefits and shortcomings of digital reconnaissance, findings are compared with those of traditional, field reconnaissance for two hazard events. The 2018 digital reconnaissance database is analyzed to discern regional, structural, and event-type trends and the fragility of specific rural structural systems. The investigation identified that, in 2018, damaged rural structures substantially outnumbered damaged urban structures, and the vast majority of damaging events occurred in the South and Midwest regions of the United States. Structures typical of rural areas, particularly barns, grain bins/silos, and manufactured homes, proved especially vulnerable, with many of these structures suffering complete failure in events causing only minor damage to structures more typical of urban areas. However, a comparison with field reconnaissance indicated that quantities of damaged structures are likely underestimated through digital reconnaissance, particularly in rural areas. **DOI: 10.1061/(ASCE)CF.1943-5509.0001460.**

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Introduction

From 1980 to 2019, the National Oceanic and Atmospheric Administration tracked more than 250 climate-related events that caused more than $1 billion in damage (NOAA 2019). Although many of these events impact urbanized areas, creating media buzz and drawing the public eye, many occur in rural regions, where their impact is more quietly broadcast but certainly not without consequence. Rural regions support significantly smaller populations than urban clusters, but a non-negligible amount of damage is still inflicted on them by natural hazards. Based on the database of billion-dollar climate-related disasters (NOAA 2019), Texas, Florida, Louisiana, California, and North Carolina top the list with respect to total damage cost over the past 39 years. Each of these states is along the coast with high population densities and urbanized areas. However, the same data can be normalized by the population of the state impacted (NOAA 2019), which substantially alters this list of states with Louisiana, North Dakota, Mississippi, South Dakota, and Montana rounding out the top five states impacted per capita. With the exception of Louisiana, the most heavily impacted states lie in the Midwest region of the country and are highly rural regions.

Rural Infrastructure and Resilience

Rural communities are vital to the wellbeing of the greater regions they serve. As they house the agricultural industry and critical transportation routes, the health of a country's rural areas is directly related to the health of the country itself (Smit and Brklacich 1989). Unfortunately, these communities tend to be less resilient to disasters than urban regions. This lower resilience is theorized by Cutter et al. (2016) to be partly the result of the geographic remoteness and lack of economic diversity typical of rural areas. In a separate quantitative study by Cutter et al. (2014), counties in the United States were compared across various factors of resilience, including social, economic, housing, infrastructure, community capital, institutional, and environmental. Ultimately, the counties were ranked on their overall resilience to natural disasters. Economic resilience, which is one measure of disaster resilience, is shown to be inversely related to the percentage of a region's employees that are involved in farming. The US counties deemed most and least resilient in this study are included in Table 1, along with the average population densities per the US Census Bureau (2010a). The population densities of the least resilient counties are very low with an average of 2.3 people/km^2 (5.9 people/mi^2), whereas the more resilient counties had much larger population densities with an average of 40.7 people/km^2 (105.3 people/mi^2). Whereas population density was not explicitly used as a criterion for ranking counties' resilience, its inverse correlation with resilience further emphasizes the stark difference in resilience between urban and rural areas.

Furthermore, the types of structures typically found in rural areas tend to be more susceptible to damage in a natural hazard event than those of an urbanized region. For example, most urban areas are characterized by densely spaced houses and commercial buildings, whereas many rural areas are characterized by

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Table 1. Most and least resilient counties in the United States and corresponding population densities

Most resilient			Least resilient		
Rank[a]	County, State[a]	Population density persons/km^2 (persons/mi^2)[b]	Rank[a]	County, State[a]	Population density persons/km^2 (persons/mi^2)[b]
1	St. Charles, Louisiana	73.0 (189.0)	3,108	Imperial, California	16.2 (42.0)
2	Shelby, Iowa	8.1 (21.0)	3,107	Presidio, Texas	0.8 (2.0)
3	St. John the Baptist, Louisiana	83.4 (216.0)	3,106	Esmeralda, Nevada	0.1 (0.2)
4	McLeod, Minnesota	29.0 (75.0)	3,105	La Paz, Arizona	1.8 (4.6)
5	Yellow Medicine, Minnesota	5.4 (14.0)	3,104	Hudspeth, Texas	0.3 (0.8)
6	Putnam, Ohio	27.8 (72.0)	3,103	Daggett, Utah	0.6 (1.5)
7	Big Stone, Minnesota	4.2 (11.0)	3,102	Catron, New Mexico	0.2 (0.5)
8	Red Lake, Minnesota	3.7 (9.5)	3,101	Nye, Nevada	0.9 (2.4)
9	Goodhue, Minnesota	23.6 (61.0)	3,100	Eureka, Nevada	0.2 (0.5)
10	Winnebago, Wisconsin	148.3 (384.0)	3,099	Greenlee, Arizona	1.8 (4.6)
—	Average	40.7 (105.3)	—	Average	2.3 (5.9)

[a]Data from Cutter et al. (2014).
[b]Data from US Census Bureau (2010a).

agricultural support structures, including irrigation systems, storage silos, and barns, which are not designed to the same standards as houses and other buildings. This may lead to a rural community incurring severe damage to its structures in events that would have caused only minor damage to the structures in an urban area as a result of the different structural portfolio. This is evidenced in the Enhanced Fujita scale, which approximates the wind speed to destroy a barn at 180 km/h (112 mi/h), whereas the expected wind speed for the total destruction of a standard residential home is 247 km/h (170 mi/h) (Storm Prediction Center 2007). Due to the different structural portfolios and anticipated poor response combined with the potential for substantial impact on the agricultural economy, further study is warranted to better understand the most vulnerable structures and failure mechanisms in rural areas.

Reconnaissance in Rural Areas

After an area is impacted by a natural hazard, engineers typically perform reconnaissance to glean information on the performance of affected structures. However, reconnaissance is costly and requires substantial manpower. In the interest of efficiency, then, reconnaissance is limited to only the most significant events. Reconnaissance of a minor wind event in a rural community may provide useful data regarding the response of rural structures and communities, but it is often not practical. Because the structural portfolios of rural and urban areas differ greatly, significant types of damage may be evading consideration entirely, simply because they do not occur in more densely populated areas.

Digital (or virtual) reconnaissance presents a promising alternative to traditional methods. Whereas traditional reconnaissance requires the physical presence of a team of engineers in an affected area, digital reconnaissance simply involves the extraction of relevant structural damage information from social media, local news, and government databases. By eliminating the need for travel, this method allows for a data collection process whose efficiency is independent of both the severity and the remoteness of the event. Because of these advantages, in conjunction with an increasingly active social media environment, digital reconnaissance is gaining traction in the structural and geotechnical engineering communities. In recent years, digital reconnaissance has been employed to bolster geotechnical data in the wake of the 2013 Colorado floods (Dashti et al. 2014), and it has been used to compile a damage summary amidst a bevy of events in the June 2014 tornado outbreak in the Midwest (Graettinger et al. 2014). Additionally, the Virtual Earthquake Reconnaissance Team (VERT), a group within the Earthquake Engineering Research Institute (EERI), has been performing digital reconnaissance on major earthquakes since 2015. By rapidly collecting online data after a seismic event, VERT helps the traditional, in-person reconnaissance teams better direct their efforts in the impacted region and provides a baseline record of the impact of other significant earthquake events for which a field team is not dispatched (e.g., Fischer and Hakhamaneshi 2018; Fischer et al. 2019). Similarly, the Structural Engineering Extreme Events Reconnaissance (StEER) network is increasingly incorporating an initial wave of virtual/digital reconnaissance following extreme events since the network's formation in 2018 (e.g., Mosalam et al. 2018; Alipour et al. 2018).

Ideally, every natural disaster would be followed by a thorough structural reconnaissance. Reconnaissance provides information vital to improving the resilience of current and future structures to the various loading scenarios of these events. Although traditional field reconnaissance is being streamlined through organizations such as StEER, it is not practical to conduct field reconnaissance for every event. Digital reconnaissance, however, can provide engineers access to structural damage information for a much broader number of events across a wider range of locations. By bolstering traditional reconnaissance portfolios and providing cursory data in cases where traditional reconnaissance is not feasible, digital reconnaissance can help to paint a more complete picture of the structural damage inflicted by natural hazards.

