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ABSTRACT

Exposure has amplified rapidly over the past half century and is one of the primary drivers of increases in disaster frequency and consequences. Previous research on exposure change detection has proven limited since the geographic units of aggregation for decennial censuses, the sole measure of accurate historical population and housing counts, vary from one census to the next. To address this shortcoming, this research produces a set of gridded population and housing data for the Chicago, Illinois, region to evaluate the concept of the “expanding bull’s-eye effect.” This effect argues that “targets”—people and their built environments—of geophysical hazards are enlarging as populations grow and spread. A collection of observationally derived synthetic violent tornadoes are transposed across fine-geographic-scale population and housing unit grids at different time stamps to appraise the concept. Results reveal that intensifying and expanding development is placing more people and their possessions in the potential path of tornadoes, increasing the likelihood of tornado disasters. The research demonstrates how different development morphologies lead to varying exposure rates that contribute to the unevenness of potential weather-related disasters across the landscape. In addition, the investigation appraises the viability of using a gridded framework for assessing changes in census-derived exposure data. The creation of uniformly sized grid data on a scale smaller than counties, municipalities, and conventional census geographic units addresses two of the most critical problems assessing historical changes in disaster frequencies and magnitudes—highly variable spatial units of exposure data and the mismatch between spatial scales of population/housing data and hazards.

1. Introduction

Over the past 80 years—the life span of an average American—the United States has more than doubled its population, transitioned from a rural to urban development character, and effectively escalated the exposure of its population and built environment to weather hazards. Exposure to weather extremes contains components of both vulnerability and weather hazard risk and, in a broad sense, constitutes the characteristics of the natural and/or built environment that position a system to be affected by a hazard (Morss et al. 2011). Human and engineered structure exposure has amplified rapidly throughout the United States and is arguably one of the primary drivers of increases in disaster frequency and consequences. Urban regions have continually outpaced overall national growth (Census Bureau 2012a), illustrating that weather hazard exposure landscape is not uniform or fixed, but rather is focused in specific areas and continually evolving.

The Chicago, Illinois, metropolitan area is a prime example of the enormous growth that American cities have witnessed during the twentieth and early twenty-first centuries (Auch et al. 2004; Greene and Pick 2012). The Chicago region is characterized by a dense urban core and has experienced extensive, spatially fragmented suburban and exurban growth (Theobald 2005; Greene and Pick 2013), or sprawl (Duany et al. 2000; Gillham 2002; Hall and Ashley 2008), during the last 60 years. To what extent has the growth of Chicago population and households increased exposure to weather hazards? To what degree have demographic shifts and transformations in Chicago’s developed landscapes, such as that created by sprawl, led to a greater potential for a weather disasters? We assess these questions by 1) employing historical census data in a gridded framework and 2) using a portfolio of significant contemporary and synthetic tornado paths to produce a set of tornado disaster scenarios. Together, these methods are used to evaluate
changes in potential tornado hazard impacts on the metropolitan Chicago population and its housing. Ultimately, the goal of this research is, first, to appraise a methodological framework for the spatiotemporal assessment of potential microscale disaster events and, second, to inform policy makers, emergency managers, and the public of the potential for catastrophic tornado scenarios to stimulate future mitigation strategies.

2. Background

Weather-related disasters and losses have steadily increased though time (Changnon et al. 2000; Bouwer 2011; Field et al. 2012). Uncovering and quantifying the source(s) of these trends is an area of continual dialogue and controversy in hazard assessment research (e.g., Trenberth et al. 2011; Kunkel et al. 2013), largely because of the inadequacies of current geophysical event and socioeconomic datasets (Kunkel et al. 1999; Höppe and Pielke 2006; Lerner-Lam 2007; Bouwer 2011; Kahn and Kelman 2012). However, certainties do exist—human populations continue to increase and cluster in physically vulnerable locations (Nicholls and Small 2002; Auch et al. 2004; Field et al. 2012), placing ever-increasing amounts of people and their assets in harm’s way (Changnon and Burroughs 2003; Wilson and Fischetti 2010; Paulikas and Ashley 2011; Burkett and Davidson 2012). Despite decades of improvement in mitigation activities aimed at reducing impacts from extreme events (Nicholls 2001, 2011), the rapid increase in disaster losses and people affected suggests that swelling populations, development trends, and vulnerabilities are outpacing mitigation and adaptation, leading to greater disaster frequencies and amplified impacts. Through demographic and asset normalization methods, long-term, macroscale hazard impact assessments [cf. Table 1 in Bouwer (2011) and Table 3 in Barthel and Neumayer (2012)] have suggested that societal change and economic development are the primary factors responsible for the increasing trend in disaster losses (Kunkel et al. 1999; Pielke 2005; Höppe and Pielke 2006; Bouwer 2011; Barthel and Neumayer 2012; Field et al. 2012) and will likely remain at the forefront of loss attribution in the future (Pielke 2007; Barthel and Neumayer 2012; Simmons et al. 2013). However, the large-scale application of socioeconomic normalization functions used in these studies often prevents a focused appraisal of exposure changes, especially across complex spatiotemporal landscapes such as those found in metropolitan regions.

Advances in computing capabilities and software have permitted the ability of models to predict impacts of hazards using components that represent weather events, exposure rates, and measures of social and/or physical vulnerabilities (Burton 2010). Modeling research has focused most notably on hurricane, flood, and earthquake effects (e.g., Pinelli et al. 2004; Burton 2010; Dell’Acqua et al. 2013; Remo et al. 2012; Remo and Pinter 2012; Peduzzi et al. 2012), with Federal Emergency Management Agency’s (FEMA’s) Hazards U.S. (HAZUS; http://www.fema.gov/hazus) application allowing a spectrum of users and agencies to conduct impact loss estimations for these hazards (e.g., Scawthorn et al. 2006). Methodologies have also been developed to gauge the potential impact from microscale events, such as significant tornado events on urban locations (Rae and Stefkovich 2000; Wurman et al. 2007, hereafter WUR). These investigations transpose historical tornado cases, or their likeness, onto contemporary spatial datasets to gauge the potential effects of a violent tornado or outbreak of tornadoes on select metropolitan areas. However, this scenario research has ignored how and where changes in exposure altered the disaster geographies of extreme weather hazards. Additional scenario work by Hall and Ashley (2008) and Paulikas and Ashley (2011) formulated methods to evaluate these spatiotemporal changes at the metropolitan scale but were limited by an inability to overcome the spatial unit variation problem (Cai et al. 2006) associated with evolving enumerations that depict census data. We plan to eliminate these methodological concerns by using a homogenized procedure for assessing and quantifying changes in finescale weather hazard exposure to populations and their housing.

