Applied Geography 94 (2018) 18–29

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

How land use alters the tornado disaster landscape

Stephen M. Strader[a,*], Walker S. Ashley[b], Thomas J. Pingel[b], Andrew J. Krmenec[b]

[a] *Department of Geography and the Environment, Villanova University, 800 Lancaster Ave, Villanova, PA 19085, USA*
[b] *Department of Geography, Northern Illinois University, 1425 Lincoln Hwy, DeKalb, IL, 60115, USA*

ARTICLE INFO

Keywords:
Tornado
Exposure
Risk
Monte Carlo simulation
Land use
Disaster

ABSTRACT

This research assesses how the spatial character of land use influences tornado disaster potential at regional and metropolitan scales. Fine-scale, residential built-environment data for the Central Plains (regional) and Wichita, KS (metropolitan) domains are used in a Monte Carlo tornado simulation framework to estimate significant tornado impact magnitude and disaster potential. The land use patterns of the domains are hypothetically adjusted using the 2010 observed data surface as a baseline to explore how the density and spatial character of land use affects the possibility of significant tornado impacts. As residential built-environment density is reduced and the footprint of developed land grows, tornado impact probability and magnitude increases. Conversely, restricting sprawl while, at the same time, adopting a more concentrated land use pattern, lowers the odds of tornado impact and disaster. Results reveal that the geographic character of land use is important in determining an area's tornado disaster potential. This finding is especially unique and critical for develop proactive disaster mitigation strategies. Pre-disaster mitigation efforts such as effective land planning and building code improvement and enforcement are required to reduce future tornado impacts.

1. Introduction

Previous research (Ashley & Strader, 2016; Ashley, Strader, Rosencrants, & Krmenec, 2014; Rosencrants & Ashley, 2015) has illustrated that spatially expanding built environment has led to greater hazard impacts and heightened disaster potential. For instance, within the past 80 years, the conterminous U.S. population has more than doubled, and the footprint of development has increased by over 600 percent. While a majority of this population and built-environment growth has been associated with rapidly increasing urban populations, the outward expansion of population and built-environment variables on the fringes of urban cores (i.e., sprawl) also greatly influences hazard impact and disaster probability (Alig & Healy, 1987; Ashley & Strader, 2016; Benfield, Raimi, & Chen, 1999; Bhatta, Saraswati, & Bandyopadhyay, 2010; Ewing, 1994; Ewing, Kostyack, Chen, Stein, & Ernst, 2005; Katz & Liu, 2000; Theobald, 2005). During this same period, the frequency and magnitude of weather-related hazard impacts have also increased (e.g., Bouwer, 2011; Changnon, Pielke, Changnon, Sylves, & Pulwarty, 2000; IPCC, 2012). The surge in disaster frequency can be, at least at this time, primarily attributed to growth in underlying human and built-environment vulnerabilities (Ashley & Strader, 2016; Ashley et al., 2014; Bouwer, 2011; Hall & Ashley, 2008; Höppe & Pielke, 2006; IPCC, 2012; IPCC, 2014; Mohleji & Pielke, 2014; Pielke, 2005; Preston, 2013; Strader & Ashley, 2015; Strader, Pingel, & Ashley, 2016a; Strader, Ashley, Pingel, & Krmenec, 2016b; Strader, Ashley, Pingel, & Krmenec, 2017). Although disasters are social constructs and primarily driven by extreme events interacting with human, social, and physical vulnerabilities, this study defines disaster magnitude and severity as the number of housing units (**HU**) potentially damaged or destroyed by a tornado (Ashley & Strader, 2016; Strader et al., 2016a; Strader et al., 2016a, 2016a). The study also makes the assumption that the greater the total number of HUs impacted (i.e., damaged) by a tornado path, the higher the probability of tornado disaster.

Overall, this research is motivated in part by previous studies and analyses (e.g., Ashley & Strader, 2016; Ashley et al., 2014; Hall & Ashley, 2008; Paulikas & Ashley, 2011; Rae & Stefkovich, 2000; Rosencrants & Ashley, 2015; Strader et al., 2016b; Wurman et al., 2007). This particular study asks similar questions, but in the context of tornado disaster outcomes across a variety of land use patterns. Specifically, we isolate and assess the effects of the spatial character of the residential built environment on tornado disaster potential for the first time by controlling for population and development magnitude at both the regional and metropolitan scales. Thus, the research provides a unique and fundamental understanding of how the geographic patterns of development (i.e., shape), residential concentration (i.e., HU density), and structure (i.e., the combination of residential concentration and spatial pattern of development) influences tornado hazard impact and disaster potential. Hypothetical land use and tornado scenarios are

---

[*] Corresponding author. Dept. of Geography and the Environment, Villanova University, Mendel Hall, Rm. G65A, Villanova, PA 19085, USA.
E-mail address: stephen.strader@villanova.edu (S.M. Strader).

https://doi.org/10.1016/j.apgeog.2018.03.005
Received 21 March 2017; Received in revised form 11 March 2018; Accepted 13 March 2018

used to illustrate how land use policies and planning may influence tornado disaster frequency and consequences.

2. History of U.S. urbanization and development

Over the last 200 years, the U.S. has transitioned from a primarily rural development character to clustered, urban and suburban land use (Kim, 1999). Urban sprawl started in the mid-1940s when the middle class populations began to swell (i.e., Baby Boom), war bonds matured, and a well-educated workforce began to develop. This newfound middle class prosperity resulted in the migration or spreading outward of populations from city cores toward more single-family, suburban housing (Whyte, 2013). By 1970, the number of people living in suburban locations had surpassed those living in urban areas due to ever-increasing suburban community projects (e.g., Levittowns), the U.S. Interstate Highway System, and affordable automobiles (Greene & Pick, 2011; Jackson, 1987). This urban sprawl land use change ultimately led to the development of edge cities or micro-economic cores located within the suburban landscape by 1960 that were characterized by a high concentration of leasable office space, retail space, and jobs (Garreau, 2011). The advancement of edge cities also acted to reduce the dependence on a single, large central business district (**CBD**) and encouraged an even greater amount of urban sprawl (Lang, 2003). In all, the processes of urban sprawl and the existence of edge cities transformed the traditional metropolitan shape from a monocentric to polycentric form (Greene & Pick, 2011). Polycentric cities can be described by their high suburban employment rates, interconnected public transportation, sprawling character, and multiple CBDs (Kloosterman and Musterd, 2001).

By the early 1990s, researchers and interest groups became increasingly concerned about the influence urban sprawl had on the loss of agricultural and natural land (Buchanan & Acevedo, 1997; Platt, 1991), traffic congestion (Downs, 1992), poor air quality (Frumkin, 2002), and the socioeconomic disparity between inner cities and suburbs (Powell, 1998). In reaction to these issues, the smart growth, or new urbanism movement, began to gain traction (Burchell, Listokin, & Galley, 2000; Knaap & Talen, 2005). Broadly, smart growth can be thought of as "growing up" (increased density) instead of the "growing out" (increased low density areal coverage) affiliated with sprawl. Thus, in recent years smart growth has resulted in the migration of people back to the urban cores or primary CBDs (Atkinson, 2004).

As U.S. population increased and developed land area expanded over the last 200 years, weather-related disaster frequency and consequences also increased (Kunkel et al., 2013; Smith & Katz, 2013). A number of studies have examined the interconnections among land use, population density, and hazard consequences. Most notably, researchers have investigated how land use is linked to the risk of urban flooding (e.g., Pottier, Penning-Rowsell, Tunstall, & Hubert, 2005; Shepherd, 2005; Brath, Montanari, & Moretti, 2006; O'Connell et al., 2007; Ferguson & Ashley, 2017), landslides (e.g., Leighton, 1976; Sidle & Ochiai, 2006; Sidle, Pearce, & O'Loughlin, 1985), and coastal inundation (Wheater & Evans, 2009). In addition, studies (Ashley & Strader, 2016; Ashley et al., 2014; Hall & Ashley, 2008; Paulikas & Ashley, 2011; Rae & Stefkovich, 2000; Rosencrants & Ashley, 2015; Strader et al., 2016b; Wurman et al., 2007) have investigated the role large population centers, population growth, and urban sprawl serve in influencing tornado impacts. Others (i.e., Hall & Ashley, 2008; Ashley et al., 2014; Rosencrants & Ashley, 2015; Ashley & Strader, 2016; Strader et al., 2016b) have focused on how *changes* in population and land use, especially in the form of suburban and exurban sprawl, is leading to greater numbers of people and homes potentially in harm's way and, moreover, increasing tornado disaster potential. The effects of escalating tornado hazard exposure have been observed with recent tornado events such as the 2011 Joplin, MO EF5; 2013 Newcastle-Moore, OK EF5; 2015 Washington, IL EF4; etc. (Ashley & Strader, 2016; Hall & Ashley, 2008; Strader & Ashley, 2015). While studies such as Hall and Ashley (2008), Ashley et al. (2014), Strader et al. (2016b), etc. have examined the combined effects built-environment magnitude (e.g., number of homes and people) and land use morphology (e.g., development density and spatial character), no study to date has assessed the relationship between tornado disaster potential and land use morphology in isolation within a controlled methodological framework.