Objective and Scope

The goal of this investigation is to assess the performance of various structural typologies, particularly those in rural areas, in natural hazard events. It is intended that the results of this investigation shed light on the performance of key structures that contribute to rural resilience. To this end, a database of structural damage due to natural hazards was created for calendar year 2018. For the assessment to be worthwhile, it needed to be expansive, containing as many events as possible. To populate the database with a large number of events and attempt to collect as many natural hazard damage events as possible for 2018, digital reconnaissance was implemented. Because digital reconnaissance is a budding field, the investigation was also taken as an opportunity to compare digital reconnaissance to traditional reconnaissance for two events in dominantly rural areas. In doing so, the benefits and limitations of digital reconnaissance may be better understood. The investigation was limited regionally to the United States, and only events occurring during calendar year 2018 were included.

Methodology

The overarching methodology employed in this digital reconnaissance investigation is presented in a flowchart in Fig. 1. Most simply, the process of this digital reconnaissance consisted of four phases: (1) Gather data, in which several online sources and data pools were scoured for natural hazard events, (2) Identify hazard event, in which the event was determined viable for digital reconnaissance by verifying that there was documentation of damage, (3) Perform event-level digital reconnaissance, in which event-level information was collected, such as the event intensity and the quantity, types, and modes of structural damage, and (4) Data analysis, in which the results for the entirety of 2018 were analyzed. The following subsections detail each of these phases of the digital reconnaissance.

Phase 1: Gather Data

The digital reconnaissance described herein was performed for the entirety of calendar year 2018. To form the digital reconnaissance database, the process of scouring online sources and collecting information was repeated until 2018 was exhausted of events. This process was conducted manually, although filters on rough damage estimators such as cost estimates and earthquake magnitudes were applied to exclude events in which the likelihood of structural damage was negligible. All collected information was stored in a Microsoft Excel spreadsheet, in which each row corresponds to an event, and each individual event was assigned a unique folder to

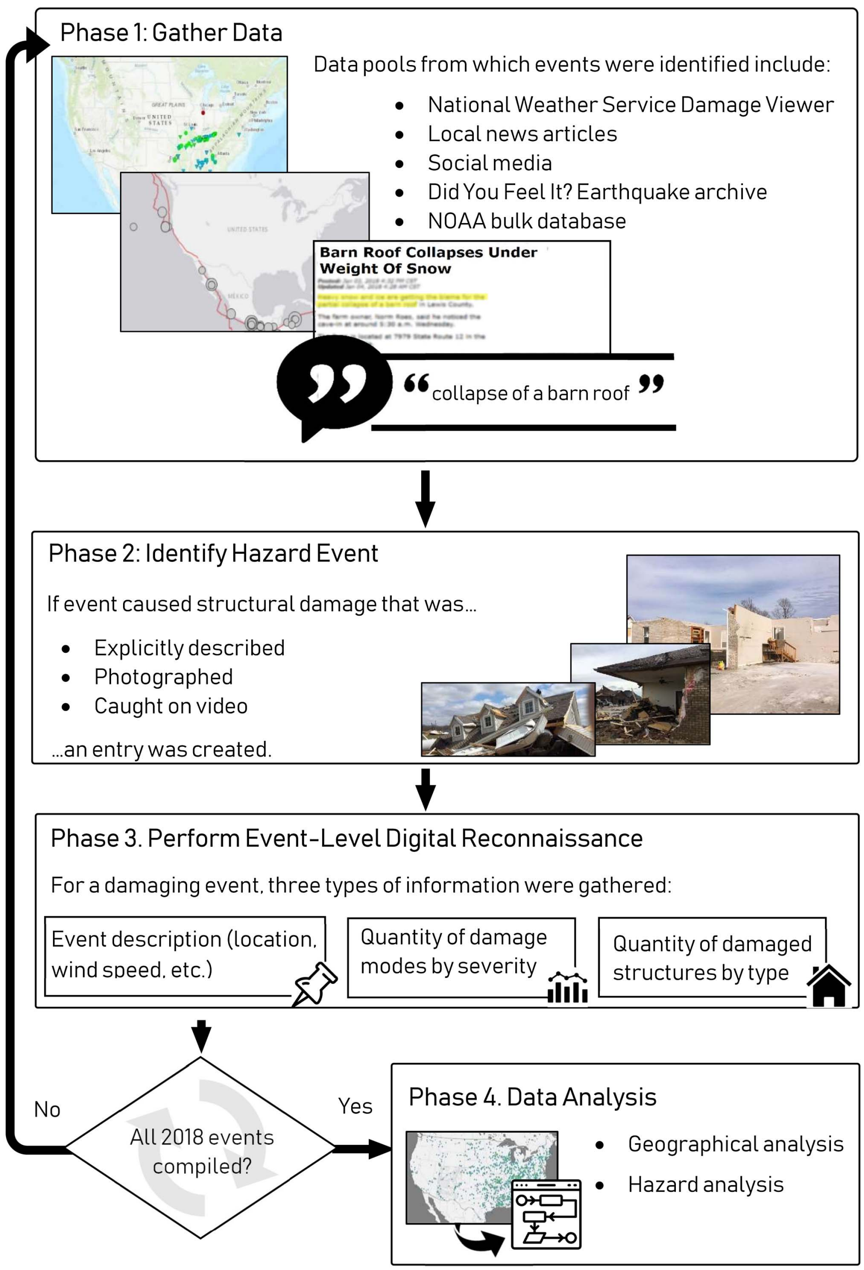

Fig. 1. Flowchart of digital reconnaissance procedure. (Map data © 2019 Google; Images reproduced from NWS 2018, courtesy of the National Weather Service.)

Table 2. Applicable data pools by hazard type

Hazard type	Data pools				
	Local news	Social media	NOAA	NWSDV	DYFI?
Tornado	Yes	Yes	Yes	Yes	—
Wind	Yes	Yes	Yes	Yes	—
Flood	Yes	Yes	Yes	—	—
Lightning	Yes	Yes	Yes	—	—
Snow	Yes	Yes	Yes	—	—
Hail	Yes	Yes	Yes	—	—
Rain	Yes	Yes	Yes	—	—
Wildfire	Yes	Yes	Yes	—	—
Earthquake	Yes	Yes	—	—	Yes

hold supplementary files, like photos and articles. Because the goal of this project was to amass a database of damage to structures in rural areas that was as inclusive as possible, a variety of online sources was tapped for potential events. Ideally, the reconnaissance would incorporate government reports, local journalism, and citizen observations into one cohesive database. With this in mind, the following data pools were selected as potential sources of damage events:

1. National Weather Service Damage Viewer (National Weather Service 2018)
2. Local news articles
3. Social media (e.g., Facebook, Twitter, Snapchat, and Instagram)
4. Did You Feel It? Earthquake Archive (USGS 2018)
5. NOAA Storm Events Database (NOAA 2018)

These data pools vary significantly in the resolution of their data, the reliability of their claims, the types of information they provide, and the natural hazards of interest. A single data pool rarely provides a complete description of an event. Shortcomings of a particular data pool can be overcome by tapping other data sources, ideally resulting in a more complete understanding of the impacts of the event. As such, a brief discussion of the strengths and weaknesses of these data pools, and the information contained within, is described in the subsections that follow. A summary of the utilized data pools and the associated event types is listed in Table 2.

National Weather Service Damage Viewer

The National Weather Service Damage Viewer (NWSDV) is a data interface that is populated with data collected during NWS Post-Event Damage Assessments (NOAA 2018). This data pool provides high-resolution information for wind and tornado events, including estimated maximum wind speed, type of damaged structure, and photos of damage. Although this can act as a valuable data pool for digital reconnaissance of windstorms, the NWSDV is not a structural damage catalog—instead, its primary purpose is to archive weather events and estimate surface-level wind speeds for meteorological purposes. Structural damage is often presented as a gauge of storm intensity. As such, if several of the same type of structures experience the same type of damage in close proximity to one another, only a representative structure may be shown, whereas the redundant instances may be left out. For this reason, the NWSDV may underestimate the number of damaged structures as a digital reconnaissance data pool but is likely to capture whether a certain severity of damage occurred to a particular type of structure.