3. Data and methodology

a. Population and housing grid construction

Previous research on detection of changes in hazard exposure or vulnerability has proven limited since the geographic units of aggregation for decennial censuses, the sole measure of accurate historical population and housing counts in the United States, vary from one census to the next. To address this methodological shortcoming, we produced a collection of fine-geographic-scale population and housing data for the Chicago metropolitan region by employing an areal weighting (AW), or proportionate allocation, algorithm similar to those used by the Socioeconomic Data and Applications Center (SEDAC) to develop a set of 2000 U.S. grids (SEDAC 2011) and global population grids (Deichmann et al. 2001). The AW procedure apportions a raster grid representation of population or other variable from a census-defined enumeration unit (e.g., tract or block) according to the area proportion of the census unit that the grid cell encompasses (Balk et al. 2005). The creation of uniformly sized grid data on a scale smaller than counties, municipalities, and conventional census geographic units will...
address two of the most critical problems we have in assessing historical changes in disaster frequencies and magnitudes: 1) highly variable spatial units of exposure data and 2) the mismatch between spatial scales of population/housing data and weather hazards. Previous research (Schlossberg 2003) suggests that small area interpolation is best served by using the smallest census areal unit available and that the AW method is superior to other procedures for extracting data under a buffer, neighborhood boundary, or similar administrative overlay. Dasymetric mapping, which applies ancillary information (e.g., land use/cover data) to inform the areal estimation and interpolation of attributes such as population or housing units, is also suggested in the literature (Holt et al. 2004; Mennis 2009). Although arguably superior for appraising demographic attributes (Wu et al. 2005), it suffers from illogical stationarity when, for example, only one time stamp of ancillary data is available for informing a model that is being used in multiperiod change detection. Unfortunately, consistent ancillary data to inform dasymetric estimation of population and housing units for our series of time stamps do not exist.

Initially, census block boundary information for 1990, 2000, and 2010 was acquired from the University of Minnesota’s National Historical Geographic Information System (NHGIS); 1990 is chosen as the initial year since this was the first census for which the block unit—the smallest geographic entity for which the Census Bureau presents data—was available. We evaluate 11 counties (Table 1, Fig. 1) in the northeast Illinois region; these counties were chosen to represent the full spectrum of development (or lack thereof) character found in the area. A grid resolution of 0.16 km² was used for the AW procedure at the block level; this resolution represents the mean size of all blocks in the region for 1990, which is the initial time stamp of analysis and the coarsest of the three analysis iterations. Population and housing count data at the block level were obtained from the Census Summary File 1 (SF1) archives at NHGIS for each of the three censuses. Boundary and demographic attribute datasets were conflated in a geographic information system (GIS).

In constructing the grids in the GIS, a “fishnet” at each resolution was constructed for the area of interest on an Albers equal-area conic projection. Population and housing counts at the block level were transformed from their native irregular geographic units by proportionally allocating to the grid. If a hypothetical grid cell contains 50% of the area of one census block and 20% of the area of a second census block, the housing count for that grid cell will be 50% of the housing count of the first census block and 20% of the housing count of the second census block (SEDAC 2011).

To evaluate long-term changes in potential hazard exposure for Chicago, we also assess census tract population data for two counties in the region: Cook, which is representative of an urban core, and Kane, which is typified by recent suburban/exurban development character (Greene and Pick 2012). Tracts are larger enumerations in comparison to blocks (Table 1) and, consequently, employing the AW method on a coarser grid is required. The use of tract data promotes a more informed temporal perspective of any hazard scenario research at the cost of reduced spatial resolution. We constructed population grids at 2.21 km² resolution for

<table>
<thead>
<tr>
<th>Year</th>
<th>Boone</th>
<th>Cook</th>
<th>DeKalb</th>
<th>DuPage</th>
<th>Kane</th>
<th>Kendall</th>
<th>Lake</th>
<th>LaSalle</th>
<th>McHenry</th>
<th>Will</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>—</td>
<td>2.21</td>
<td>—</td>
<td>16.14</td>
<td>—</td>
<td>45.25</td>
<td>—</td>
<td>34.76</td>
<td>197.85</td>
<td>70.96</td>
<td>7.59</td>
</tr>
<tr>
<td>1970</td>
<td>121.70</td>
<td>2.11</td>
<td>13.21</td>
<td>—</td>
<td>30.16</td>
<td>20.98</td>
<td>34.76</td>
<td>197.85</td>
<td>113.06</td>
<td>55.00</td>
<td>7.44</td>
</tr>
<tr>
<td>1980</td>
<td>121.70</td>
<td>2.02</td>
<td>9.47</td>
<td>—</td>
<td>25.14</td>
<td>119.39</td>
<td>16.44</td>
<td>93.11</td>
<td>46.81</td>
<td>7.39</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>121.70</td>
<td>1.84</td>
<td>78.31</td>
<td>7.51</td>
<td>123.86</td>
<td>19.96</td>
<td>104.46</td>
<td>12.54</td>
<td>110.13</td>
<td>60.88</td>
<td>9.40</td>
</tr>
<tr>
<td>2000</td>
<td>121.70</td>
<td>1.85</td>
<td>78.31</td>
<td>5.93</td>
<td>123.86</td>
<td>20.26</td>
<td>104.46</td>
<td>8.06</td>
<td>110.13</td>
<td>33.68</td>
<td>8.91</td>
</tr>
<tr>
<td>2010</td>
<td>104.34</td>
<td>1.88</td>
<td>78.27</td>
<td>4.03</td>
<td>111.47</td>
<td>16.56</td>
<td>83.48</td>
<td>7.95</td>
<td>106.17</td>
<td>30.42</td>
<td>8.30</td>
</tr>
<tr>
<td>1990</td>
<td>0.6988</td>
<td>0.0474</td>
<td>0.6384</td>
<td>0.0798</td>
<td>0.5873</td>
<td>0.2162</td>
<td>0.5952</td>
<td>0.1333</td>
<td>0.3456</td>
<td>0.2777</td>
<td>0.1646</td>
</tr>
<tr>
<td>2000</td>
<td>0.5291</td>
<td>0.0387</td>
<td>0.5188</td>
<td>0.0541</td>
<td>0.4797</td>
<td>0.1597</td>
<td>0.4403</td>
<td>0.0950</td>
<td>0.4999</td>
<td>0.2221</td>
<td>0.1938</td>
</tr>
<tr>
<td>2010</td>
<td>0.4124</td>
<td>0.0251</td>
<td>0.4137</td>
<td>0.0501</td>
<td>0.2280</td>
<td>0.1273</td>
<td>0.2154</td>
<td>0.0762</td>
<td>0.4446</td>
<td>0.1965</td>
<td>0.0910</td>
</tr>
<tr>
<td>1970–2010 pop.</td>
<td>112.9%</td>
<td>5.4%</td>
<td>46.8%</td>
<td>87.9%</td>
<td>88.7%</td>
<td>105.3%</td>
<td>335.0%</td>
<td>2.3%</td>
<td>176.8%</td>
<td>173.4%</td>
<td>21.0%</td>
</tr>
<tr>
<td>1990–2010 pop.</td>
<td>75.8%</td>
<td>1.8%</td>
<td>34.9%</td>
<td>17.3%</td>
<td>54.8%</td>
<td>62.3%</td>
<td>191.1%</td>
<td>6.6%</td>
<td>68.5%</td>
<td>89.6%</td>
<td>16.0%</td>
</tr>
<tr>
<td>1970–2010 HU</td>
<td>144.7%</td>
<td>17.5%</td>
<td>102.7%</td>
<td>152.4%</td>
<td>126.4%</td>
<td>136.2%</td>
<td>418.7%</td>
<td>32.7%</td>
<td>219.8%</td>
<td>223.9%</td>
<td>47.4%</td>
</tr>
<tr>
<td>1990–2010 HU</td>
<td>74.0%</td>
<td>7.8%</td>
<td>50.2%</td>
<td>21.8%</td>
<td>58.0%</td>
<td>63.3%</td>
<td>193.3%</td>
<td>14.0%</td>
<td>75.9%</td>
<td>93.3%</td>
<td>20.5%</td>
</tr>
</tbody>
</table>
FIG. 1. (a) The Chicago-area counties under investigation in this research with historical and synthetic tracks placed across the study area. The Chicago central business district, or “The Loop,” is denoted by a star. The tornado paths and numeral labels correspond to the track information found in Table 2. (b) The percentage change in population from 1990 to 2010 for each 0.16 km² grid cell, with 10-km-long tornado segment (cf. section 4a; width attribute derived from WUR Hybrid, or path 10 in Table 2) and scenario path S2 placed across northern Kane and Cook Counties (cf. section 4b). (c) The 2010 land-use classification based on Theobald (2005) housing density criteria, with five full-length scenario (S2) paths placed across the developed core of the study area [cf. section 4d(1)]. Eight 10-km-long S2 segments—two for each land-use type—are also placed on the map, with Ru corresponding to rural, Ex to exurban, Su to suburban, and Ur to urban [cf. section 4d(2)]. (d) The land-use change for the study area from 1990 to 2010 for three transformations assessed; white cells indicate no change or (less common) reversal of land use (urban to suburban). Five 10-km S2 segments are placed across areas that experienced notable land-use transformation, with T1 and T2 assessing rural to exurban change and T3, T4, and T5 evaluating exurban to suburban change [cf. section 4d(2)].
Cook County and at 19.96 km² for Kane County. These resolutions were chosen since they were the mean size of the tracts during the first year of our tract-level analysis (1960 for Cook and 1990 for Kane).