3. Data and methods

This research seeks to answer the question, "How do different types and spatial morphologies of land use influence tornado impact magnitude and probability?" We preface with a *hypothetical*: What if we could decide to fundamentally change the way we allocate land, plan land use, and grow and maintain our developed spaces? To explore the question, a two-part analysis—regional and metropolitan—was conducted. This U.S. Central Plains region (Fig. 1) was chosen for the regional analysis because of its large proportion of rural land surrounding densely populated metropolitan areas (i.e., Oklahoma City, OK; Omaha, NE; Tulsa, OK; Wichita, KS) and high tornado risk (Ashley & Strader, 2016; Brooks, Doswell, & Kay, 2003; Dixon & Mercer, 2012; Dixon, Mercer, & ChoiAllen, 2011; Gagan, Gerard, & Gordon, 2010; Marsh & Brooks, 2012). Wichita, KS was used to investigate the role metropolitan-scale land use character has on tornado impact potential (Fig. 2). Wichita has a monocentric land use pattern with a primary CBD (Mills, 1981) and is in the center of what is colloquially known as "Tornado Alley." For the regional and metropolitan area domains, observed and projected distributions of housing unit (**HU**) density were modeled using the Spatially Explicit Regional Growth Model (**SERGoM;** Theobald, 2005; EPA, 2009) and juxtaposed with the tornado hazard utilizing the Tornado Impact Monte Carlo (**TorMC**) model (Strader et al., 2016a).

The SERGoM model comprises gridded fine-scale (100-m resolution) historical and projected HU density approximations for the conterminous U.S. The HU estimates are obtained using a variety of geospatial information such as road density, developable lands, protected areas, accessibility to urban areas, etc. (Theobald, 2005). Model reliability and accuracy were assessed by utilizing a hindcast technique with the historical U.S. Census Bureau population and HU block enumerations (Theobald, 2005). Cross-validation results revealed that the SERGoM model contained accuracies from 80 percent to 91 percent for the conterminous U.S. (Theobald, 2005).

The TorMC is a spatially explicit Monte Carlo model that simulates thousands of tornado events and estimates their potential costs on an underlying surface (Strader et al., 2016a). TorMC model details, components, validation, and examples are outlined in Strader et al. (2016a). In this study, we used the TorMC to simulate 10,000 years of significant (i.e., greater than or equal to Enhanced Fujita Scale 2, or EF2+, magnitude) tornado footprints (i.e., tornado path length multiplied by path width, which represents the theoretical maximum extent of tornadic winds) across the Central Plains domain, and 20,000 years of significant tornado footprints across the Wichita domain. In order to isolate the effects of land use morphology on tornado impact potential, this study also does not consider any regional differences in tornado historical tornado occurrence. Specifically, the likelihood or probability that a simulated tornado occurs at any location within the study domains is equal (c.f., Strader et al., 2016a their Fig. 5b). Because of this TorMC simulation control, any geospatial or statistical difference in tornado impact potential between development centers in Fig. 1, Panel I-K is directly related to the land use morphology rather than any underling tornado risk differences across the region. Additionally, simulation lengths of 10,000 and 20,000 years were selected because they produced functional, yet computationally efficient, TorMC model output for the domains investigated. For example, although simulation lengths on 1,000, 5,000, 10,000, and 15,000 were used to generate tornado impact statistics for the Central Plains domain, the 10,000 year simulation yielded tornado impact statistics that were relatively "smooth"

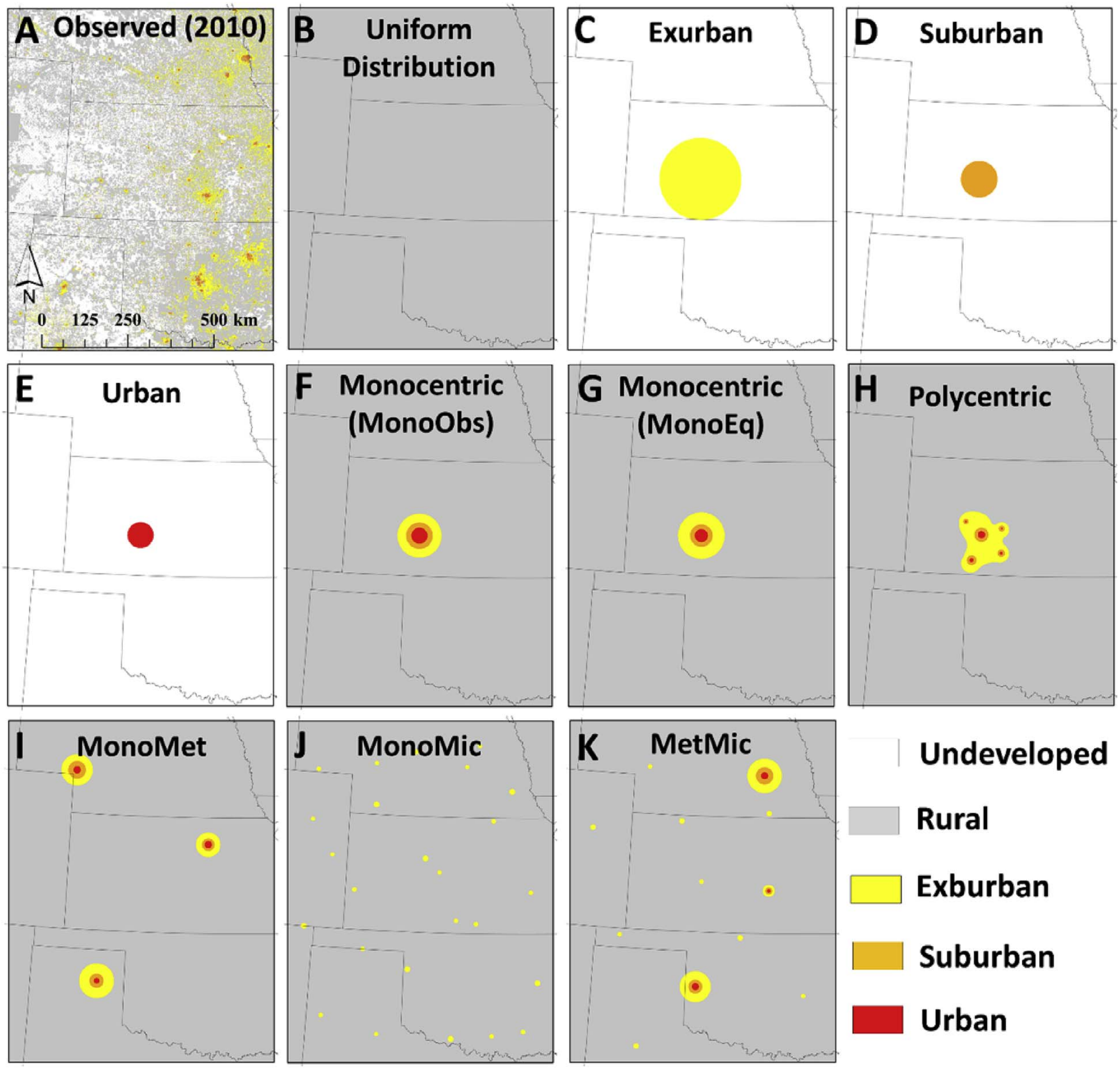


Fig. 1. Observed and theoretical land use morphology surfaces for the Central Plains region (c.f., Table 1).

distributions and not subject to outliers.

Only significant tornadoes were simulated for this study since they have been responsible for nearly 99 percent of all fatalities and 75 percent of damage from U.S. tornadoes since 1950 (Ashley et al., 2014). Further, their annual counts have been stable over time compared to non-significant tornado frequencies, which suffer from a number of non-meteorological biases (Brooks et al., 2003; Verbout, Brooks, Leslie, & Schultz, 2006; Doswell, 2007).

The TorMC simulations use solely those annual tornado counts from 1954 onward since the reporting of tornadoes prior to 1954 was deficient (Agee & Childs, 2014; Ashley & Strader, 2016; Strader, Ashley, Irizarry, & Hall, 2014). Tornado widths by EF-scale magnitude were determined by using Weibull parameters from Brooks et al. (2003), while tornado path lengths, azimuths, and magnitudes were chosen based on repeated random sampling with replacement (i.e., bootstrapping). This study also uses the TorMC random tornado touchdown probability technique that removes any potential tornado reporting bias due to population density (e.g., Brooks et al., 2003; Doswell et al., 2005; Grazulis, 1993; Strader et al., 2014). To extract simulated tornado costs, the TorMC "intersect" cost-extraction method was selected (see Fig. 4 in Strader et al., 2016a). This method ensures all cost surface grid cells intersecting a tornado footprint are included in the tornado footprint cost estimation statistic.

The SERGoM and TorMC models were used to assess tornado impact and disaster potential for eleven regional and seven metropolitan HU surfaces, each demonstrating a different observed or theoretical land use character (Tables 1 and 2; Figs. 1 and 2). The 2010 SERGoM HU surface was used as a baseline, representing the *observed* regional and metropolitan 2010 HU totals, density, and land use pattern (Fig. 1a and 2a). All other theoretical land use cost surfaces were created by adjusting the 2010 observed HU densities and spatial characteristics, but *not* the total number of HUs within the regional and metropolitan domains. The total number of HUs was held constant for each theoretical land use surface in order to isolate the effects the residential built-environment spatial character has on tornado impacts and disaster potential.