Local News Articles

Local news articles contain important data but are far sparser than NWSDV events. The goal of a local news article is often to inform the community of the event's impact; an estimate of the number of damaged structures is often reported, which makes this data pool critical for obtaining more accurate quantities of damaged structures. Additionally, these articles occasionally include quotes from local experts regarding topics such as the age of an affected structure, the estimated load experienced by a structure, or the financial impact of an event on a community. This data pool may provide higher-resolution data than the NWSDV in many cases, but less extreme events or those that damage few structures may not be reported. In addition, the NWSDV is compiled by meteorological experts trained in estimating wind speeds, which leads to a more consistent interpretation of the event compared with the local news articles. It is noted that when extracting information from a local news article, the article was archived as a PDF file to preserve the source in the event that the article is deleted (a frequent occurrence for small local news outlets).

Social Media

Social media serves as an excellent source for damage photos and videos. After an event, especially one causing severe damage, local citizens often post photos and videos of damage to sites like Twitter, Facebook, Snapchat, and Instagram. With no quality control, this data pool is the least reliable of the five, but so long as the event is identified through another avenue, this source is helpful for supplementing an entry with damage photos and/or updating a number of structures damaged. Particular attention was paid to ensure that an event or structure was not double-counted. That is, social media was utilized only to supplement a previously identified event, and the structures referenced were cross-checked with the quantities and descriptions from the other sources.

Did You Feel It? Earthquake Archive

The Did You Feel It? (DYFI?) Earthquake Archive is a database in which citizens can report if they felt a seismic event (USGS 2018). More importantly, it serves as a collection of earthquakes recorded by the USGS and is, therefore, a helpful tool for identifying potentially damaging earthquake events and the geographic extents for potential damage identification. The archive provides the USGS-determined earthquake source characteristics (e.g., magnitude, depth, epicenter, faulting mechanism), but also provides estimates of ground shaking amplitude and potential for damage through the Modified Mercalli Intensity Scale. Actual damage data must be extracted from other sources, such as local news articles or social media.

Low-magnitude earthquakes are unlikely to cause damage, so searching for information on every seismic event contained in this archive would be inefficient. Instead, a system for filtering these events was decided upon at the onset of the investigation to simplify this effort. Offshore and onshore seismic events with magnitudes greater than 5.5 and 4.5, respectively, were utilized in this study due to the likelihood for strong ground shaking and potential for damage. Events not meeting these criteria were not queried in the other data pools.

NOAA Storm Events Database

The final data pool is the Storm Events Database from the NOAA (2018). The database includes a record of all storm events and other significant weather phenomena, and includes event locations, magnitudes, and narratives describing the event and damage. Additionally, this database contains an estimate of the cost of damage for each event, which serves as a tool for comparing event magnitudes on a consistent basis. These cost estimates, however, are not always comprised entirely of structural damage. For example, in wildfire events, the containment cost is included in the property damage estimate. Whereas this database contains a vast amount of information and includes a substantial number of events, it does not include photos of damage. Rather, the provided event narrative is the only means of tallying damaged structures and rating damage severity. Similar to the use of social media, particular attention was paid such that the events identified and quantities of structures damaged were not duplicating information collected through the other data pools.

Phase 2: Identify Hazard Event

In order for a damage event to be included in the investigation, structural damage documentation needed to pass a threshold of information such that a meaningful entry into the database would be generated. It is noted that the results from this digital reconnaissance are likely to be conservative in terms of the number of damaging events as a result of this requirement for inclusion in the study. Upon identifying a potential event from one of the aforementioned data pools, the event was added to the digital reconnaissance database if any of the following questions could be positively answered:

1. Is the damage explicitly described, either in severity, type, or affected structure?
2. Are there photographs of the damage?
3. Was the damage caught on video?

Nine event types were investigated in this reconnaissance: tornadoes, windstorms, floods, lightning, snow, hail, rain, wildfires, and earthquakes. For most events, this distinction was self-evident; however, some event types required further definition. Tornadoes differ from other wind events, for example, in that tornadic events must involve vorticity; and this distinction was typically gleaned from the information provided by NOAA or NWS. In addition, rain events are different from floods—in this investigation, a rain event is one in which rain ponding on the roof of a structure caused damage to the structure. Similarly, a snow event is one in which snow accumulation on the roof of a structure caused damage to the structure.

Phase 3: Perform Event-Level Digital Reconnaissance

Once an event was identified as described above, an event-level digital reconnaissance was conducted. Data collection for an individual event includes classifying and quantifying the types of structures impacted, assessing the severity of damage to those structures, and determining if the structural damage occurred in a rural or urban area. Each of these aspects is discussed in detail in the following subsections, along with an overall discussion of the uncertainties. The final phase of the digital reconnaissance, Phase 4: Data Analysis, is described in the following section along with the results of this process for 2018.

Structural Classification

The first step in the event-level data collection involves classifying and quantifying the structures that have been impacted. Individual structures were classified and quantified based upon photographs and/or text descriptions from the data sources listed above. This task was completed with particular attention not to double-count any structures that were described in multiple data sources. To gain a general understanding of structural performance, structures were classified into five primary categories, as shown in Fig. 2: residential structures, agricultural structures, other building structures, transportation systems, and lifeline networks. *Residential Structures* were subdivided as single-family homes, multifamily complexes, and manufactured homes. *Agricultural Structures* were subdivided as barns or other agricultural storage buildings, irrigation pivots, and grain bin/silos. All nonresidential and nonagricultural buildings were categorized under a general *Other Buildings* classification, which included office buildings, schools, and hospitals. *Transportation Systems* included roadways, bridges, and culverts. The final classification, *Lifeline Network Components*, included high-voltage transmission lines, utility poles, communication towers, and pipelines. It is noteworthy that this category considers individual lifeline network components, such as a single utility pole or pipe and is not indicative of the damage inflicted to the broader network.

Fig. 2. General classifications for structures in the digital reconnaissance, excluding the *other*, *lifeline*, and *unspecified* categories. (Images by authors.)

Each classification also included an *unspecified* category for structures which could be classified as residential, agricultural, building, transportation, or lifeline, but could not be further classified. Additionally, other structures that fall outside of the five primary categories were included in the digital reconnaissance and identified in an *Other* category. Examples of such structures within the *Other* category include carports and billboards. Due to the focus on rural and agricultural areas, crop damage was also reported within the *Other* category.

Structural Damage

For every event, an attempt was made to classify and quantify the mode and severity of damage. Structural damage was separated into three modes—roof damage, wall damage, and foundation damage—each of which was separated into four severities ranging from minor to extreme. Damage to an individual structure could be categorized in one or more of the damage modes, depending upon available information. Damage severity is, by nature, subjective; however, effort was made to align the severity levels used in this study with typical levels used in traditional reconnaissance (e.g., Kijewski-Correa et al. 2019). For this reason, severity in each of the three damage modes was defined by conventions outlined at the onset of the reconnaissance, as outlined in Table 3 and Fig. 3. It is noted that the damage severity ratings were primarily based on established criteria for tornado and wind events (e.g., Kijewski-Correa et al. 2019). However, these criteria are used for all hazards in this study because they are largely based on interruptions to the structural load path. For a similar reason, the damage severity ratings were also not refined by construction style, and the photographs in Fig. 3 are intended for general understanding only.

As described in Table 3, roof and wall damage were similarly described at the minor and moderate levels based upon cover loss. In both cases, severe damage was largely dictated by a reduction in the load-bearing capacity of the structure (e.g., loss of an individual wall or damage to the roof truss). Extreme damage was reserved for structural collapse. Whereas the roof and wall damage severities are broadly applicable to most building and house structures, the foundation damage mode was largely motivated by unanchored or weakly anchored housing (e.g., manufactured housing) due to the inability to identify foundation failures without being on-site for most other structures. Given that this study particularly focuses on rural areas, many nonbuilding structures, such as grain bins and

Table 3. Criteria for damage severity in digital reconnaissance

	Definition/Criteria			
Damage mode	Minor	Moderate	Severe	Extreme/Total loss
Building/House—roof	Roof cover loss less than 50%	Roof cover loss greater than 50%	Any damage to the roof truss or rafters	Substantial damage to roof structure; complete loss of roof
Building/House—wall	Siding loss less than 50%	Siding loss greater than 50%; minor cracks	Any indication of a reduction of weight-bearing capacity; leaning/bowing of a wall; loss of one wall	Multiple walls removed; complete collapse
Building/House—foundation[a]	Less than 50% foundation siding/skirting loss	Greater than 50% foundation siding/skirting loss	Permanent shift of house/foundation	Overturning or complete removal of house from foundation
Other (e.g., silo, irrigation system)	n/a	n/a	n/a	Any damage

[a]Foundation damage specific to housing.