b. Historical and synthetic tornado tracks

Since 1950, long-track, significant (≥8 km and ≥EF2; EF is the Enhanced Fujita scale) tornadoes have produced 85% of fatalities and 75% of reported damage; infrequent violent (≥EF4) events have been the cause of over two-thirds of all tornado deaths (Ashley 2007; Simmons and Sutter 2011). Thus, in scenario-based research and in resulting mitigation actions, it is imperative to focus on these relatively rare events. Improvements in data collection practices associated with post-hazard-event surveying (e.g., Speheger et al. 2002; Yuan et al. 2002) have generated a portfolio of hazard cartographies to utilize in hypothetical scenario assessments. In particular, extreme tornado events in the past few years have been surveyed by the National Weather Service (NWS), National Institute of Standards and Technology, Federal Emergency Management Agency, private meteorologists (e.g., Marshall et al. 2012), etc., supplying GIS-ready maps illustrating damage path attributes and, in some cases, detailed structure damage information.

Initially we gathered GIS-ready tornado paths that contain damage attribute information (Fujita (F) or Enhanced Fujita scale; Doswell et al. 2009) for contemporary, high-end tornado events (Table 2). In addition, we constructed two sets of synthetic paths that included 1) parameters and track widths constructed from 3 May 1999 mobile Doppler radar data and postevent analysis (cf. WUR) and 2) mean length and width dimensions of recorded violent (EF4 and EF5) tornadoes from 1995 to 2011 (Table 3) in conjunction with the percentage area of each EF-scale damage class swept out by the 22 May 2011 Joplin, Missouri, tornado. The Joplin tornado is the prototypical tornado case to employ in our synthetic research since it 1) was the deadliest (158 direct fatalities) U.S. tornado since 1947 and 2) is a contemporary representation of a catastrophic tornado scenario in a densely settled area. In constructing

### Table 2. Tornado parameters and attributes from 1) violent events from 1990, 1999, 2011, and 2013, 2) WUR synthetics, and 3) our synthetics [i.e., Ashley et al. (ASH)], which are based on mean length (km) and width (m) information gathered from all U.S. violent tornadoes from 1995 to 2011 that contained information on those elements. Area (km²) swept out by each tornado’s reported (Enhanced) Fujita-scale class is provided.