Following Theobald (2005) and EPA (2009), four primary land use classifications were used in developing observed and theoretical land use models—the classifications include rural (< 0.062 HU per hectares (**ha**)); exurban (0.062–1.236 HU per ha); suburban (1.237–9.884 HU

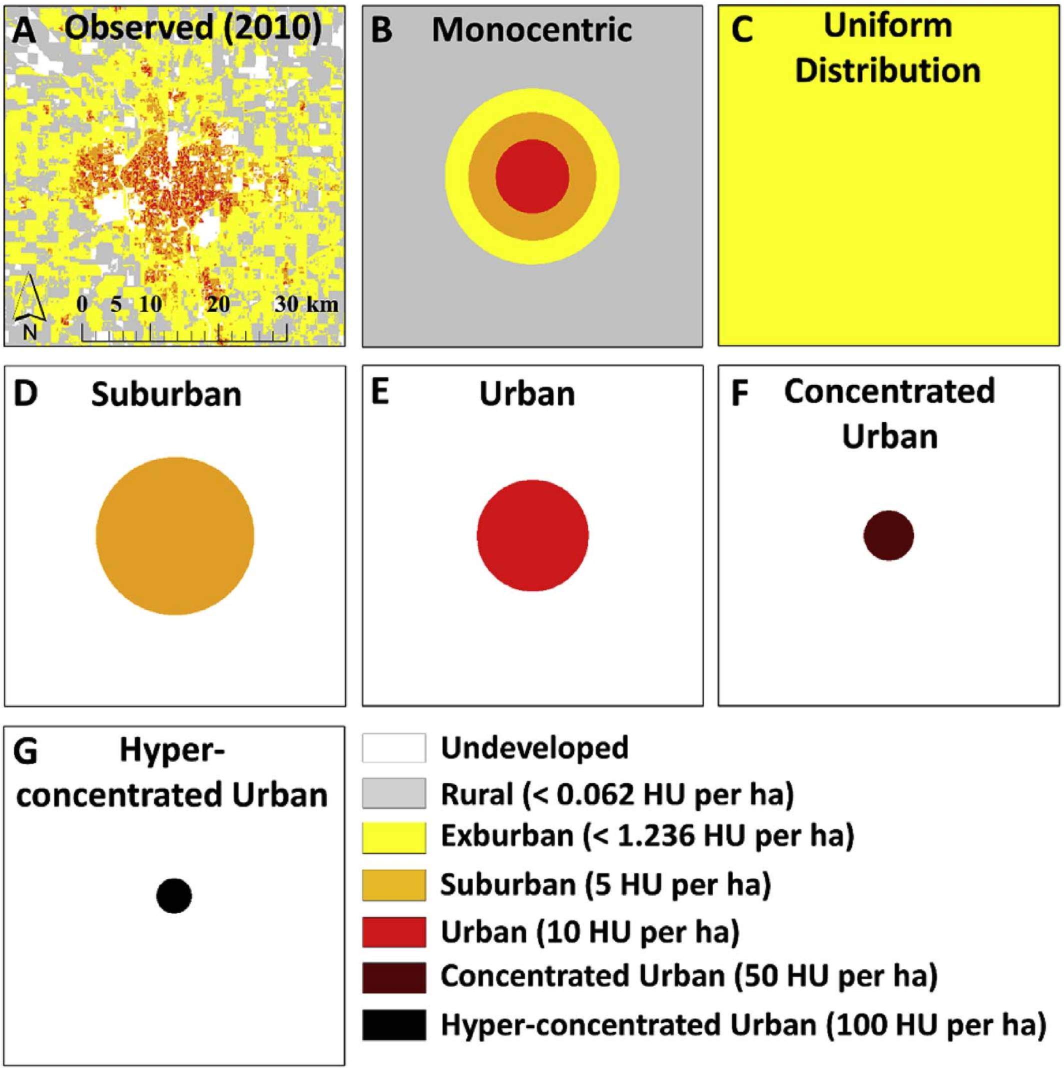


Fig. 2. Observed and theoretical land use morphology surfaces for Wichita, KS. (c.f., Table 2).

Table 1
Central Plains observed and theoretical land use surfaces with urban, suburban, exurban, rural land use classification (housing units (HU) per hectare (ha)), and land use morphology description.

Surface	Land Use Classification (HU per ha)				Morphology Description
	Urban	Suburban	Exurban	Rural	
Observed	> 9.884	1.237–9.884	0.062–1.236	< 0.062	2010 SERGoM observed HU magnitude, density, and spatial morphology
Uniform	–	–	–	0.058	All HUs within the region are spaced equally within the domain representing an “extremely sprawled” regional HU morphology.
Exurban	–	–	1.000	–	All HUs within the regional domain are placed into a single, monocentric exurban area
Suburban	–	5.000	–	–	All HUs within the regional domain are placed into a single, monocentric suburban area
Urban	10.000	–	–	–	All HUs within the regional domain are placed into a single, monocentric urban area
Monocentric Observed HU distribution (MonoObs)	10.000	5.000	1.000	0.006	All HUs within in each land use class are grouped and placed into a monocentric development morphology
Monocentric Equal HU distribution (MonoEq)	10.000	5.000	1.000	0.015	All HUs within the regional domain are divided equally into urban, suburban, exurban, and rural land use classes and placed into a monocentric development morphology
Polycentric	10.000	5.000	1.000	0.016	All HUs within the regional domain are placed into a single, polycentric development form.
Monocentric-Metropolitan (MonoMet)	10.000	5.000	1.000	0.005	All HUs within the regional domain are placed into multiple monocentric metropolitan (> 20 k HUs) communities
Monocentric-Micropolitan (MonoMic)	–	5.000	–	0.053	All HUs within the regional domain are placed into multiple monocentric micropolitan (> 10 k HUs but < 20 k HUs) communities
Metropolitan-Micropolitan (MetMic)	10.000	5.000	1.000	0.013	All HUs within the regional domain are placed into multiple monocentric metropolitan and micropolitan communities

Table 2
As in Table 1, except for Wichita, KS metropolitan area.

Surface	Land Use Classification (HU per ha)				Morphology Description
	Urban	Suburban	Exurban	Rural	
Observed	> 9.884	1.237–9.884	0.062–1.236	< 0.062	2010 SERGoM observed HU magnitude, density, and spatial morphology
Monocentric	10.000	5.000	1.000	0.012	All HUs within in each land use class are grouped and placed into a monocentric development morphology
Uniform	–	–	0.844	–	All HUs within the metropolitan domain are spaced equally within the domain representing an “extremely sprawled” regional HU form.
Suburban	–	5.000	–	–	All HUs within the metropolitan domain are placed into a single, monocentric suburban area
Urban	10.000	–	–	–	All HUs within the metropolitan domain are placed into a single, monocentric urban area
Concentrated Urban	50.000	–	–	–	All HUs within the metropolitan domain are placed into a single, monocentric concentrated urban area
Hyper-concentrated Urban	100.000	–	–	–	All HUs within the metropolitan domain are placed into a single, monocentric hyper-concentrated urban area

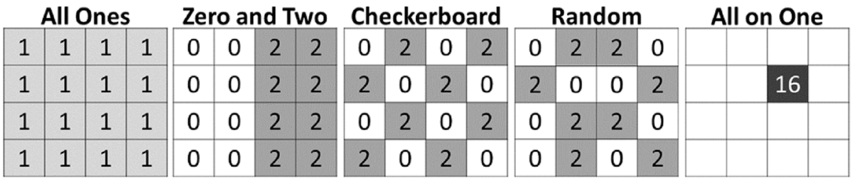
per ha); and urban (> 9.884 HU per ha). In addition, two increasingly concentrated urban land use classes are also applied in this study, concentrated urban (50 HU per ha) and hyper-concentrated urban (100 HU per ha). The theoretical uniform land use surface (Fig. 1B) represents a residential built environment where the total number of HUs within the region are spaced equally within the domain. This type of pattern characterizes an “extremely sprawled” landscape. The theoretical exurban, suburban, and urban surfaces in panels Fig. 1C-E illustrate land use patterns where all HUs within the domain are placed into single, monocentric areas representing each of their corresponding land use densities surrounded by undeveloped land (Table 1). The monocentric observed (**MonoObs**) and monocentric equal (**MonoEq**) HU distribution land use surfaces in Fig. 1F-G represent patterns that encompass a traditional urban-to-rural land use density curve (Newling, 1969; i.e., HU density decreases outward radially from a primary urban core). The MonoObs surface uses the observed regional number of HUs within each land use class and groups them into a monocentric development with concentric land use rings—i.e., urban core surrounded by suburban land use which is then enclosed by exurban, etc. The equal HU distribution surface in Fig. 1G was created by taking all HUs within the regional domain, distributing them equally into the four land use classes, and placing them in a monocentric development form increasing HU density radially outward from urban to rural. The monocentric-metropolitan (**MonoMet**), monocentric-micropolitan (**MonoMic**), metropolitan-micropolitan (**MetMic**), and polycentric surfaces in Fig. 1H-K denote a variety of commonly occurring regional land use patterns found in the U.S. Metropolitan communities contain 20,000 or more HUs, while micropolitan communities encompass greater than 10,000 HUs but less than 20,000 HUs (OMB, 2009). In general, the MonoMet, MonoMic, and MetMic development patterns contain multiple metropolitan and micropolitan communities enclosed by exurban and rural land use.