Fig. 3. Classifications for structural damage, except nonbuilding structures (e.g., grain bin) which were classified as *extreme damage* if any damage was apparent. (Images by authors.)

irrigation pivots, are included in the reconnaissance. However, damage to these systems was treated differently because detailed descriptions are not typically available. For this reason, damage at any level for these structures was conservatively noted as extreme or a total loss. In addition to severity for the roof, wall, and foundation, an overall assessment of the severity was included for each damage point. This was based on the highest severity across all damage modes.

Urban and Rural Classification

In addition to event-level digital reconnaissance and in keeping with the goals of this investigation, each event was separated into rural and urban categories. The US Census Bureau defines rural areas as those that do not meet the requirements of an urban cluster or an urbanized area (US Census Bureau 2010b). Based on this definition, a rural area has a clustered population of fewer than 2,500 people. This delineation is available for the United States as a downloadable shapefile (US Census Bureau Geography Program 2019). The latitude and longitude of each event in the database was compared against this delineation through a custom code. An event was considered urban if it was contained in either an urban cluster or an urbanized area and was considered rural otherwise. Whereas events with data from NWSDV, NOAA, or DYFI? typically contained latitude and longitude information for points of structural damage, the exact location was oftentimes not available for events with data pulled only from social media and/or local news sources. For these cases, the latitude and longitude of the town mentioned in the source was used for a location. Because of this, a rural event could potentially be determined to be urban if the nearest town was an urban cluster. To correct these distinctions, events without NWSDV, NOAA, or DYFI? data were separated from the other entries and investigated on a case-by-case basis. Photos of the event were used to determine, using best judgment, whether the event or the damage point was in a rural or urban area. For events affecting large regions, such as severe floods and long-path tornadoes, both rural and urban areas could be impacted by the same event. Effort was made to separate damage occurring in rural and urban areas for these events; however, this was not always possible. For this reason, events that impacted both urban and rural areas, but for which damage was not able to be differentiated, were considered entirely urban.

Limitations and Uncertainty

The primary limitation of the event-level digital reconnaissance is the availability of digital data, upon which this study relies. Despite the use of multiple governmental and private data pools, it is not guaranteed that there will be sufficient digital data to accurately reflect the structural typologies impacted and the severity of damage for a given natural hazard event. This results in a digital reconnaissance that is expected to underreport damage in comparison to field reconnaissance, which is explored further later in this paper. The availability of digital data is expected to impact both the structural classification and the structural damage steps of this reconnaissance. Specifically, many data sources use generic terms to refer to structures that incurred damage. For example, a data source may describe a *house* as being damaged, but there is not sufficient information to further classify that house. Likewise, the house may be described as having suffered *roof damage*, but there is not sufficient information to appropriately classify the damage severity. The availability and detail of the digital data also impact the number of structures damaged. Many data sources may report *many* or *some* of a given structural typology as being damaged. It is clarified that the authors took a conservative approach in this regard, and *many* or *some* were reported as two.

A second limitation of this study stems from the categories designated for structural classification and structural damage. Structures were classified primarily by use, such as residential or agricultural, but are not classified by construction style. In addition, *Other* structures encompass a wide variety of systems, including carports, billboards, and crops. This prevents detailed analysis of the performance of these individual structures. Likewise, the damage classification is not hazard specific and reports damage in only a broad sense—that is, a rating based on a degree of interruption to the structural load path. Specific damage and failure mechanisms are not reported. Another limitation within the damage classification relates to all nonbuilding structures, which includes *Other* and *Lifeline Network Components*. In these cases, any damage was reported as *Extreme*. This prevents a detailed analysis of the performance of these structures but is expected to be conservative.

As mentioned, the availability and detail of digital data limit the analyses that can be conducted using this digital reconnaissance database. This paper analyzes the digital reconnaissance database with respect to geography, hazard, structure type, and cost. Whereas the digital data's impact on the analyses with respect to structure type has been discussed in detail in this section, it is specifically noted that the analysis with respect to cost is limited to tornadic events only. Conclusions made with respect to the analysis by cost should be taken with caution due to the limited hazard inclusion.

Statistical Analysis and Damage Patterns

The digital reconnaissance methodology described above was followed for the entirety of 2018 and compiled into a database of events. This database is analyzed according to the following subsections along multiple dimensions. First, the events are analyzed with respect to location, because structure and hazard typologies vary across the United States. The events are further analyzed by hazard type, which impacts the likely modes of structural damage. An additional analysis with respect to damage cost estimates is presented as an overall measure of the damage incurred in both rural and urban areas. A final analysis is presented, which aims to summarize the impact of natural hazards by structural typology in both rural and urban areas with particular attention to the unique structures found in rural areas.

Analysis by Geographic Location

A total of 1,572 events was identified over the course of 2018 in the contiguous United States. Each of these events is shown overlaid on a map of the United States in Fig. 4, where the marker indicates the type of hazard. The events are distributed across the country with damage-inducing hazards occurring in nearly every state. However, the majority of events are concentrated in the southern and midwestern regions with substantial numbers of events occurring outside of the major metropolitan areas. As expected, most of the events in these dominantly rural regions are tornadoes, which impact a relatively small area compared with other hazards, such as floods. In an effort to further explore these data with respect to geographic location, a bar chart with event count across the major regions of the United States is included in Fig. 5. The chart is clustered to separate the events that occurred in rural and urban areas of these regions. Out of the 1,572 events in 2018, more than 50% of the events occurred in the south, and more than 30% occurred in the Midwest—both of which are predominantly rural. This is compared with less than 10% of all events in 2018 occurring in each of the more densely populated northeastern