<table>
<thead>
<tr>
<th>Path Event</th>
<th>Date</th>
<th>Min-Max Path Length (F/EF scale)</th>
<th>Fatalities</th>
<th>Path Max Width</th>
<th>F/EF0 Area</th>
<th>F/EF1 Area</th>
<th>F/EF2 Area</th>
<th>F/EF3 Area</th>
<th>F/EF4 Area</th>
<th>F/EF5 Area</th>
<th>Total Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tornado event</td>
<td>1) Plainfield, IL</td>
<td>28 Aug 1990 F1-F5 29</td>
<td>26.4</td>
<td>548</td>
<td>8.57</td>
<td>2.57</td>
<td>0.44</td>
<td>0.12</td>
<td>0.02</td>
<td>11.72</td>
<td></td>
</tr>
<tr>
<td>2) Bridge creek-Moore, OK</td>
<td>3 May 1999 F1-F5 36</td>
<td>61</td>
<td>1609</td>
<td>18.11</td>
<td>12.31</td>
<td>12.70</td>
<td>5.51</td>
<td>0.87</td>
<td>49.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Mulhall, OK</td>
<td>3 May 1999 F1-F4 2</td>
<td>63</td>
<td>1609</td>
<td>31.00</td>
<td>17.36</td>
<td>6.41</td>
<td>12.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Joplin, MO (NWS)</td>
<td>22 May 2011 EF1-EF5 158</td>
<td>35</td>
<td>1463</td>
<td>28.71</td>
<td>9.58</td>
<td>3.85</td>
<td>2.22</td>
<td>1.34</td>
<td>45.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) El Reno, OK</td>
<td>24 May 2011 EF0-EF4 9</td>
<td>101</td>
<td>1609</td>
<td>32.63</td>
<td>21.83</td>
<td>17.06</td>
<td>2.55</td>
<td>0.42</td>
<td>99.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6) Washington-Goldsby, OK</td>
<td>24 May 2011 EF0-EF4 0</td>
<td>37</td>
<td>805</td>
<td>3.58</td>
<td>3.43</td>
<td>3.16</td>
<td>2.21</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7) Chickasha-Newcastle, OK</td>
<td>24 May 2011 EF0-EF4 1</td>
<td>53</td>
<td>805</td>
<td>10.17</td>
<td>5.12</td>
<td>2.68</td>
<td>1.12</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>8) Newcastle-Moore, OK</td>
<td>20 May 2013 EF0-EF5 23</td>
<td>27</td>
<td>1737</td>
<td>5.45</td>
<td>2.57</td>
<td>1.90</td>
<td>1.38</td>
<td>0.12</td>
<td>23.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9) El Reno, OK</td>
<td>30 May 2013 EF0-EF3 9</td>
<td>26</td>
<td>4184</td>
<td>13.07</td>
<td>9.97</td>
<td>7.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wurman et al. (WUR) synthetics</td>
<td>10) Mulhall, OK (MH)</td>
<td>3 May 1999 F1-F4 —</td>
<td>60</td>
<td>7050</td>
<td>225.33</td>
<td>91.05</td>
<td>99.79</td>
<td>45.87</td>
<td>462.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11) Bridge creek/Moore, OK (BC)</td>
<td>3 May 1999 F1-F5 —</td>
<td>60</td>
<td>2151</td>
<td>65.02</td>
<td>27.44</td>
<td>20.09</td>
<td>11.28</td>
<td>19.28</td>
<td>143.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12) Hybrid (HB)</td>
<td>— F1-F5 —</td>
<td>60</td>
<td>8800</td>
<td>235.19</td>
<td>105.40</td>
<td>73.59</td>
<td>36.88</td>
<td>72.70</td>
<td>523.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13) Hybrid Reduced (HR)</td>
<td>— F1-F4 —</td>
<td>60</td>
<td>6580</td>
<td>174.85</td>
<td>73.47</td>
<td>73.52</td>
<td>61.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14) Small (SM)</td>
<td>— F1-F3 —</td>
<td>60</td>
<td>548</td>
<td>13.07</td>
<td>9.97</td>
<td>7.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ashley et al. (ASH) synthetics</td>
<td>15) Synthetic 1 (S1)</td>
<td>— EF0-EF5 —</td>
<td>45.21</td>
<td>873</td>
<td>20.63</td>
<td>4.36</td>
<td>4.22</td>
<td>5.06</td>
<td>4.37</td>
<td>1.44</td>
<td>40.09</td>
</tr>
<tr>
<td>16) Synthetic 2 (S2)</td>
<td>— EF0-EF5 —</td>
<td>67.3</td>
<td>1390</td>
<td>9.57</td>
<td>9.99</td>
<td>12.00</td>
<td>10.37</td>
<td>3.41</td>
<td>95.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17) Synthetic 3 (S3)</td>
<td>— EF1-EF5 —</td>
<td>45.21</td>
<td>873</td>
<td>9.04</td>
<td>8.71</td>
<td>10.42</td>
<td>8.97</td>
<td>2.95</td>
<td>40.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18) Synthetic 4 (S4)</td>
<td>— EF1-EF5 —</td>
<td>67.3</td>
<td>1390</td>
<td>21.46</td>
<td>20.66</td>
<td>24.71</td>
<td>21.25</td>
<td>6.98</td>
<td>95.06</td>
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<td>3.03</td>
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<tr>
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<td>1390</td>
<td>34.99</td>
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<td>19.75</td>
<td>11.87</td>
<td>7.18</td>
<td>95.06</td>
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</tbody>
</table>
our synthetics, we used two sources of damage path information from the Joplin event: 1) the NWS’s assessment (http://www.crh.noaa.gov/sgf/?n=event_2011may22_tornadotracks) and 2) aerial and structure-by-structure ground surveys conducted by Marshall et al. (2012).

Dual damage path sources were used to illustrate and evaluate the differences in findings that can be found by two surveys of the same event (Fig. 2). In both cases, we focused specifically on the 10-km portion of the track that went through the settled areas of Joplin (from Schifferdecker Ave. to the west to South Kenser Ct. to the east) as this is most representative of a tornado striking a developed region. Since the damage isopleths in the NWS and Marshall et al. (2012) surveys were EF1+, we constructed an EF0 contour to represent the totality of the tornado that was based on the tornado width officially reported in NOAA’s Storm Data (i.e., 1463 m). Comparisons (not shown) with the EF0 contour generated with Marshall et al.’s damage indicators suggest that this width corresponds with the size of the hazard as it traversed South Joplin. We fit this contour to the Marshall et al. path since this will be our primary synthetic path tool of assessment. The area swept out by each damage class was then converted to a percentage of the total 10-km track segment (Table 4) to promote synthetic tornado path construction (Fig. 2).

c. Path and grid intersect

To evaluate changes in tornado exposure and assess “worst case” (Clarke 2005) tornado scenarios for Chicago, we conflated the exposure attribute grids with our tornado path portfolio in a GIS. In this step, we used the underlying census attribute grid (population or housing unit) and placed a single tornado path, or path segment, over a desired location. Path placement was not random; the paths were placed purposely over areas to evaluate how changing development patterns influence the potential tornado disaster landscape. As in Hall and Ashley (2008), we assess specifically areas that have experienced a considerable increase in development due to sprawl. Similar to Rae and Stefkovich (2000) and WUR, but using both temporal and spatial perspectives, we evaluate how the evolving demographics of urban cores have influenced worst-case scenarios. Finally, we examine changes in rural and exurban development characteristics in the Chicago region. The goal of this analysis was not to produce a comprehensive inventory of all possible scenarios for the area; rather, we focus on specific development characters and changes in those landscapes to reveal how disaster consequences may be amplified by exposure.

Once the path is overlaid on the exposure attribute grid, we “intersect” the demographic grid and tornado path layers in the GIS to combine the geospatial data into a single layer that retains both field and boundary data. Thereafter, we used a “dissolve” tool to generate attributes for each year considered (e.g., population affected by a specific damage rating for scenario in 1990) that may be used in subsequent analysis. In overlaying their block-level attribute data with the 1990 Plainfield tornado path, Hall and Ashley (2008) employed the “intersecting” method (Schlossberg 2003). This procedure generates the total number affected by the hazard by summing the attribute values for all blocks that are within or intersect the tornado path, even if the path clipped merely a small proportion of the block enumeration. This methodology leads to overestimation of those affected (Schlossberg 2003; Hall and Ashley 2008). Conversely, in our calculation approach, we use the AW method to produce a more accurate representation of the number of people potentially affected. Specifically, along the edges of the tornado and EF classes, where the track/classes will transect only parts of a grid cell, we use the AW procedure to adjust tallies of population and/or housing based on the fraction of the grid cell impacted.

The scenario tallies of affected people are estimates based on places of residence, since census population data are based on number of residents in an enumeration area. While the number of people affected may vary depending on the situation, the number of housing units impacted should be a relatively robust marker for assessing spatiotemporal changes in disaster potential landscape.