The seven metropolitan built environment surfaces are similar to the regional observed, uniform, suburban, urban, and multiple land use monocentric patterns but are focused at the local scale and use the Wichita metropolitan area's HU totals (Table 2; Fig. 2). However, two additional development surfaces were generated for the Wichita, KS metropolitan analyses: concentrated urban and hyper-concentrated urban. These morphologies are classified as urban land use but with increasing HU densities (i.e., 50 HU per ha (concentrated) and 100 HU per ha (hyper-concentrated)).

We defined tornado or HU “impacts” as the sum number of HUs a simulated tornado damages. To assess how each land use morphology surface uniquely influences tornado impact magnitude and disaster potential, probability of exceedance (**POE**) curves are generated using regionally aggregated annual simulated tornado HU impacts. Essentially, each individual simulated tornado HU impact value is summed and added to the year's total, culminating in a total number of HUs affected by tornadoes in a given year. This process is repeated 10,000 (20,000) times in order to generate POE curves for each regional (metropolitan) development surface. While POE curves could have been generated from individual tornado impact values, the annual aggregation process provides a normalized measure of tornado disaster potential by smoothing the POE curve distributions. Descriptive impact statistics (median, mean, standard deviation, 95th percentile, and 99th percentile (metropolitan level only)) are used to characterize the POE curves associated with each observed or theoretical cost surface. Given the POE impact curves illustrate an extreme value distribution with many outliers (e.g., Weibull, Gamma, etc.), mean and median tornado impact values are reported to describe central tendency. Each measure of annual tornado impact central tendency serves useful for understanding how land use patterns influence tornado impact probabilities. The standard deviation of annual tornado impacts reveals each region's impact variability, while the 95th and 99th percentiles signify potential high-end (POE > 0.05) impact years.

4. Does the spatial pattern of land use influence tornado impact potential?

Initially, a prototype Monte Carlo model was used to simulate the effects of tornadoes on the residential built environment for five representative development scenarios (Fig. 3). This simple proof of concept is used to determine if the spatial pattern of land use affects tornado disaster potential, providing a catalyst to explore observed and theoretical cost surfaces at the regional and metropolitan scales. The physical dimensions of simulated tornado events were drawn from distributional summaries of tornado events in the contemporary record, where the number assigned in each cell represents the number of hypothetical HUs. The first diagram shows a uniform distribution that may characterize a more rural environment of the U.S. through the early parts of the 20th century; the “Zero and Two” scenario is a simplified conceptual model of a modern rural/suburban interface; the “All



All Ones

1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1

Zero and Two

0	0	2	2
0	0	2	2
0	0	2	2
0	0	2	2

Checkerboard

0	2	0	2
2	0	2	0
0	2	0	2
2	0	2	0

Random

0	2	2	0
2	0	0	2
0	2	2	0
0	2	0	2

All on One

		16	

Fig. 3. Five 4 × 4 grids that exemplify scenarios of HU counts used to drive a simple Monte Carlo model (500 px^2 grid at 100 m).

Table 3
Results of five one million cycle Monte Carlo simulations on impact surfaces illustrated in Fig. 3.

Representation	Surface Mean	Surface Std. Dev.	Mean Impact	Std. Dev. Impact
All Ones	1	0	48.2	66.5
Zero and Two	1	1	48.1	99.7
Checkerboard	1	1	48.2	66.5
Random	1	1	47.2	66.5
All on One	1	500	69.9	3382.2

on One" is illustrative of a more concentrated land use pattern as seen in the core of cities. Results from the simple spatial model (modeled on a 500 px^2 grid at 100-m resolution) demonstrate that the expected number of HUs impacted by a random tornado is proportional to the mean density of HUs, as one would naturally expect (Table 3). However, the important discovery is that the spatial distribution of HUs fundamentally changes the measure of central tendency and variance in the expected number of units impacted (Table 3). The variance in this case represents how the magnitude of impact can be expected to vary across sample eras of tornado events. Further, this prototype Monte Carlo model also illustrates the importance of examining higher-impact tornado events using measures of variance and the 95th and 99th percentiles rather than simply the median or mean. In short, this illustration demonstrates that the spatial distribution of HUs and, correspondingly, population influences average and high-end tornado impacts while establishing why exposure geography needs to be examined within the context of disasters.

5. Regional monocentric pattern with a single land use classification

Findings from the regional simulations indicate that there are substantial differences in annual tornado impact potential among all regional surfaces (Table 4; Fig. 4). The 2010 observed surface yields median (mean) annual tornado impacts of 3109 HU (4846 HU), a standard deviation of 5371 HU, and a 95th percentile of 15,715 HU (Table 4). For this *observed* cost surface, there is approximately a 13 percent chance in any given year that significant tornadoes will affect more than 10,000 HUs in the Central Plains (Table 5). The observed regional development surface (Fig. 1A) and associated impact statistics serve as a control, permitting comparisons of the observed land use pattern to a variety of theoretical land use morphologies. Note that all impact probability results are slightly overestimated because of the "intersect" tornado cost-extraction method employed (Strader et al., 2016a), the spatial and computational limitations of the modeled HU estimates (Theobald, 2005), and the footprint representation of a tornado path (i.e., a theoretical tornado footprint (length x width) that may overestimate the actual tornado footprint by as much as 50 percent; Strader et al., 2016a). The overestimation is a systematic error that results in positive bias. For this reason, we stress that the focus should be on the *relative* differences among all observed and theoretical land use morphology surface impact results, rather than absolutes.

Table 4
Central Plains annual tornado impact statistics for the observed and theoretical land use surfaces.

Surface	Median	Mean	Std. Dev.	95th percentile
Observed	3109	4846	5371	15,715
Uniform	4457	4886	2856	10,162
Exurban	2000	2676	2781	8105
Suburban	0	887	1581	4116
Urban	0	3178	8493	24,004
Monocentric Observed HU distribution (MonoObs)	704	3754	7670	19,994
Monocentric Equal HU distribution (MonoEq)	1555	2994	5081	13,094
Polycentric	2081	4965	8374	19,703
Monocentric-Metropolitan (MonoMet)	949	5108	10,311	26,451
Monocentric-Micropolitan (MonoMic)	4437	4929	2985	10,573
Metropolitan-Micropolitan (MetMic)	1806	4948	9077	21,767

The uniform distribution surface (Fig. 1B) comprises higher (43 percent) median tornado impacts compared to the observed, or control, morphology due to the extremely sprawling pattern represented in the uniform HU density landscape (Table 4; Fig. 4A). However, because of the uniform surface's lack of clustered development and large HU centers, annual tornado impact standard deviation and 95th percentile are reduced. Evidence of this effect is illustrated in Fig. 4A where the shape of the uniform distribution POE curve highlights a distinct decrease in impact variability and 95th percentile compared to the observed POE curve. In general, uniformly distributing HUs throughout a region may lower the probability of high-end tornado disaster years, but increase the annual potential for more mid-to low-end ($POE < 0.5$) tornado impacts. This reduction is because the tornado impact magnitude is controlled by the simulated tornado footprint area rather than the clustering of HUs into cities or communities. The lower tornado impact variability is also highlighted in the annual tornado impact threshold magnitudes where the results suggest that there is a 95 percent chance significant tornadoes will affect 1000 HUs or more in a given year and only a 0.6 percent chance of significant tornadoes damaging 15,000 or more HUs (Table 5).

The exurban, suburban, and urban regional land use patterns (Fig. 1C-E, respectively) all result in lower median (< 2000 HU) and mean (< 3200 HU) tornado impact probabilities compared to the observed morphology (Table 4). These lessened central tendencies are attributed to the contraction of regional HUs into single exurban, suburban, and urban monocentric areas that, on average, reduce tornado impact magnitudes and probabilities. The regional exurban and suburban patterns' annual tornado impact standard deviations are around 90 percent lower than the observed regional control land use pattern, while the urban surface yields a tornado impact standard deviation that is 58 percent higher than the observed pattern (Table 4). Whereas the regional exurban and suburban morphologies reduce tornado impact variability and 95th percentile due to their relatively more dispersed and sprawling character, the urban (Fig. 1E) results in increased tornado impact standard deviation and 95th percentile because of its more concentrated HU density pattern. These findings indicate that, while less sprawl may reduce mid to low ($POE < 0.5$) tornado impact potential, increased HU density may actually lead to greater high-end ($POE > 0.05$) tornado impact magnitudes or disasters. This concept is illustrated in Fig. 4B-D where the extreme tails of the exurban and suburban patterns' POE curves lie below the observed POE curve tails while the urban POE tail surpasses the observed POE curve near 0.12. Although 95th percentile tornado impact magnitude may be inflated for the regional urban morphology compared to the observed, overall tornado impact probabilities and tornado exposure as a whole are reduced (Table 4).

