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"