4. Results

The results of this research are presented in four parts. First, we demonstrate the methodological framework used to measure changes in residential exposure to high-end, microscale hazards such as violent tornadoes. Exposure is assessed under three event scenarios: the previous synthetic worst-case scenario, contemporary violent events, and our own synthetic path constructions. Second, we address the implications of downscaling
demographic data from alternative enumeration geography (county or tract versus block level). In the last sections, we calculate the spatiotemporal changes in exposure consequences to potential violent tornadoes across the Chicago region to discover how the disaster landscape has evolved across time and differing development settings.

a. Comparison of path attributes

The areal extent of tornado damage is controlled by basic length and width dimensions of the hazard, whereas the damage magnitude is related to tornado core wind speed and modulated by construction practices, the age and quality of structures affected, the length of time a structure is affected by the tornado, and, in the case of events that cross over areas devoid of engineered structures, the lack of viable damage indicators that can result in inaccurate assessments of intensity (McDonald and Mehta 2006; WUR). Before performing any scenario-based research, including that which may be considered worst-case (Clarke 2005; WUR), it is important to evaluate the validity of spatial and intensity attributes of tornado events that may be used to model potential
disaster circumstances. As argued by Brooks et al. (2008), it is important to provide emergency managers and planners with an assessment of realistic high-end events so that they are not overwhelmed by casualty and damage estimates and, possibly, disregard disaster prospects.

Of the roughly 1500 tornadoes that occur each year in the United States, less than 0.6% (or approximately 9 yr⁻¹) are rated violent (Table 3). While intensity (as inferred by the EF scale) of tornadoes cannot be correlated explicitly with length or width, there is evidence that, generally, both path length and width tend to increase with increasing F/EF scale (Brooks 2004). The mean length (width) of violent tornadoes is much longer (wider) than all tornadoes as well as significant tornadoes (Table 3). The mean area theoretically swept out (length × maximum width) by a violent tornado is 39.46 km², whereas tornadoes across all (significant) damage classes were a modest 0.51 km² (6.74 km²).

Therefore, based on contemporary tornadoes, violent events have theoretical damage footprints that are over 5 times the size of all significant tornadoes and nearly 80 times the size of all documented tornadoes. Logically, the larger the area swept out by the core flow of a tornado, the greater the likelihood that casualties and damage to the built environment will occur.

There were 144 recorded tornadoes from January 1950 to June 2012 with path widths greater than 1.76 km (1 mi) with only three events reported wider than 3.5 km (2 mi), including 22 May 2004 Hallam, Nebraska, F4 (4.4 km, 2.5 mi; McCarthy and Schaefer 2005); 4 May 2007 Hopewell, Kansas, EF3 (3.9 km, 2.2 mi; Lemon and Umscheid 2008); and 7 June 2008 Pardeeville–Cambria, Wisconsin, EF2 (3.52 km, 2 mi) (Fig. 3). Two Oklahoma tornadoes in May 2013 provide additional, contemporary evidence of extremely wide cases. The Newcastle-Moore, Oklahoma, tornado of 20 May 2013 was over

<table>
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</thead>
<tbody>
<tr>
<td></td>
<td>Area</td>
<td>% area of track segment</td>
<td>Area % area of track segment</td>
</tr>
<tr>
<td>EF0</td>
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<td>51.1</td>
<td>—</td>
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<tr>
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<tr>
<td>EF2</td>
<td>1.645</td>
<td>10.57</td>
<td>1.645</td>
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<tr>
<td>EF3</td>
<td>1.982</td>
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<td>1.982</td>
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<td>EF4</td>
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<td>1.719</td>
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<td>EF5</td>
<td>0.567</td>
<td>3.64</td>
<td>0.567</td>
</tr>
<tr>
<td>Total</td>
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<td>100</td>
<td>7.608</td>
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</table>

FIG. 3. Tornado and damage: intensity widths for the observed and synthetically derived events in Table 2. The segments for observed tornadoes represented were selected by subjectively determining where the tornado was at its widest during its most intense (as inferred by F/EF scale) phase. Numbers correspond to 1) WUR Mulhall, OK (MH), 2) WUR Bridgecreek/Moore (BC), 3) WUR Small (SM), 4) WUR Hybrid Reduced (HR), 5) WUR Hybrid (HB), 6) ASH Synthetic 6 (S6), 7) ASH Synthetic 5 (S5), 8) ASH Synthetic 4 (S4), 9) ASH Synthetic 3 (S3), 10) ASH Synthetic 2 (S2), 11) ASH Synthetic 1 (S1), 12) Plainfield, IL, 13) Joplin, MO (NWS), 14) Washington–Goldsbly, OK, 15) El Reno, OK (2011), 16) Chickasha–Blanchard–Newcastle, OK, 17) Mulhall, OK, 18) Bridgecreek/Moore, OK (1999), 19) Newcastle–Moore, OK (2013), 20) El Reno, OK (2013) EF3, 21) 22 May 2004 Hallam, NE F4, 22) 4 May 2007 Hopewell, KS EF3, 23) 7 Jun 2008 Pardeeville–Cambria, WI EF3, 24) mean significant (F/EF2+) events from 1995–2011 (Table 3), and 25) mean violent (F/EF4+) from 1995–2011.
1.7 km wide and the El Reno, Oklahoma, tornado of 30 May 2013 was assessed at nearly 4.2 km wide, surpassing the 2004 Hallam, Nebraska, event as the widest tornado recorded. The mean width of contemporary significant (violent) tornadoes is less than 0.4 km (0.9 km), illustrating that the synthetic tornadoes and affiliated impact tallies generated by WUR may not be “realistic high-end cases” as suggested by Brooks et al. (2008) (Tables 2 and 3, Fig. 3). The WUR “observation-constrained model” synthetics were generated using 1) observed Doppler on Wheels (DOW) wind speed and size attributes at the time of maximum DOW-observed intensity for the 3 May 1999 Mulhall and Bridgecreek/Moore tornado events and 2) hypothetical cases that were representative of the worst of the tornado size/magnitude characteristics from the remotely sensed, DOW-derived attributes of these events (Table 2). Specifically, the path widths of three of the five synthetics used by WUR—that is, the 6.6-km-wide Hybrid Reduced (HR), 7.1-km-wide Mulhall (MH), or 8.8-km-wide Hybrid (HB)—are between 50% and 100% wider than the widest tornadoes ever recorded, the 2004 Hallam F4 and the 2013 El Reno EF3. The EF0+ path widths of the WUR tornadoes could be considerably wider than the reported values in WUR’s Table 1 since the diameters stated in their study only included winds greater than 43 m s$^{-1}$, which is equivalent to the midrange of an F/EF1 (the F1 range includes estimated three second gusts of 35–52 m s$^{-1}$, whereas the EF1 spans 38–49 m s$^{-1}$). In the most extreme synthetic, the area swept out by $\geq$43 m s$^{-1}$, or EF1, winds is over 500 km$^2$, or almost the entire size of the city of Chicago (588 km$^2$). While there is historical precedent for extreme long-track events with over 30 events surpassing reported lengths of over 200 km since 1950, there is considerable discrepancy in the extreme width attributes found in the reported tornado record and WUR synthetics. Brooks et al. (2008) and Blumenfeld (2008) document concerns with the probability of death values used by WUR; however, our comparison of reported and derived tornado widths suggests that at least part of the extreme impact tallies found in the WUR study may be due to the improbable tornado widths. This dimensional argument suggests that the area, residents, housing units, and death estimates found in WUR’s scenarios may not be plausible even in “hyper-worst case” situations.