6. Single regional development centers with multiple land use classes

Both the MonoObs and MonoEq surfaces (Fig. 1F-G) yield lower median and mean HU impact values when compared to the 2010 observed land use pattern. Similar to the regional exurban, suburban, and urban surfaces, the lower MonoObs and MonoEq central tendency impact metrics are attributed to the restriction of sprawl that lowers overall tornado exposure. In addition, the MonoObs surface results in greater tornado impact variability than the observed pattern due to its

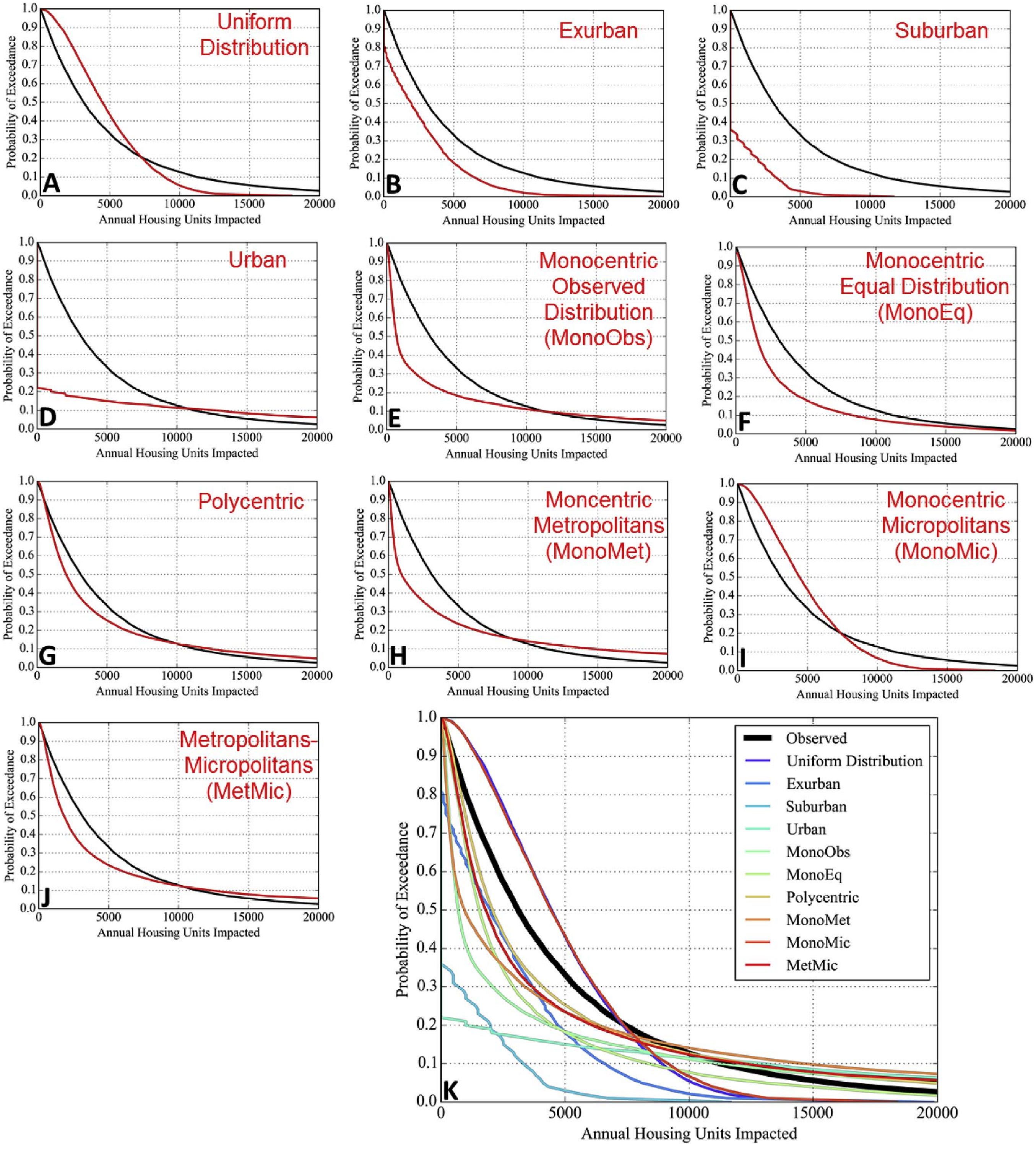


Fig. 4. Probability of exceedance curves (POE) for the Central Plains observed (black lines) and theoretical land use morphology surfaces (red lines) (A–J). Panel K represents all regional theoretical land use morphology surface POE curves on a single plot compared to the 2010 observed surface (thick black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

more concentrated HU density morphology surrounded by a vast rural land. However, the standard deviation associated with MonoEq surface is very similar to the observed pattern's impact variability because of MonoEq's greater concentration of exurban and more sprawling monocentric character. Although the MonoObs land use pattern comprises increased 95th percentile HU impacts compared to the observed surface, the MonoEq 95th tornado impact percentile is less than the observed pattern's 95th percentile probability due to its urban and suburban land use footprint (Table 4).

There are subtle differences between the MonoObs and MonoEq impact descriptive statistics and POE curves. For instance, the MonoObs comprises lower median impacts, but higher mean impacts compared to the MonoEq surface (Table 4). This difference is attributed to the more concentrated urban, suburban, and exurban land use footprints associated with the MonoObs pattern. Similarly, the MonoObs surface represents greater impact variability and 95th percentile impacts due to

Table 5
Annual tornado impact magnitude probabilities for the regional observed and theoretical surfaces. Housing unit (HU) magnitude impact threshold probabilities of 1000; 5000; 10,000; 15,000; and 20,000 are presented.

Surface	Threshold (Annual# HUs Affected)				
	1000	5000	10,000	15,000	20,000
Observed	0.803	0.332	0.127	0.056	0.026
Uniform	0.949	0.431	0.055	0.006	0.000
Exurban	0.630	0.181	0.021	0.006	0.000
Suburban	0.280	0.030	0.003	0.000	0.000
Urban	0.210	0.151	0.115	0.085	0.063
Monocentric Observed HU distribution (MonoObs)	0.409	0.185	0.112	0.074	0.050
Monocentric Equal HU distribution (MonoEq)	0.666	0.182	0.078	0.039	0.017
Polycentric	0.744	0.253	0.127	0.078	0.049
Monocentric-Metropolitan (MonoMet)	0.492	0.235	0.140	0.097	0.073
Monocentric-Micropolitan (MonoMic)	0.940	0.434	0.067	0.007	0.000
Metropolitan-Micropolitan (MetMic)	0.687	0.235	0.124	0.078	0.057

its more concentrated HU density pattern and greater proportion of suburban and urban land use. Supporting evidence is illustrated in the POE curves associated with the MonoObs and MonoEq surfaces (Fig. 4) and impact threshold statistics where the MonoObs mid-to low-end impact probabilities are lower than the MonoEq surface. The 10,000 HU, 15,000 HU, and 20,000 HU annual impact probabilities for the MonoEq morphology are 3.4 percent, 3.5 percent, and 3.3 percent lower, respectively, than the MonoObs surface, although the MonoEq morphology comprises greater 1000 HU annual threshold impact probability (Table 5). This slight disparity in tornado impact threshold statistics is due to the MonoEq surface's greater sprawl and less concentrated urban and suburban HU density. Overall, the differences between the MonoObs and MonoEq impact statistics suggest that regions with less exurban growth within monocentric morphology produce lower tornado impact probabilities.

Analogous to previous findings, the polycentric surface's median annual HU impacts are 50 percent lower than the observed surface's median impacts due to a more concentrated land use pattern (Table 4). However, because there are multiple high-density HU cores within the polycentric morphology, mean annual impacts for the polycentric surface are slightly higher compared to the observed, MonoObs, and MonoEq surfaces. Annual polycentric impact variability and 95th percentile are 56 percent and 25 percent larger, respectively, than the observed surface because of the geographically close monocentric urban and suburban communities. Thus, when a simulated tornado does traverse the polycentric pattern, it has the potential to affect multiple urban and suburban cores leading to increased mean impact magnitude. Although the polycentric POE curve most closely matches the observed POE curve and statistics (Fig. 4), the subtle shape differences between the polycentric and observed curves reveal that there is more impact variability associated with the polycentric morphology. Again, this finding is largely attributed to the more concentrated HU density and closer geographic spacing of urban and suburban land use illustrated in the polycentric surface (Fig. 1H).

7. Multiple regional development centers

Tornado impact descriptive statistics derived from the Monocentric-Metropolitan (**MonoMet**; Fig. 1I), Monocentric-Micropolitan (**MonoMic**; Fig. 1J), and Metropolitan-Micropolitan (**MetMic**; Fig. 1K) surfaces are diverse and provide insight into how multiple development centers within a region act together to influence tornado impact potential and magnitude. The MonoMet surface represents numerous highly-populated monocentric cities surrounded by rural land. MonoMet impact results indicate that this type of pattern reduces annual median impacts by 228 percent compared to the observed regional land use (Table 4). However, mean HU impacts are slightly higher for the MonoMet surface than the 2010 observed surface because of the greater number of monocentric communities within the region. The MonoMet surface also comprises the greatest annual impact variability and 95th percentile of all theoretical patterns due to its multiple monocentric communities. While the MonoMet morphology limits exurban and suburban sprawl, the enhanced HU clustering within multiple monocentric communities leads to increased impact variability and 95th percentile impact magnitude. Increased MonoMet 95th percentile impact is a result of tornadoes traversing high HU density areas more frequently than in the single, monocentric surfaces (i.e., regional Exurban, Suburban, Urban, MonoObs, and MonoEq morphologies). The MonoMet morphology also greatly lowers impact thresholds (Table 5), suggesting that if multiple communities within a region contain less sprawl, tornado impact magnitude and probabilities should be greatly reduced.