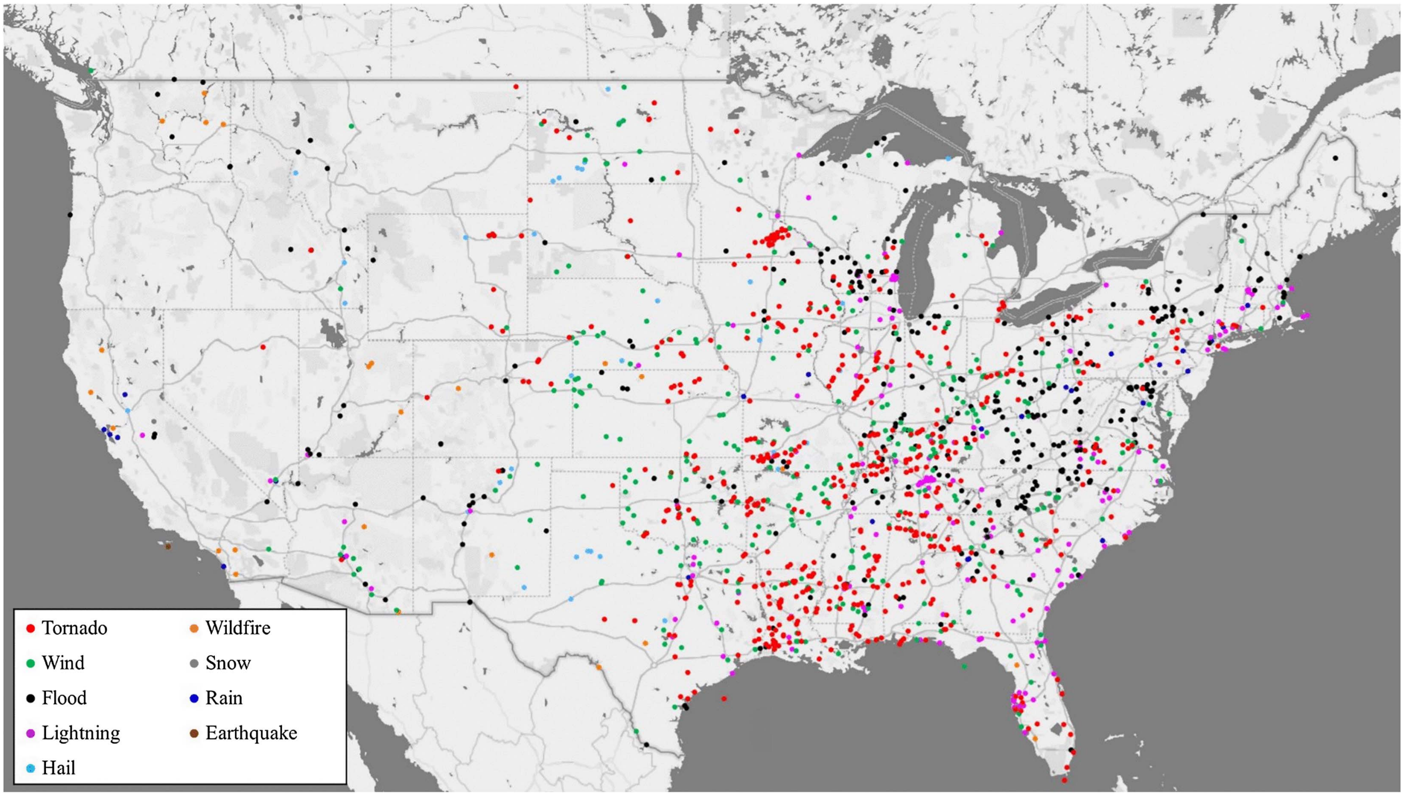

Fig. 4. Identified events in the contiguous United States. (Map data © 2019 Google.)

and western regions. The large quantity of rural hazards is further emphasized by noting that more than 75% of all events across all regions of the contiguous United States occurred in rural areas compared with less than 25% in urban clusters and urbanized areas. It is noted further that the rural event majority is likely quite conservative, because rural events identified through local news articles were, at times, classified as urban if the town listed in the article was large enough to classify as an urban cluster and there was no additional location information for the damage. Furthermore, most events in every region were in rural areas—even in the densely populated northeast, though to a lesser degree. Whereas the number of damage-inducing hazard events in rural areas is widely apparent from this dataset, the reconnaissance is further explored with respect to structural typology, hazard, and cost in the following sections to gauge the impact that these events have in rural areas.

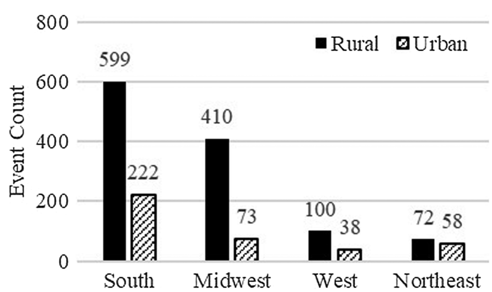

Fig. 5. Identified events for urban and rural regions in each region of the contiguous United States.

Analysis by Hazard Type

Building upon the geographical analysis of the previous section, the digital reconnaissance is analyzed with respect to the various hazard types in the current section. The total number of events for each hazard type is quantified in Table 4 for rural and urban regions in the United States and for the total number of states impacted. The rows of the table are ordered with the most commonly identified hazards at the top and the least frequent at the bottom. From this table, it is apparent that tornadoes and wind account for the majority of hazard events in the United States with 949 damage-inducing events across 44 states in 2018. Of the wind-related events, the majority are associated with tornadoes. The next most frequently reported damage-inducing event is flood, which had 333 events across 46 states. There were much fewer instances of other hazard types reported in 2018, including lightning, snow, hail, rain, wildfire, and earthquakes; however, multiple damage-inducing events were

Table 4. Event quantities by type

Hazard type	Rural events	Urban events	Total events	Number of states
Tornado	508	89	597	39
Wind	300	52	352	44
Flood	249	84	333	46
Lightning	66	101	167	45
Snow	14	27	41	32
Hail	31	6	37	13
Rain	7	26	33	17
Wildfire	17	7	24	10
Earthquake	4	1	5	4

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identified for each hazard type. The least frequently reported event was earthquake, which included only five events across four states.

Table 4 also highlights the impact on rural areas with more than 85% of all damage-inducing tornadoes and wind occurring in rural areas. However, not all hazard types impacted rural areas in the same way. For example, damage due to lightning was more commonly identified in urban areas, which makes sense given the height of buildings in most urban areas. Similarly, the larger number of urban snow and rain events is likely due to the differences between rural and urban structures. These events indicate damage due to the weight of snow and ponded rain on the roofs of structures. In urban areas, many roofs, especially those of small commercial buildings, are flat, allowing for deep snow accumulation and heavy ponding. Alternatively, in rural areas, almost every roof is pitched, preventing significant snow accumulation or rain ponding.

The hazards were further analyzed by the damage severity. Fig. 6 is a bar chart showing rural (R) and urban (U) event quantities for each hazard type, where each bar is stacked according to the quantities of events that caused up to a certain level of damage. These severities are based on the previously defined damage categories (Fig. 3 and Table 3) and are based on the worst damage caused by an individual event. For example, if a windstorm caused both the total collapse of a barn and minor roof damage to a home, that storm would be recorded as an extreme wind event only, rather than both a minor and extreme wind event. Events for which no severity information was determined are included in the unspecified category.

Based on this chart, extreme damage is most commonly identified in rural windstorms and tornadoes with the majority of events falling into this severity category (collapse). Although the high number of recorded collapses in rural areas could be due to the structural typology present in rural areas, it could also be the case that events causing only minor damage in a rural area may simply not be reported. In this case, the numbers presented in this digital reconnaissance are likely to be conservative; however, this will be explored later in this paper through a comparison with traditional reconnaissance. In addition to the high number of extreme damage due to wind in rural areas, other events dominantly resulted in minor damage. Hail events, for example, rarely caused more than minor roof or wall damage. On the other hand, if noteworthy damage occurred in rain ponding or snow accumulation events, the damage was most often a complete roof failure, which would be identified in the extreme damage category.

It is worth noting that earthquakes are not a weather-related hazard like the other hazards in this database, but are geological; and, as such, it is expected that earthquake occurrence would be substantially less frequent compared with the other studied hazards. This is reflected in the lower total number of events seen in Table 4. However, earthquake events more frequently resulted in severe or extreme damage, as seen in Fig. 6. This is due, in part, to the quality of digital data available for earthquakes, for which structural damage data are not typically reported by a governmental agency, and the widespread impact of earthquakes over a region.

Analysis by Structure Type

Whereas previous sections analyzed the number of hazard events in 2018 by hazard type and location, the analysis is furthered in this section by looking at the types and counts of various structural typologies that were damaged. The total quantities of damaged rural and urban structures are presented in Fig. 7 according to the general structural categories presented in Fig. 2. It is clarified that the data presented in this figure exclude the two major hurricanes that impacted the United States in 2018, namely Hurricane Florence and

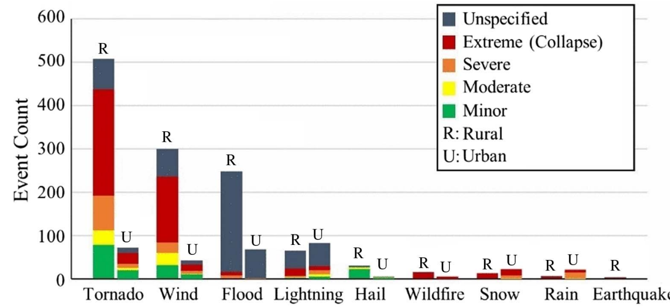

Fig. 6. Event quantities by type and most severe damage caused.