We evaluated the tornado width characteristics found in Table 2 and illustrated in Fig. 3 by transposing each scenario onto a high-density, single-family housing area that typifies the developed landscape outside the Chicago central business district (CBD). Specifically, each of the path segments was constrained by a 10-km length, whereas the width was determined by the maximum F/EF0 or F/EF1 width attribute in Table 2. The 10-km length approximates the worst portion of the 2011 Joplin EF5 tornado segment that directly affected the developed area of the city (Figs. 1b and 2). Thereafter, we centered each tornado segment over the intersection of Diversey and Laramie Avenues in Chicago’s northwest side, calculating the area, 2010 population, and number of 2010 housing units and households affected in each scenario. The results highlight the dichotomy between WUR tornado scenarios and observed cases or scenario events based on the 2011 Joplin EF5 (Table 5). For example, the WUR HR, MH, and HB scenarios affect nearly 3.5 to 4.5 times the area of the “worst of” observed 2011 Joplin segments, even when length is restricted. The increase in area affected in these WUR scenarios leads to subsequent amplification of population (2.1–2.7 times the number of people compared to Joplin scenario), housing units (2.8–3.7 times), and households (2.8–3.6 times) impacted. The 31 May 2013 El Reno tornado was over 3 times the size of the Joplin event, suggesting that this recent case may provide the most realistic high-end width attribute to be employed in scenario work. In comparison, WUR HB, MH, and HR scenarios all affect areas 1.3 to 1.8 times larger than this modern width record holder. While it is possible that the widths found in WUR study could occur, they appear improbable based on even the most extreme cases found in the historical tornado record. The probability of WUR’s high-end widths occurring over a high-density developed landscape such as that found in the Chicago region appears even more remote since only 2.2% of the conterminous United States was characterized as urban and/or suburban (<0.69 ha per housing unit) in 2000, rising to a forecasted 3.1% by 2020 (Theobald 2005).

b. Comparison of data metrics

Census attribute data are available for a spectrum of geographic entities, from blocks, block groups, and tracts at the finescale, to counties and states at the intermediate scale, to divisions, regions, and the nation at the coarse scale (Census Bureau 1994). Vulnerability analysis of relatively small spatial-scale hazards, such as tornadoes, necessitates the use of fine-resolution datasets to instruct the spatiotemporal understanding of physical exposure’s culpability in weather disaster composition. Both block and tract spatial dimensions can change extensively across a geography, from very small regions in urban areas to very large regions in exurban or rural locations. For example, the mean block (tract) size of urban Cook County in 2010 is 0.0251 km$^2$ (1.88 km$^2$) and the mean block size of more rural Boone, DeKalb, or LaSalle County is over an order of magnitude larger, or, in excess of 0.41 km$^2$ (78–106 km$^2$) (Table 1). Consequently,
the use of block-level data to inform the grids is desirable when analyzing microscale hazards, such as tornadoes, and their potential impacts. Unfortunately, block- and block-group-level data were first available in 1990, and only complete at that scale for the entire United States in 2010. Tract-level data exist for some counties in metropolitan statistical areas (MSAs) for a longer record, but data availability is restricted largely to those counties that constituted or are near the urban core. How do these different scales of census enumeration units affect the AW-gridded downscale exposure tallies and, ultimately, conclusions?

To evaluate this scale issue, we positioned synthetic tornado track 2 (S2; Table 2, Fig. 1b) across the northern portions of Cook and Kane Counties and calculated the number of people hypothetically affected in this scenario for 1990, 2000, and 2010 (Table 6). We chose these two counties since Cook represents an urban area with high-resolution block and tract enumerations, whereas Kane typifies suburban and exurban development characteristics; the two counties have disparate mean block and tract enumerations (Table 1).

Results reveal a bimodal relationship between impacts by county across all data frameworks (i.e., gridded versus base census geographies, which we call “raw” data) and enumeration types (i.e., county, tract, block) for the same year (Table 6). The much larger enumerations in Kane County versus Cook lead to percentage differences that are consistently greater in Kane.

When examining variation across the gridded and raw census enumeration frameworks of analysis (Tables 6 and 7), impacted population counts and percentage differences are close except for the case of Kane tract-level analysis. Broadly, this finding confirms that down-scaled gridded data can be substituted as an areal unit of measurement in scenario-based work to provide an efficient structure for assessing not only the spatial changes in impacts, but also differences found across time stamps. Appropriately scaled gridded data overcome the spatial irregularity, variation in scale, and degree of aggregation problems present in raw census data; all issues that can affect the reliability of subsequent spatiotemporal analyses. Another benefit of the gridded framework is its capability of tracking developed landscape evolution and possible scenario impacts in a consistent manner. A gridded framework also promotes the inclusion of forthcoming censuses and potential conflation of supplemental data types.

At coarser resolutions, differences between Cook gridded tract and raw census tract population are much less than those of Kane for all years. While gridded block to census block population differences seem to illustrate
less difference, the much larger tract size in Kane (Table 1) leads to variation in population estimates that are greater than those of Cook. These results indicate that finescale hazard scenario studies based on tract-level data may be reliable for areas with consistently high population densities (e.g., Cook County) because of their finer enumeration sizes and consistency among areal units. However, scenario investigations using raw or gridded data based on tract-level geography in more sparsely populated areas, or regions that have undergone substantial development during the period under investigation, will be less reliable due to their large and spatiotemporally varying enumerations. Population impact count extractions based on county-level data are the poorest areal unit of measurement appraised as illustrated by the consistent large percentage differences found in the county versus tract and block for both gridded and raw frameworks. A variation-range matrix (Table 7) confirms that the use of county data can lead to large count and percentage differences, suggesting that the use of county-level demographic data to gauge sub-county-level, microscale hazard impacts can lead to inaccurate conclusions. In summary, no matter how one estimates exposure attributes, there is always potential error—but that error is far less when attribute information is more closely matched to the scale of the event.

c. Macroscale changes in Chicago exposure

To understand how tornado disaster potential has evolved, it is necessary to appreciate the character and trends of land-use dynamics through time and how those development patterns contribute to changes in exposure. Chicago has experienced a dramatic growth with a shift of population from the old industrial suburbs to the regions’ new economy suburbs (Greene and Pick 2012, 2013). This pattern of expansion has led to decentralization of people and a metropolitan region with a polycentric quality—that is, it has multiple downtowns, with many of those “new” downtowns in edge cities (Greene and Pick 2012). This development pattern is
dominated by sprawl, which leads to an “expanding bull’s-eye effect.” This effect argues that targets—that is, humans and their possessions—of geophysical hazards are enlarging as populations grow and spread. Consequently, it is not solely the population magnitude that is important in creating disaster potential; rather, it is how the population, and its affiliated built environment, is distributed across space that determines how the underlying disaster components of risk and vulnerability are realized.