The MonoMic morphology is representative of multiple micropolitan cities, or communities, within the region. The restriction of high HU density, metropolitan development and the creation of many small, isolated suburban HU density communities notably influences impact probabilities and magnitude. The MonoMic surface yields higher median and mean impacts compared to the 2010 observed surface. The greater number of micropolitan communities within the region leads to elevated average impacts because the odds of a tornado traversing suburban land use is increased. However, because of the increased number of micropolitan communities, impact variability is less than the observed surface's impact variability. Annual MonoMic 95th percentile HU impacts are also halved when compared to the observed surface because of its lack of large metropolitan communities that can exacerbate impact magnitude. MonoMet and MonoMic impact trends are counter to each other (Fig. 4); while the MonoMet surface reduces median and mean impact potential, the MonoMic surface inflates median and mean impacts because of its more spread out, suburban communities. Yet, because of the MonoMic's lack of high-HU density, urban communities, 10,000 HU, 15,000 HU, and 20,000 HU impact threshold probabilities are notably lower than the MonoMet and observed surfaces (Table 5). MonoMic 10,000 and 15,000 HU impact thresholds are 7.3 percent and 9 percent less, respectively, than the MonoMet threshold probabilities.

The MetMic surface combines multiple metropolitan and micropolitan communities within the same region. Although a more stringently controlled land use, this type of pattern is similar to the development shape and character many U.S. regions experience. Similar to the MonoMet surface, this type of morphology reduces median impact, increases mean impact, and amplifies impact variability, suggesting that this type of land use pattern may marginally reduce average tornado impacts due to its more compact HU morphology compared to the observed surface. In general, the MetMic surface contains the lowest 1000 HU impact threshold probability compared to the MonoMet and MonoMic (Table 5).

In all, the regional results suggest that concentrating HUs into smaller development clusters reduces median and mean tornado impacts but intensifies impact variability and disaster potential (Table 4; Fig. 4). Increasing sprawl lowers impact variability and 95th percentile but increases average impact magnitudes. Thus, there is an impact trade-off between sprawl and concentrated growth.

8. Metropolitan land use scenarios

The metropolitan (Wichita, KS) land use morphologies indicate that sprawling and concentrated development types strongly influence tornado impact potential at the community spatial scale (Table 6; Fig. 5). For example, metropolitan area with sprawling land use character will result in more frequent tornado impacts that are mid-to lower-

Table 6
As in Table 4, except for the Wichita, KS domain.

Surface	Median	Mean	Std. Dev.	99th percentile
Observed	35	428	1342	5492
Monocentric	4	413	1462	7444
Uniform	183	426	717	3424
Suburban	0	410	1289	6164
Urban	0	459	1742	8406
Concentrated Urban	0	388	2722	10,600
Hyper-concentrated Urban	0	468	3241	15,011

magnitude (POE < 0.5), while simultaneously reducing high-end impacts. Conversely, a more concentrated land use pattern leads to lessened mid-to low-impact tornado events whilst amplifying high-end impact potential and magnitude. A more compact HU density metropolitan pattern will also enhance impact variability because of the stark contrast between undeveloped and developed land. As such, there is ultimately a balance between land use density patterns and tornado impact potential as illustrated by the Monocentric and Uniform land use morphologies (Table 6; Fig. 5).

The primary benefit of examining tornado impact magnitude and disaster potential at the metropolitan scale is that it permits the analysis of potential “worst-case” tornado event frequency, magnitude, and probability. By focusing on the 99th percentile and tornado impact threshold probabilities (Tables 6 and 7), a greater understanding of the relationship between land use and tornado disaster potential at the local scale is reached. The observed metropolitan control surface has a 37.1 percent probability of 100 HUs affected in a given year and a 5.6 percent chance of 2000 HU affected in a given year (Table 7). To put these impact values in perspective, Atkins, Butler, Flynn, and Wakimoto (2014) estimated the number of residential structures damaged by the 2013 Newcastle-Moore, OK tornado to be 3531 HUs. These impact threshold statistics indicate that there is a two percent annual probability that a tornado disaster on the scale of the 2013 Moore, OK tornado could affect the Wichita, Kansas, community.

Although the Wichita metropolitan area can be described as monocentric in character, the theoretical land use surface represents and ideal monocentric form (Fig. 2B). The total number of HUs in each land use class (i.e., urban, suburban, exurban, and rural) within the metropolitan domain were grouped into congruent land use categories and placed in a radially outward expanding monocentric pattern (Fig. 5). Due to the more compact HU density pattern found with the monocentric morphology, impact 99th percentile is 36 percent (7444 HU) greater than the 2010 observed, or control, pattern. In addition, the monocentric surface has greater 1500 HU and 2000 HU impact potential compared to the metropolitan observed control as a result of the more concentrated land use pattern (Table 6). In general, results from the monocentric surface test illustrate that by grouping development by land use classes and creating more centralized and controlled HU morphology, and tornado exposure is decreased.

Analogous to the regional experiments (section 5.b), the metropolitan uniform, suburban, urban, concentrated urban, and hyper-concentrated urban theoretical surfaces (Fig. 2C-G, respectively) represent increasingly concentrated HU density in a monocentric pattern. As expected, increasing HU density at the metropolitan level increases 99th percentile impact magnitude, although the total area of developed footprint is reduced (Table 6). Although the more sprawling uniform surface comprises a lower 99th percentile impact magnitude than all other metropolitan morphologies, this type of land use indicates that there is still a one percent chance that as many as 3000 HUs could be affected in a given year. Comparatively, the urban morphology contains a five percent annual chance of 3000 HUs or more being damaged. In addition, there is a three percent chance that more than 3500 HUs would be affected by significant tornadoes with the suburban and urban surfaces in a given year. The urban morphology has the greatest odds for annual significant tornado impact of 2000 HU or greater (Table 7). Although the 99th percentile of impacts for the concentrated and hyper-concentrated urban morphologies are the highest of all theoretical surfaces, their individual 2000 HU impact threshold probabilities are lower than the suburban and urban surfaces (Table 7). This outcome indicates that, although the HU density is greater in the concentrated urban and hyper-concentrated urban morphologies, even high-end tornado impact probabilities at the metropolitan level are reduced because of more concentrated land use character. Overall, the metropolitan simulation results illustrate that, as sprawl is constrained, tornado exposure is also reduced. Restricting the outward expansion of development at the metropolitan level will lower the odds of significant tornado impacts.

9. Conclusions and discussion

We have illustrated using theoretical regional and metropolitan land use patterns that tornado impact magnitude and probability are strongly influenced by the spatial character of the residential built environment. By controlling for HU magnitude (i.e., the total number of HUs within the domain), the study was able to isolate the effects of land use character on tornado disaster potential for a number of theoretical land use scenarios. Findings suggest that regions and communities should be aware of how land use patterns and the spatial morphology of their communities influence tornado disaster magnitude and impact probability. In general, communities with greater development sprawl have a higher overall tornado impact probability. Unfortunately, simply moderating this sprawl to lower the odds of tornado impact may not be financially feasible nor does this modified development come without consequences. Although tornado disaster magnitude might be elevated with a more compact built-environment form (e.g., regional urban, concentrated urban, hyper-concentrated urban, etc.), the likelihood a tornado traverses compact development decreases incrementally as HU density and the geographic area of development is minimized.

Although we began this manuscript with a hypothetical, “*What if we could decide to fundamentally change the way we allocate land, plan land use, and grow and maintain our developed spaces?*”, this study does not contend that it is feasible to start from “scratch” and completely redistribute population, housing, and development across the U.S. landscape. Rather, we used theoretical development patterns to illustrate how land use morphology can potentially influence tornado disaster magnitude and frequency. By employing theoretical development patterns, results illustrate specific trends in land use morphology (e.g., urban sprawl, smart growth) that can be used to inform land use planning with a goal of mitigating disaster potential. For example, many current land-use planning strategies focus their efforts on protecting communities from floods (e.g., Bell & Morrison, 2015), tropical storms (e.g., Frazier, Wood, Yarnal, & Bauer, 2010), earthquakes (e.g., Burby, 2000), landslides (e.g., Cascini, Bonnard, Corominas, Jibson, & Montero-Olarte, 2005; Glade, Anderson, & Crozier, 2006), and wildfires (e.g., Fleeger, 2008; Theobald & Romme, 2007). Yet, very little attention has been given to the tornado hazard for communities in regions prone to tornado impacts. Most of the tornado disaster mitigation efforts in these tornado prone regions have been centered on improving communities and structures *following* a devastating event (e.g., 27 April 2011 Southeast tornado outbreak (Prevatt et al., 2012); 2011 Joplin tornado (Prevatt et al., 2013); 2013 Newcastle-Moore, OK tornado (Simmons, Kovacs, & Kopp, 2015)). As such, land use planning strategies should be accompanied by additional preemptive tornado disaster mitigation approaches such as improving building codes, the allocation of funding for retrofitting existing structures so that they are more wind-resistant, or for safe room implementation. Proactive—rather than reactive—tornado disaster mitigation strategies such as land use planning should be employed in areas with enhanced tornado risk, tornado exposure, and disaster potential (e.g., Central Plains, Southeast U.S., etc.). Since 1980, 47 percent of all billion dollar weather-related