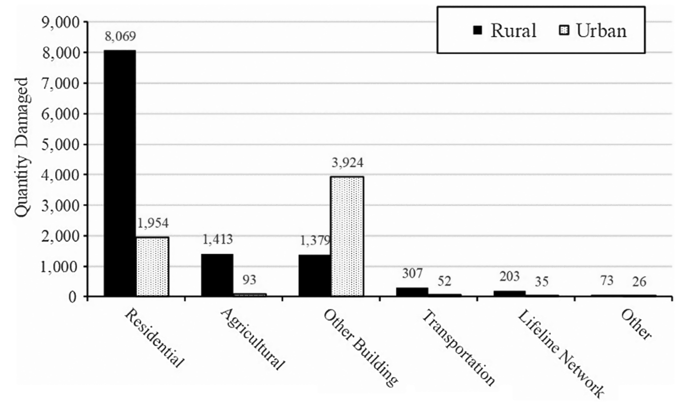

Fig. 7. Event quantities by structural typology in rural and urban areas.

Hurricane Michael. The hurricanes were excluded from this analysis due to the extremely large number of impacted structures, which prevents comparison between urban and rural damage due to more common events.

Despite the exclusion of Hurricanes Florence and Michael, the majority of damaged structures were residential buildings, which, in this analysis, included standard, mobile, complex, and unspecified residential structures. The next-most frequently damaged structure classification was the nonresidential, nonagricultural building category, which included office or professional buildings, schools, hospitals, and other unspecified buildings. This was followed by the agricultural structure category, transportation systems, and other structures. Although not surprising that residential construction dominated the damage count, these data highlight that nearly four times as many residential homes were damaged in rural areas compared with urban areas. The higher number of houses damaged in rural areas appears tied to the larger number of events occurring in rural areas (Fig. 5). Considering that most of the damage-inducing events were either tornadoes or windstorms, there were more than five times as many tornadoes and windstorms in rural areas (Table 4). Whereas only four times as many residential houses were damaged in rural areas, that mild discrepancy is likely attributed to the lower density of structures in rural areas.

The trend of higher damage counts in rural areas was followed by all categories except for the *Other Building* category. This exception is plausible given that buildings of this type are generally located in some sort of an urban cluster (e.g., the small downtown center of a rural town). In addition, it is highlighted that although the agricultural structure classification did not see the highest

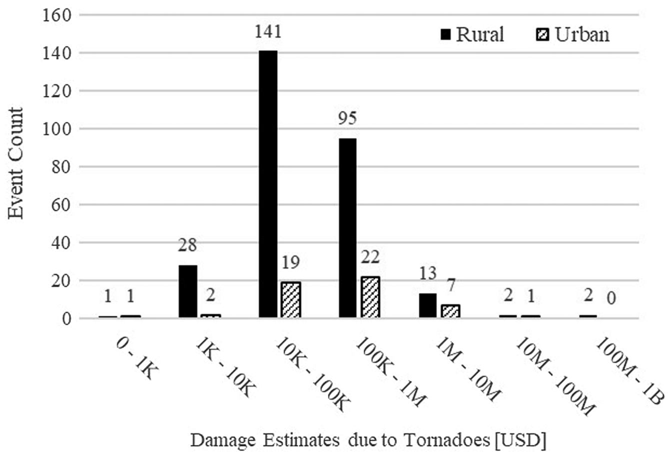

Fig. 8. Tornado event quantities by NOAA cost estimate range.

quantity of damaged structures, a relatively large number of damaged systems were still identified (1,506). In fact, the number of damaged agricultural structures outweighed the total number of transportation and other systems combined (638) by more than a factor of two.

Analysis by Cost

Although detailed estimates of damage cost are not typically readily available, the NOAA bulk database provided an estimate of damage for most tornadoes in 2018. Given that these cost estimates are all derived by the same entity, they provide the most consistent basis upon which the overall impact of different events can be compared. This analysis is presented in Fig. 8 for tornado events only as a function of the total damage cost in both urban and rural areas. The event quantities roughly follow a normal distribution, with the majority of tornadic events having damage estimates between $10,000 and $1 million. Whereas the number of tornadic events costing more than $1 million was similar between urban and rural areas, a substantially higher number of events costing about $100,000 occurred in rural areas. This is evidenced by the total cost estimates for tornadoes in 2018 in rural areas is approximately $467 million, whereas the total for urban areas ranges is an order of magnitude less at approximately $73 million. This is significant because most rural communities have substantially fewer resources and redundancy to absorb these costs compared with more urban areas. It is reiterated that this analysis is with respect to 2018 tornadic events, only, and does not account for other hazard events due to data availability. Despite the limited focus with respect to hazard type, tornadoes were the most frequent hazard event encountered, and the costs presented are expected to represent a substantial percentage of the total costs in rural areas.

Comparison with Traditional Reconnaissance

The digital reconnaissance conducted for 2018 is noted to likely be a conservative understanding of the impact of natural hazards in rural areas. This largely stems from the conservative interpretations of qualitative damage counts (e.g., *dozens* = 24, *many* = 2) and the partial reliance on local news sources, which may not widely report on more minor events. To this end, the following subsections compare the information gleaned from the digital reconnaissance with that obtained in the field during traditional engineering reconnaissance. This comparison is presented for two individual events: (1) a windstorm in Fremont County, Iowa, and adjacent Cass County, Nebraska, in June 2018; and (2) tornadoes near Pella and Marshalltown, Iowa, in July 2018. These events were selected for the comparison because they primarily impacted rural regions, which is a particular focus of this study and can be considered fairly typical of the data collected during the digital reconnaissance in terms of data quantity and data sources.

Fremont and Cass Counties Windstorms

On June 11, 2018, severe thunderstorms producing hail, straight-line winds in excess of 152 km/h (95 mi/h), and EF-0 tornadoes [105–137 km/h (65–85 mi/h)] struck parts of Fremont County, Iowa, and adjacent Cass County, Nebraska, along the Missouri River. Field reconnaissance was conducted by a subset of the authors on June 15. In an effort to separate the digital and field reconnaissance, a random sampling strategy was employed in the field. This largely consisted of visual surveying from a vehicle traversing the primary roads in the area. Given that the area is largely agricultural and that structures are sparse, this strategy enabled a moderately detailed assessment of the region. Individual structures were assessed using a rapid evaluation approach based loosely on the ATC-20 Rapid Evaluation Safety Assessment, in which the following was collected: (1) Structural description: general information, such as structure type (Fig. 2), location, and method of construction; and (2) Evaluation: functionality and/or operability (e.g., binary metric associated with whether or not the structure could be utilized for its intended purpose), location and severity of damage (e.g., roof, wall, foundation) in accordance with Fig. 3 and Table 3.

The digital reconnaissance for this particular event received data from only two of the five data pools, namely the NWSDV and local news sources. The results of the digital and field reconnaissance are presented in Tables 5 and 6, respectively. As seen for the digital reconnaissance, a wide range of structures was noted to have some level of damage including common structures such as residential housing and agricultural structures including grain bins/silos. Despite this observed breadth of structures from the digital reconnaissance, an even wider range was observed in the field. The structures missed digitally include center-pivot irrigation systems and crops, indicating that only rural or agricultural components were missed for this specific event with respect to structure type identification.

In addition to the type of structures identified, the quantity of damaged structures is compared. In general, the field reconnaissance identified a greater number of damaged structures for nearly every structural classification. However, the digital reconnaissance oftentimes implied that several of a structural type were damaged without a specific quantity. In these cases, the digital reconnaissance noted the values as $X+$. The most substantial underestimates by the digital reconnaissance were for the primarily rural or

Table 5. Summary of digital reconnaissance: windstorms in Fremont and Cass Counties

Structure	Identification	Quantity	Severity
Irrigation pivot	No	0	N/A
Grain bin/silo	Yes	2+	Extreme: damage
Crop damage	No	0	N/A
Barn	Yes	1	Minor: roof cover loss
Other building	Yes	1	Extreme: roof tear off
Other structures	Yes	10+	Extreme: (9) overturned semis; (2) untethered boats;
Residential	Yes	2+	Minor: roof cover loss

Table 6. Summary of field reconnaissance: windstorms in Fremont and Cass Counties

Structure	Identification	Quantity	Severity
Irrigation pivot	Yes	1	Extreme: (1) overturning
Grain bin/silo	Yes	7	Moderate: (5) roof buckling, (1) sidewall buckling; extreme: (1) overturning
Crop damage	Yes	1	N/A: field loss
Barn	Yes	11	Extreme: (9) roof tear off, (1) partial collapse, (1) total collapse
Other building	Yes	1	Extreme: roof tear off
Other structures	Yes	5[a]	Extreme: (3) collapsed equipment, (2) overturned windmills
Residential	Yes	11	Minor: (6) roof shingle loss, (2) siding loss, (3) curtain wall loss

[a]Quantity comparison with Table 5 reflects different structures.

agricultural structures, including grain bins/silos which totaled seven in the field but only 2+ in the digital reconnaissance and barns which totaled 11 in the field but only one in the digital reconnaissance.