The total population for our study area has increased from just over 7.2 million in 1970 to 8.8 million in 2010, a 21% surge. Most of the population gain was witnessed in the latter two decades, signifying population growth acceleration (Table 1). The number of housing units during the 1970–2010 period swelled from 2.4 million to just over 3.5 million, an increase of nearly 47.4%. Thus, the built environment (as measured by housing units) has increased at a faster rate than the number of people. As a consequence, any amplification in tornado losses from potential tornado disasters would be greater for insured or uninsured housing damages than human casualties.

To examine the development exposure change across our study area, we employed Theobald’s (2005) land use classification on the grids and, thereafter, examined the changes temporally. “Urban” was defined as a grid cell that contained housing densities less than 0.1 ha per unit, “suburban” as 0.1–0.68 ha per unit, “exurban” as 0.68–16.18 ha per unit, and “rural” as greater than 16.18 ha per unit. For the region examined in this study (Fig. 1c), the number of urban classified cells increased from 4.5% to 5% from 1990–2010, whereas the number of rural cells decreased from 58.4% to 53.1% during the same period

<table>
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<th>Land-use type</th>
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<th>2000</th>
<th>2010</th>
<th>Count</th>
<th>% of total area sq. km</th>
<th>% change</th>
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<td>57068</td>
<td>58.4</td>
<td>55.9</td>
<td>53.1</td>
</tr>
</tbody>
</table>

(Table 8). The rural–urban interface, which is characterized by suburban and exurban sprawl, witnessed a dichotomy in change by classification type. The percentage area that was categorized as suburban increased from 13.2% to 18% over the 20-yr period, resulting in the largest change (4.8%) in development type for the region. Conversely, the exurban classification changed relatively little during the same time period. These data suggest that far more land was converted to a relatively high-density sprawl mode in comparison to the low-density development that typifies exurban areas. Collectively, the potential number of hazard “targets” has grown in magnitude and expanded, confirming the expanding bull’s-eye effect and increasing potential for disaster, at least on the scale of the metropolitan region.

d. Spatiotemporal assessment of exposure impacts for worst-case scenarios

To evaluate change in exposure to potentially catastrophic tornadoes, we employ two scenario-based approaches. The first uses a full-dimension synthetic tornado and the second uses a 10-km synthetic tornado segment. In both scenario procedures, we overlay the tracks/segments atop the block-level, AW-gridded exposure data to estimate the residents and numbers of housing units exposed to each hypothetical tornado case.

1) FULL-DIMENSION SYNTHETIC SCENARIOS

Initially, we superimpose five full-length tornado paths based on synthetic S2 across the study area, with the paths spaced north to south, 15–20 km apart, and ceasing at the Lake Michigan shoreline. The use of a synthetic path removes the methodological concern expressed by Wurman and Alexander (2005), WUR, and Wurman et al. (2008) that transposing historical events that tracked over largely rural locations (in the case of many of the tornadoes in the 3 May 1999 outbreak or the Plainfield event 28 August 1990) atop urban conglomerations [Dallas–Fort Worth in Rae and Stefkovich (2000) and Chicago suburbs in Hall and Ashley (2008)] leads to underestimation of tornado disaster potential in more dense residential areas. Wurman and Alexander (2005)
and Wurman et al. (2008) argue that there can be notable differences between the EF-scale quantified damage caused by strong-to-violent winds on the observable developed landscape and the likely extent of strong-to-violent modeled surface winds based on observations from DOWs due to the lack of damage indicators in rural locations. This discrepancy surfaced in the contentious rating of the 31 May 2013 El Reno tornado. The lack of damage indicator restriction can minimize damage potential of tornadoes when historical events, and their damage-intensity patterns, are transposed to a location with dramatically different development character. Based on prior assessments, the S2 path comprises plausible “worst case” dimensions and magnitude attributes since it is constructed from contemporary violent tornado footprints and damage spatial characteristics from the worst segment of the Joplin EF5 path. The scenario paths were oriented from west-southwest to east-northeast, which is the dominant tornado direction mode found in a prior climatology (Suckling and Ashley 2006).

Four of the five scenarios experienced greater than double-digit percentage increases in population and housing units from 1990 to 2010 (Table 9). The only scenario that had a decrease in an exposure metric was scenario P5. This case traversed the urban south side of Chicago, a region that has witnessed a notable loss in population during this period (Greene and Pick 2012). Despite the population loss, the hypothetical tornado path affected 7.3% more housing units. This dichotomy in exposure is due to the population decrease found in the aforementioned urban region, a lack of corresponding housing unit decrease in that same area, and increases in suburbanization and exurbanization across the first half of the track. Scenario P1 had the largest increase in population (housing unit) change, with 49% (57%) increase in exposure metrics. The P1 scenario impacted the north side of Chicago, an area that has undergone some of the greatest population and housing unit increases in the region (Table 1), with most of that development falling into suburban and exurban land use types (Figs. 2c,d). Scenario P4 moved through locations consisting largely of suburban and urban development, terminating near the Chicago CBD. The population increase along this path was bimodal, with no notable increase along the middle of the track, bounded by a large increase in both population (Fig. 2b) and housing units (not shown) due to suburban development near the first third of the track and urban-core, high-rise residential development near the tornado’s terminus. The latter, CBD-focused increase in population and housing units is a recent reversal in long-term development trends found in many cities (Census Bureau 2012b). While suburbanization and exurbanization has continued in the past decade, a secondary, focused “inward migration” has taken place as more jobs in and near the CBD have attracted more residents desiring to move downtown that, in turn, becomes a magnet for more employers (Ehrenhalt 2013). From 2001 to 2010, Chicago underwent the largest numeric and percentage gain in its downtown area of any of the largest cities in the United States (Census Bureau 2012b). This demographic transformation illustrates how the continually evolving spatiotemporal character of development can dramatically

### Table 9. Number of people and housing units affected and affiliated 1990–2010 percentage changes of total impacted for five simulated tracks of tornadoes across Chicago region based on the S2 scenario (cf. Fig. 2c). Counts for those areas affected by significant (EF2+) and violent (EF4+) damage are provided.