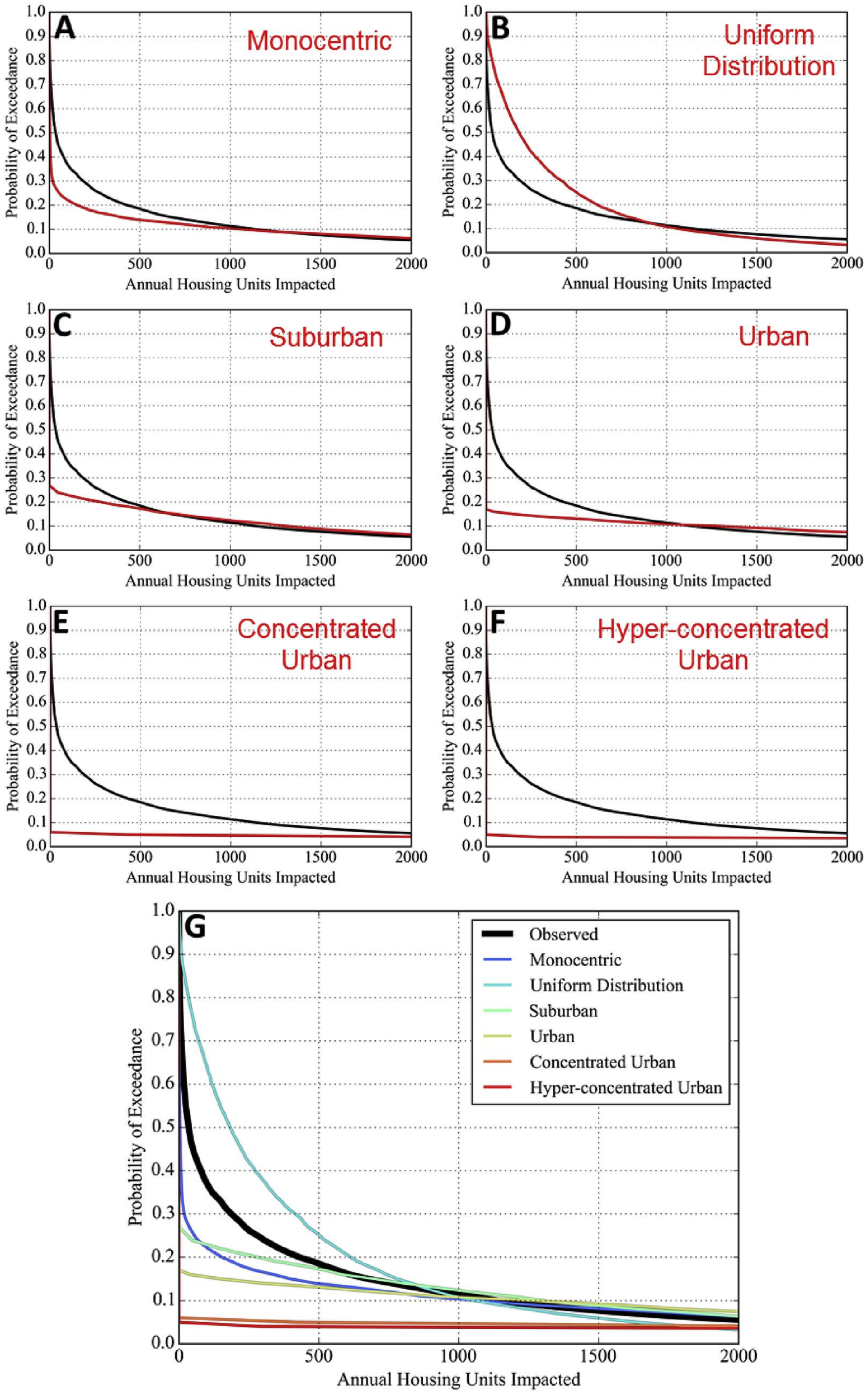


Fig. 5. Probability of exceedance curves (POE) for the Wichita, KS observed (black lines) and theoretical land use morphology surfaces (red lines) (A–F). Panel G represents all metropolitan theoretical surface POE curves on a single plot compared to the 2010 observed surface (thick black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 7
Annual tornado impact magnitude probabilities for the Wichita, KS observed and theoretical land use surfaces.

Surface	Threshold (Annual# HUs Affected)				
	100	500	1000	1500	2000
Observed	0.371	0.185	0.114	0.077	0.056
Monocentric	0.222	0.139	0.104	0.081	0.063
Uniform	0.640	0.251	0.108	0.059	0.032
Suburban	0.229	0.173	0.124	0.088	0.063
Urban	0.154	0.131	0.108	0.092	0.074
Concentrated Urban	0.058	0.050	0.047	0.044	0.041
Hyper-concentrated Urban	0.047	0.039	0.038	0.037	0.036

disasters in the Central Plains and Southeast U.S. have been associated with severe storms and tornadoes (Smith & Katz, 2013). Many of these states' disaster mitigation plans consider land-use planning as a sound mitigation strategy for hazards such as floods, but do not provide strategies toward effective land use or city planning in the context of reducing tornado disaster probability and magnitude. Some of the resistance to implementing new zoning policies aimed at reducing tornado disaster impacts is due to the lack of scientific research on the topic as well the non-stationarity in tornado hazard occurrence. For example, understanding a community's vulnerability to flooding is much more apparent than defining its tornado vulnerability because the geographic position and source of the flooding (e.g., river, coastal, etc.) is generally known. Nevertheless, this research presents an initial step toward understanding not only how land use planning and zoning policies at the regional and metropolitan level could attenuate tornado impact and disaster consequences, but also help communities improve resilience following a disaster. At the very least, policy makers and emergency managers should be aware of how land use patterns, shape, and density may influence tornado disaster potential within their communities and region.

Overall, this research provided a perspective to disaster potential, which may be used to address policy or affect changes in policy that could be implemented on both short- and long-term horizons. For example, although this research is exploratory and theoretical, results from this study may assist decision makers as they decide where to direct available tornado risk mitigation funding. Along with the continued improvement of state and local building codes to address tornado built-environment vulnerability, adopting zoning policies that consider tornado impact potential and magnitude may reduce tornado disasters in the future.

Acknowledgment

The authors thank the anonymous referees for their thoughtful suggestions, feedback, and reviews.

References

Agee, E., & Childs, S. (2014). Adjustments in tornado counts, F-scale intensity, and path width for assessing significant tornado destruction. *Journal of Applied Meteorology and Climatology, 53*, 1494–1505.

Alig, R. J., & Healy, R. G. (1987). Urban and built-up land area changes in the United States: An empirical investigation of determinants. *Land Economics, 63*, 215–226.

Ashley, W., & Strader, S. (2016). Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bulletin of the American Meteorological Society, 97*, 767–786.

Ashley, W. S., Strader, S., Rosencrants, T., & Krmenec, A. J. (2014). Spatiotemporal changes in tornado hazard exposure: The case of the expanding bull's-eye effect in Chicago, Illinois. *Weather, Climate, and Society, 6*, 175–193.

Atkins, N. T., Butler, K. M., Flynn, K. R., & Wakimoto, R. M. (2014). An integrated damage, visual, and radar analysis of the 2013 Moore, Oklahoma, EF5 tornado. *Bulletin of the American Meteorological Society, 95*, 1549–1561.

Atkinson, R. (2004). The evidence on the impact of gentrification: New lessons for the urban renaissance. *European Journal of Housing Policy, 4*(1), 107–131.

Bell, J., & Morrison, T. (2015). Land use planning for flood risk: A comparative case of adaptive and precautionary governance systems. *Journal of Environmental Policy and Planning, 17*(4), 516–534.

Benfield, F. K., Raimi, M. D., & Chen, D. D. (1999). *Once there were greenfields: How urban sprawl is undermining America's environment, economy, and social fabric.* Washington, D.C.: National Resources Defense Council.

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010). Urban sprawl measurement from remote sensing data. *Applied Geography, 30*, 731–740.

Bouwer, L. M. (2011). Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society, 92*, 39–46.

Brath, A., Montanari, A., & Moretti, G. (2006). Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *Journal of Hydrology, 324*(1), 141–153.

Brooks, H., Doswell, C., III, & Kay, M. (2003). Climatological estimates of local daily tornado probability. *Weather and Forecasting, 18*, 626–640.

Buchanan, J. T., & Acevedo, W. (1997). *Defining the temporal and geographic limits for an urban mapping study.* Toronto, Canada: Paper presented at Urban and Regional Information Systems Association.

Burby, R. J. (2000). *Cooperating with Nature: Confronting natural hazards with land-use planning for sustainable communities.* Washington, D.C.: Joseph Henry Press.

Burchell, R. W., Listokin, D., & Galley, C. C. (2000). Smart growth: More than a ghost of urban policy past, less than a bold new horizon. *Housing Policy Debate, 11*, 821–879.

Cascini, L., Bonnard, C., Corominas, J., Jibson, R., & Montero-Olarte, J. (2005). *Landslide hazard and risk zoning for urban planning and development.* London, U.K.: Taylor and Francis press.

Changnon, S. A., Pielke, R. A., Jr., Changnon, D., Sylves, R. T., & Pulwarty, R. (2000). Human factors explain the increased losses from weather and climate extremes. *Bulletin of the American Meteorological Society, 81*, 437–442.

Dixon, P. G., & Mercer, A. E. (2012). Reply to "comments on 'tornado risk analysis: Is dixie Alley an extension of tornado Alley?'". *Bulletin of the American Meteorological Society, 93*, 408–410.

Dixon, P. G., Mercer, A. E., Choi, J., & Allen, J. S. (2011). Tornado risk analysis: Is dixie Alley an extension of tornado Alley? *Bulletin of the American Meteorological Society, 92*, 433–441.

Doswell, C., III (2007). Small sample size and data quality issues illustrated using tornado occurrence data. *Electronic Journal of Severe Storms Meteorology, 2*, 1–16.