On the other hand, the digital reconnaissance was able to capture the damage within the *Other Buildings* category because this was a post office and was photographed heavily in the local news. In addition to the identification, the digital reconnaissance captured the damage mechanism, which consisted of complete roof tear off.

Although this case study yielded accurate quantity and severity for the category of *Other Buildings*, this is not necessarily expected to hold true for all events because only one structure fell into this category for this event. This is demonstrated through the comparison of damage severity for the remaining structure categories. For example, residential housing structures were reported to have a loss of roof shingles. However, the field reconnaissance indicated that additional damage mechanisms were present on some houses, including loss of vinyl siding and loss of vinyl curtain walls at the foundation levels of manufactured houses. In addition, the primarily rural structure categories of grain bins/silos and barns presented a much wider range of severity between the digital and field reconnaissance findings. Specifically, grain bins were reported as *damaged* in the digital reconnaissance, but the field reconnaissance evidenced roof buckling, sidewall buckling, and overturning of these structures. Similarly, barn and other agricultural structures were reported to have roof damage in the digital reconnaissance, but the field reconnaissance evidenced roof tear off, partial collapse, and total collapse. Therefore, in summary, digital reconnaissance for this case study event was able to identify the breadth of structures impacted but provided only conservative estimates of the quantity and severity of the structural damage. However, the quantity and severity of damaged structures were captured with higher accuracy for the *Other Building* and *Residential Housing* categories compared with the primarily agricultural structures.

Pella and Marshalltown Tornadoes

On July 19, 2018, upwards of 12 tornadoes swept through central Iowa. Whereas many of these tornadoes remained weak [EF-0: 105–137 km/h (65–85 mi/h) winds], two EF-3 tornadoes [wind speed: 219–266 km/h (136–165 mi/h)] and two EF-2 tornadoes [wind speed: 179–217 km/h (111–135 mi/h)] were included. The tornadoes directly struck the towns of Pella and Marshalltown, which have populations of approximately 10,000 and 27,000 people, respectively. However, many of the tornadoes traveled the largely rural and agricultural surrounding regions. Due to the large impact on local businesses and the emergency declaration by the governor, this event received substantial coverage by national and local news agencies and by the National Weather Service. A summary of the digital reconnaissance is provided in Table 7 in a format similar to that of the previous case study event. The results of the digital reconnaissance reflect a very narrow range of structures impacted, with coverage largely reflecting damaged industrial and commercial structures and residential housing. In fact, there were no reports of damage to agricultural structures at all through the digital reconnaissance. Whereas previous studies suggest that social media activity is correlated with damage following a disaster like this (e.g., Kryvasheau et al. 2016), the lack of digital data on agricultural structures is likely attributed to the substantial damage to two very prominent manufacturing plants, which employ a large number of local people—namely, the Vermeer plant in Pella and the Lennox plant in Marshalltown. The tornadoes directly struck these structures resulting in partial and total collapses, as described and documented in multiple news sources. Additional structures identified from the digital reconnaissance within the *Other Building* category were primarily located in the downtown Pella and Marshalltown areas, including a historic courthouse, which received substantial coverage due to the proximity to the manufacturing plants.

Field reconnaissance was conducted by a subset of the authors on August 4, 2018, with a particular focus on impacts to rural infrastructure. Provided the estimated tornado tracks by the National Weather Service, all structures within approximately 1,000 m of the tornado tracks that were not within the downtown areas of Pella and Marshalltown were surveyed. Each structure underwent a rapid visual assessment, based loosely on the ATC-20 Rapid Evaluation Safety Assessment tool and previously described under *Fremont and Cass Counties Windstorms*. A summary of the field reconnaissance results is included in Table 8.

Comparing the results of Tables 7 and 8 with respect to structural identification, a much wider range of damaged structures was captured in the field. Whereas the digital reconnaissance evidenced damage to industrial buildings, residential housing, and crops,

Table 7. Summary of digital reconnaissance: tornadoes in Pella and Marshalltown, Iowa

Structure	Identification	Quantity	Severity
Irrigation pivot	No	0	N/A
Grain bin/silo	No	0	N/A
Crop damage	Yes	4	N/A: $11,000 in crop damage at four fields
Barn	No	0	N/A
Other building	Yes	10+	Extreme: (3) total collapse Severe: (1) loss of wall, (3) partial collapse Minor: (2) roof cover loss; Unspecified: (1) hospital *damaged*
Other structures	No	0	N/A
Residential	Yes	6+	Severe: (6) partial loss of roof Minor: (2+) roof shingle loss

Table 8. Summary of field reconnaissance: tornadoes in Pella and Marshalltown, Iowa

Structure	Identification	Quantity	Severity
Irrigation pivot	No	0	N/A
Grain bin/silo	Yes	24	Moderate: (9) roof and/or sidewall buckling; Extreme: (10) total collapse, (5) roof loss
Crop damage	Yes	3	N/A: Tornado track in cornfield
Barn	Yes	22	Extreme: (2) total collapse, (14) roof tear off Severe: (6) partial collapse
Other building	Yes	5	Extreme: Vermeer and Lennox plants, only
Other structures	Yes	2	Extreme: (1) collapsed carport, (1) collapsed aboveground pool
Residential	Yes	5	Minor: (4) roof cover loss, (1) siding loss

the field reconnaissance identified additional damage to grain bins/silos, barns structures, and other structures such as carports. Each of these additional damaged structural classifications was located either on the outskirts of the cities or at a considerable distance in the rural countryside. The lack of digital reconnaissance data on these structures can likely be attributed to: (1) local news focusing on the largest, most prominent structures impacted, which happened to be located within the cities; and (2) the National Weather Service documentation leveraging the EF-scale, which does not include specific guidance for these more unique agricultural structures. Even more striking are the quantities and severities of these other damaged structures. For example, 24 grain bins/silos were damaged, rendering them inoperable and resulting in the loss of the stored commodities, which digital reconnaissance completely missed. Similarly, another 22 barns and agricultural buildings were damaged with eight partially or totally collapsed structures that were only identified in field reconnaissance. Whereas it is anticipated that local news would focus on the more urban damage due to the number of people impacted in an event like this, this event's comparison underscores the likely high level of conservatism within digital reconnaissance for predominantly rural areas. Therefore, the impact of natural hazards on rural infrastructure may very well be much larger than that reported herein.

Fragility Analysis of Steel Silos

To generalize the results of the digital reconnaissance database and to understand the performance of certain rural structures, this section aims to study the probability of failure as a function of event intensity through fragility analysis. Empirical fragility functions require observation data in the form of hazard intensity, the number of structures exposed to that hazard intensity, and the number of those that failed or exceeded some damage threshold. Due to the nature of digital reconnaissance, the total number of structures exposed to a given intensity is not natively available which inhibits fragility analysis. Therefore, additional information was sought to expand the database and enable this analysis. To this end, Google Earth satellite imagery was utilized to acquire the total number of structures exposed to a given intensity for an event in the digital reconnaissance database. This was conducted for all tornadic events in the database because approximate path and width information is provided by NOAA (2018). Furthermore, this analysis is limited to steel silos because this structure is easily recognizable from satellite imagery and is a uniquely rural system for which little is known about its structural performance.