Doswell, C., III, Brooks, H., & Kay, M. (2005). Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. *Weather and Forecasting, 20*, 577–595.

Downs, A. (1992). *Stuck in traffic: Coping with peak-hour traffic congestion.* Washington D.C.: Brookings Institution Press.

EPA (2009). *Land-use scenarios: National-scale housing-density scenarios consistent with climate change storylines*Final report. EPA/600/R-08/076F.

Ewing, R. (1994). Characteristics, causes, and effects of sprawl: A literature review. *Environmental and Urban Issues, 21*, 1–15.

Ewing, R., Kostyack, J., Chen, D., Stein, B., & Ernst, M. (2005). *Endangered by sprawl: How runaway development threatens America's wildlife.* Washington D.C.: National Wildlife Federation, Smart growth America, and Nature Serve.

Ferguson, A. P., & Ashley, W. S. (2017). Spatiotemporal analysis of residential flood exposure in the Atlanta, Georgia metropolitan area. *Natural Hazards.* http://dx.doi.org/10.1007/s11069-017-2806-6.

Fleeger, W. E. (2008). Collaborating for success: Community wildfire protection planning in the Arizona white mountains. *Journal of Forestry, 106*(2), 78–82.

Frazier, T. G., Wood, N., Yarnal, B., & Bauer, D. H. (2010). Influence of potential sea level rise on societal vulnerability to hurricane storm-surge hazards, Sarasota County, Florida. *Applied Geography, 30*(4), 490–505.

Frumkin, H. (2002). Urban sprawl and public health. *Public Health Reports, 117*(3), 201–216.

Gagan, J. P., Gerard, A., & Gordon, J. (2010). A historical and statistical comparison of "tornado Alley" to "dixie Alley". *National Weather Digest, 34*(2), 145–155.

Garreau, J. (2011). *Edge city: Life on the new frontier.* New York, NY: Anchor Books.

Glade, T., Anderson, M. G., & Crozier, M. J. (2006). *Landslide hazard and risk.* West Sussex, England: John Wiley & Sons.

Grazulis, T. (1993). *Significant tornadoes, 1680-1991.* St. Johnsbury: VT: Environmental Films.

Greene, R. P., & Pick, J. B. (2011). *Exploring the urban community: A GIS approach.* Upper Saddle River, NJ: Pearson Higher Ed.

Hall, S. G., & Ashley, W. S. (2008). The effects of urban sprawl on the vulnerability to a significant tornado impact in northeastern Illinois. *Natural Hazards Review, 9*, 209–219.

Höppe, P., & Pielke, R. A., Jr. (2006). *Workshop on climate change and disaster losses. Understanding and attributing trends and projections*Final Workshop Report, Published May 2006.

IPCC (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change*Cambridge, UK, and New York, NY, USA: Cambridge University Press.

IPCC (2014). *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change*Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jackson, K. T. (1987). *Crabgrass frontier: The suburbanization of the United States.* New York, NY: Oxford University Press.

Katz, B., & Liu, A. (2000). Moving beyond sprawl: Toward a broader metropolitan agenda. *Brookings Review, 18*, 31–34.

Kim, S. (1999). Urban development in the United States, 1690-1990 (No. w7120) *National Bureau of Economic Research, 66*(4), 855–880.

Kloosterman, R. C., & Musterd, S. (2001). The polycentric urban region: Towards a research agenda. *Urban studies, 38*(4), 623–633.

Knaap, G., & Talen, E. (2005). New urbanism and smart growth: A few words from the academy. *International Regional Science Review, 28*(2), 107–118.

Kunkel, K., & Coauthors (2013). Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society, 94*, 499–514.

Lang, R. (2003). *Edgeless cities: Exploring the elusive metropolis.* Washington, D.C.: Brookings Institution Press.

Leighton, F. B. (1976). Urban landslides: Targets for land-use planning in California. *Geological Society of America Special Papers, 174*, 37–60.

Marsh, P. T., & Brooks, H. E. (2012). Comments on "tornado risk analysis: Is dixie Alley an extension of tornado Alley?". *Bulletin of the American Meteorological Society, 93*, 405–407.

Mills, D. E. (1981). Growth, speculation and sprawl in a monocentric city. *Journal of Urban Economics, 10*(2), 201–226.

Mohleji, S., & Pielke, R., Jr. (2014). Reconciliation of trends in global and regional economic losses from weather events: 1980–2008. *Natural Hazards Review*04014009. http://dx.doi.org/10.1061/(ASCE)NH.1527-6996.0000141.

Newling, B. E. (1969). The spatial variation of urban population densities. *Geographical Review, 59*(2), 242–252.

OMB, Office of Budget management (2009). *Update of statistical area definitions and guidance on their land uses.* https://www.whitehouse.gov/sites/default/files/omb/assets/bulletins/b10-02.pdf, Accessed date: 25 March 2016.

O'Connell, P. E., Ewen, J., O'Donnell, G., & Quinn, P. (2007). Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Sciences, 11*(1), 96–107.

Paulikas, M. J., & Ashley, W. S. (2011). Thunderstorm hazard vulnerability for the Atlanta, Georgia metropolitan region. *Natural Hazards, 58*, 1077–1092.

Pielke, R. A., Jr. (2005). Attribution of disaster losses. *Science, 311*, 1615–1616.

Platt, R. H. (1991). *Land use control: Geography, law, and public policy.* Washington, D.C.: Prentice Hall.

Pottier, N., Penning-Rowsell, E., Tunstall, S., & Hubert, G. (2005). Land use and flood protection: Contrasting approaches and outcomes in France and in England and Wales. *Applied Geography, 25*(1), 1–27.

Powell, J. A. (1998). Race and space: What really drives metropolitan growth. *Brookings Review, 16*(4), 20.

Preston, B. L. (2013). Local path dependence of US socioeconomic exposure to climate extremes and the vulnerability commitment. *Global Environmental Change, 23*(4), 719–732.

Prevatt, D. O., & Coauthors (2012). Making the case for improved structural design: Tornado outbreaks of 2011. *Leadership and Management in Engineering, 12*(4), 254–270.

Prevatt, D. O., Coulbourne, W., Graettinger, A. J., Pei, S., Gupta, R., & Grau, D. (2013). *Joplin, Missouri, tornado of May 22, 2011: Structural damage survey and case for tornado-resilient building codes.* Reston, V.A.: American Society of Civil Engineers.

Rae, S., & Stefkovich, J. (2000). The tornado damage risk assessment predicting the impact of a big outbreak in Dallas–Fort Worth. *Texas. Paper presented at 20th conf. On severe local storms: 9.6*. Orlando, FL: Amer.Meteor. Soc.

Rosencrants, T. D., & Ashley, W. S. (2015). Spatiotemporal analysis of tornado exposure in five U.S. metropolitan areas. *Natural Hazards, 78*, 121–140.

Shepherd, J. M. (2005). A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interactions, 9*(12), 1–27.

Sidle, R. C., & Ochiai, H. (2006). *Landslides: Processes, prediction, and land use.* Washington D.C.: American Geophysical Union.

Sidle, R. C., Pearce, A. J., & O'Loughlin, C. L. (1985). *Hillslope stability and land use.* Washington, D.C.: American Geophysical Union.

Simmons, K. M., Kovacs, P., & Kopp, G. A. (2015). Tornado damage mitigation: Benefit–cost analysis of enhanced building codes in Oklahoma. *Weather, Climate, and Society, 7*(2), 169–178.

Smith, A. B., & Katz, R. W. (2013). Billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases. *Natural Hazards, 67*, 387–410.

Strader, S. M., & Ashley, W. S. (2015). The expanding bull's-eye effect. *Weatherwise, 68*, 23–29.

Strader, S. M., Ashley, W., Irizarry, A., & Hall, S. (2014). A climatology of tornado intensity assessments. *Meteorological Applications, 22*, 513–524.

Strader, S., Ashley, W., Pingel, T., & Krmenec, A. (2016b). Observed and projected changes in United States tornado exposure. *Weather, Climate, and Society*. http://dx.doi.org/10.1175/WCAS-D-16-0041.1.

Strader, S., Ashley, W., Pingel, T., & Krmenec, A. (2017). Projected 21st century changes in tornado exposure, risk, and disaster potential. *Climatic Change*. http://dx.doi.org/10.1007/s10584-017-1905-4.

Strader, S., Pingel, T., & Ashley, W. (2016a). A Monte Carlo model for estimating tornado impacts. *Meteorological Applications, 23*(2), 269–289.

Theobald, D. M. (2005). Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology and Society, 10*. Retrieved from: http://www.ecologyandsociety.org/vol10/iss1/art32/.

Theobald, D. M., & Romme, W. H. (2007). Expansion of the US wildland–urban interface. *Landscape and Urban Planning, 83*(4), 340–354.

Verbout, S., Brooks, H., Leslie, L., & Schultz, D. (2006). Evolution of the US tornado database: 1954-2003. *Weather and Forecasting, 21*, 86–93.

Wheater, H., & Evans, E. (2009). Land use, water management and future flood risk. *Land Use Policy, 26*, S251–S264.

Whyte, W. H. (2013). *The organization man.* Philadelphia, PA: University of Pennsylvania Press.

Wurman, J., Alexander, C., Robinson, P., & Richardson, Y. (2007). Low-level winds in tornadoes and potential catastrophic tornado impacts in urban areas. *Bulletin of the American Meteorological Society, 88*, 31–46.