Fragilities were generated according to the Type-B procedures outlined by Porter et al. (2007) as applicable to observations where the peak hazard intensity is known, but the actual intensity at which a system failed is not known. The fragility is defined as $P[D \geq d|X = x]$, or the probability that at a given damage state is exceeded given a level of intensity. Assuming the fragility function to be reasonably approximated by a lognormal cumulative distribution function, the probability of exceeding a damage state is given by:

$$p_i = \Phi\left(\frac{\ln(r_i) - \ln(\theta)}{\beta}\right) \tag{1}$$

where i corresponds to the binned level of intensity, p_i = probability that any specimen in bin i fails, Φ = standard normal cumulative distribution function, r_i is the maximum level of intensity to which bin i was exposed, θ = median, and β = logarithmic standard deviation. The median and logarithmic standard deviation are determined by maximizing the likelihood of observing the data, where the likelihood is given as the product of the probabilities of all bins:

$$L(\theta, \beta) = \prod_{i=1}^{m_i} P[F_i = f_i] \tag{2}$$

where m_i = number of levels of intensity in the observed data, and $P[F_i = f_i]$ = probability that f_i failures will be observed which is represented by the binomial distribution.

Fragility curves were generated in this manner for both the entire digital reconnaissance database and the field reconnaissance for the Pella and Marshalltown tornadoes. A total of 45 and 21 damaged steel grain silos were utilized along with a total of 508 and two tornadoes in the generation of the digital and field reconnaissance fragilities, respectively. Whereas the field reconnaissance directly observed the total number of silos exposed to the tornadoes, the digital reconnaissance utilized satellite imagery to determine the total number. In both cases, the estimated wind speeds were approximated using tornado path information and EF-scale damage points obtained by the National Weather Service (2018).

The resulting fragility curves are presented in Fig. 9 for both the digital reconnaissance and the field reconnaissance. The field reconnaissance fragilities are presented with respect to two damage states: DS1: moderate damage, such as local buckling of the wall or roof, which does not preclude use of the silo; and, DS2: extreme damage, such as roof tear off or complete collapse, which does preclude use of the silo. As presented in the fragilities of Fig. 9(a) for the field reconnaissance, the median probabilities of exceeding DS1 and DS2 are 151 and 227 km/h (94 and 141 mi/h), respectively. For comparison, the Enhanced Fujita scale for rating tornado wind speeds indicates that small barns and farm outbuildings are expected to exhibit *major loss of roof panels* and *uplift or collapse of roof structure* at wind speeds of 145 and 150 km/h (90 and 93 mi/h), respectively (McDonald et al. 2006). Given that steel grain silos were frequently in close proximity to small barns or farm outbuildings that exhibited substantial damage to this effect, the resulting fragility curves are plausible. However, it is noted that the wind speeds utilized in this analysis were derived from EF-scale damage ratings, such as these, and did not include any direct wind speed measurements.

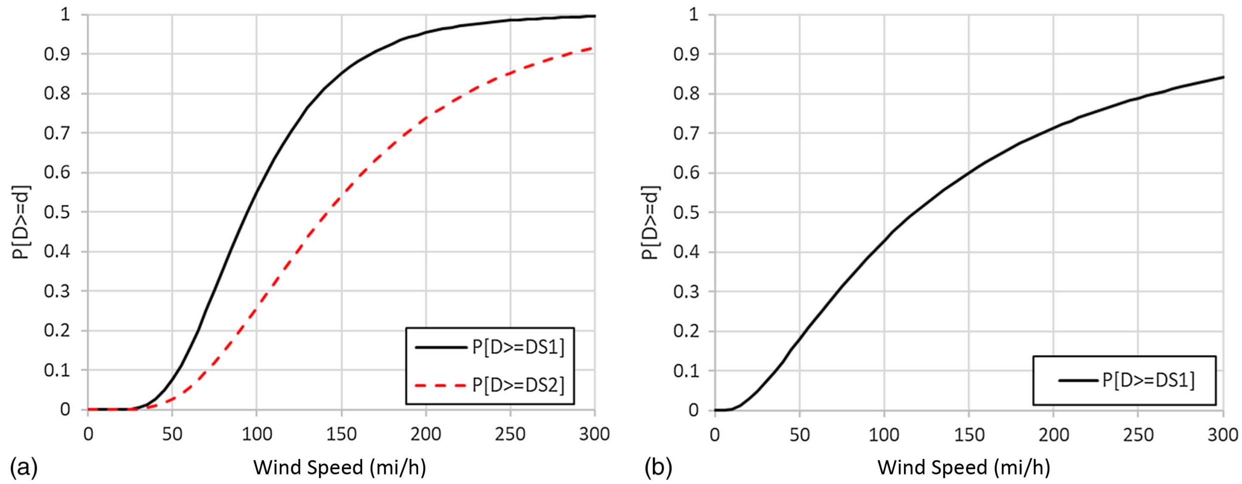

Fig. 9. Fragility curves for steel grain silos as generated using (a) field reconnaissance data from the Pella and Marshalltown tornadoes; and (b) 2018 digital reconnaissance database.

On the other hand, the digital reconnaissance did not separate individual damage states for steel silos due to the resolution of digital data. As a result, the fragility relationship in Fig. 9(b) represents only the probability of exceeding DS1, or the observation of any damage. The median probability is 190 km/h (118 mi/h), which is substantially higher than that of the field reconnaissance. This is expected due to the nature of digital reconnaissance which underreports damage, as explored in the previous section. Furthermore, the EF-scale indicates that small barns and farm outbuildings would exhibit *total destruction of building* at wind speeds of 180 km/h (112 mi/h). Whereas substantial damage was observed to nearby barns and outbuildings during the two field reconnaissance trips, total destruction or total collapse was observed in only a handful of cases. Therefore, fragility relationships derived from digital reconnaissance appear to be overly nonconservative; and, digital reconnaissance information should be interpreted qualitatively and for guidance in field missions, rather than detailed evaluations of structural performance at this time. However, fragilities derived from digital reconnaissance are expected to yield more accurate results provided higher resolution or more targeted data, such as: data regarding insurance claims, which likely have a more accurate account of damage compared with the publicly available sources utilized herein; high-resolution satellite imagery in rural areas collected on a regular basis, which would provide a more accurate count of the number of structures subjected to a hazard level; high-resolution satellite imagery or streel-view imagery in rural areas collected in the immediate aftermath of an event, which would provide a more accurate count of damaged structures; and, citizen documentation of damage to a central repository or social media platform, which would provide a more accurate count of damaged structures.

Conclusions

The goal of this investigation was to assess the performance of various structural typologies, especially those in rural areas, in natural hazard events. It is intended that the results of this investigation shed light on the performance of key structures that contribute to rural resilience. To this end, a digital reconnaissance for calendar year 2018 was conducted, which focused on various hazards and structural typologies across the United States. The benefits and limitations of the digital reconnaissance approach were further assessed through case study comparisons of field reconnaissance. In general, the digital reconnaissance methodology proved to be an effective method of gathering structural damage data. Whereas digital reconnaissance underreported estimates of structural damage, it is effective in the identification of damaging events and the primary structural types impacted. In addition, digital reconnaissance was particularly successful for tornado and wind events, which are well-documented online between government agencies like NWS and NOAA, local journalism, and citizen contributions. For these event types, many data sources were often available and teeming with useful information, making digital reconnaissance, for many events, surprisingly thorough.

The information gathered in this digital reconnaissance highlights the vulnerability of rural structures in the United States. Substantially more damage-inducing hazard events occurred in rural areas, and the total number of damaged structures and estimated costs of damage were similarly greater in rural areas. As a result, rural communities suffer great losses of homes, barns, and equipment, yet these disasters go largely unnoticed by the general public. Additionally, it is anticipated that digital reconnaissance underestimates damaged structure quantities—particularly in rural areas. This is supported by the comparison with field reconnaissance, which, in both case studies, showed that digital reconnaissance identified significantly fewer damage points than field reconnaissance.

A particular scenario analyzed in this study is the steel grain silo subjected to tornado loads, because the grain silo is a common structure in rural areas, and tornadoes are the most frequent hazard. Fragility relationships were developed using both field and digital reconnaissance data. Although the fragilities based solely on digital data were determined to be overly nonconservative, the fragility developed based on field reconnaissance data aligned well with current wind speed estimates for nearby structures. According to these fragilities, steel grain silos would be expected to exhibit moderate damage, such as local buckling, at wind speeds associated with EF1 tornadoes. However, total failure most closely aligns with wind speeds of EF3.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies (Wittich and Loken 2019).

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