<table>
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<th>Position</th>
<th>Year</th>
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<th>EF4-EF5</th>
<th>EF0-EF5</th>
<th>1990–2010 % change</th>
<th>EF2-EF5</th>
<th>EF4-EF5</th>
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<td>2000</td>
<td>43,592</td>
<td>16,743</td>
<td>115,892</td>
<td></td>
<td>16,734</td>
<td>64,50</td>
<td>43,853</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>46,300</td>
<td>17,841</td>
<td>120,828</td>
<td>15.1%</td>
<td>18,013</td>
<td>69,39</td>
<td>46,744</td>
<td>15.9%</td>
</tr>
<tr>
<td>4</td>
<td>1990</td>
<td>57,214</td>
<td>21,772</td>
<td>161,378</td>
<td></td>
<td>22,881</td>
<td>85,05</td>
<td>65,782</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>66,676</td>
<td>25,130</td>
<td>185,859</td>
<td></td>
<td>25,779</td>
<td>94,77</td>
<td>75,043</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>73,022</td>
<td>27,292</td>
<td>205,771</td>
<td>27.5%</td>
<td>32,009</td>
<td>11,599</td>
<td>95,139</td>
<td>44.6%</td>
</tr>
<tr>
<td>5</td>
<td>1990</td>
<td>37,411</td>
<td>14,240</td>
<td>102,587</td>
<td></td>
<td>12,857</td>
<td>49,32</td>
<td>34,798</td>
<td></td>
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<tr>
<td></td>
<td>2000</td>
<td>39,278</td>
<td>15,090</td>
<td>105,294</td>
<td></td>
<td>14,048</td>
<td>53,99</td>
<td>37,413</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>35,461</td>
<td>13,624</td>
<td>95,105</td>
<td>−7.3%</td>
<td>13,999</td>
<td>53,73</td>
<td>37,334</td>
<td>7.3%</td>
</tr>
</tbody>
</table>
influence the disaster potential landscape, especially at the microscale.

Scenarios P2 and P3 tracked across locales that have witnessed growth, but not of the magnitude found along the city’s more focused ring of development located approximately 60–80 km from the CBD (Greene and Pick 2013). Nevertheless, the development found near the origin of these paths still leads to 15%–22% increases in exposure metrics during this two-decade period for the scenarios.

2) 10-KM SYNTHETIC SCENARIOS

Using a synthetic’s entire path length (e.g., 45–67 km; Table 2) leads to scenarios where the damage footprint inevitably stretches across multiple development types, causing difficulty in evaluating specific land-use change effects on disaster potential. To generate a more focused analysis of how development has influenced disaster potential, we use a 10-km segment of the synthetic S2 (Fig. 2c) to target specific land use types and their changes from 1990 to 2010. As discussed in section 3c, the 10-km segment we use is representative of a tornado striking a developed region.

First, we placed the 10-km S2 segment across particular development types to assess changes in exposure where the land use has been relatively constant over the 20-yr period as determined by an evaluation of land-use data derived from the three decennial censuses (e.g., Fig. 2c). This promotes an evaluation of how each of the differing land use types is contributing to the overall change in tornado exposure (Table 10).

Both urban tornado scenarios, Ur1 and Ur2, experienced losses in population, reconfirming the slow exodus of people from the immediate area surrounding the CBD. The near-central city of Chicago, as with most large cities in the Midwest and Northeast, has been defined by perennial population declines (excluding a small expansion in the 1990s) since the 1950s (Greene and Pick 2012). These declines are due to the abandonment of the area immediately around the urban core by the middle class, giving rise to an urban underclass characterized by little upward mobility that results in poor neighborhoods, high crime rates, and diminished amenities (Wilson 1987, 1996; Hudson 2006; Greene and Pick 2012). Whereas the exposure in these areas may be stable or have decreased during the period examined, other components of vulnerability may have changed that could result in far greater disaster potential. Conceptually, vulnerability can be differentiated by three constituents: exposure (characteristics of the natural and/or built environment that position a system to be affected by a hazard; in this study, people and their housing units), sensitivity/susceptibility (the degree to which a system is affected by hazard conditions), and adaptive capacity (ability for the system to cope or adapt to hazard conditions) (Adger 2006; Polsky et al. 2007; Morss et al. 2011; Fekete 2012). We have employed a disintegrative methodology that examines a distinct component of vulnerability (exposure), which we argue promotes a more measured and quantified analysis of that element. However, this singular analysis does not permit the discovery of how important the other constituents of vulnerability are, and how they integrate with one another, in these particular cases. For instance, in areas that have witnessed urban decay, people would arguably have increased susceptibility and decreased adaptive capacity to disasters that could lead to far greater disaster consequences (Wisner et al. 2004; Paul 2011).

Scenario segments in the suburban locations, Su1 and Su2, generated mixed results. Changes in affected population in the segments were negligible, with both areas experiencing increases in housing units. These areas of DuPage (Su1) and Cook (Su2) Counties were developed largely prior to the period of analysis (Fig. 2d), with only limited, fill-in development increasing the housing unit metric. Of the segment scenarios placed over temporally consistent land-use types, exurban scenario Ex1 underwent the greatest amplification in exposure magnitude. The area of central Kane County has continued to see development, with much of the area already, or on the cusp of, converting from exurban to suburban classification. Therefore, even in low-density developed areas, there has been a continued escalation in density and, thus, exposure. Uniquely, scenario Ex2 witnessed a notable drop in population exposure, with a near 20% increase in housing units, with much of that increase occurring during the 1990–2000 period. Both exposure measurements for the two rural cases examined, Ru1 and Ru2, decreased. Although rural population loss is endemic to many rural areas in the United States (McGranahan and Beale 2002), the decreases found here must be deciphered with caution. The decreases in population are on the order of a couple dozen, with housing unit losses sometimes less than 1 unit per scenario. In comparison to the exposure values found for urban, suburban, and even exurban areas, these impacted numbers are very small.

Next, five track segments were placed explicitly across locations where kernel density estimation analyses (not shown) on land-use change data (e.g., Fig. 2d) revealed clusters of grid cells that underwent rural-to-exurban or exurban-to-suburban change (Table 10). This analysis targets how low- and high-density sprawl has contributed to the overall disaster potential picture. Track segments T1 and T2 are represented by areas that transitioned from rural to exurban land use classifications. Both T1 and T2
Table 10. Number of people and housing units affected and affiliated 1990–2010 percentage changes of total impacted for simulated 10-km tornado segments across Chicago region based on the S2 scenario (cf. Figs. 2c,d). Counts for those areas affected by significant (EF2+) and violent (EF4+) damage are also provided.

<table>
<thead>
<tr>
<th>Position</th>
<th>Year</th>
<th>Population</th>
<th>Housing units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1990–2010% change</td>
<td>1990–2010% change</td>
</tr>
<tr>
<td>Ur1</td>
<td>1990</td>
<td>61 24</td>
<td>173 20</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>62 26</td>
<td>175 22</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>69 69</td>
<td>188 7.3%</td>
</tr>
<tr>
<td>Ur2</td>
<td>1990</td>
<td>35 505</td>
<td>13 257</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>33 908</td>
<td>12 939</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>27 001</td>
<td>10 299</td>
</tr>
<tr>
<td>Su1</td>
<td>1990</td>
<td>971 115 18 424</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>883 150</td>
<td>3010</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>70 006 3097</td>
<td></td>
</tr>
<tr>
<td>Su2</td>
<td>1990</td>
<td>2288</td>
<td>2288</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>22 560</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>17 120</td>
<td></td>
</tr>
<tr>
<td>Ex1</td>
<td>1990</td>
<td>23 759</td>
<td>3595</td>
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<tr>
<td></td>
<td>2000</td>
<td>13 357</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>9 172</td>
<td></td>
</tr>
<tr>
<td>Ex2</td>
<td>1990</td>
<td>36 666</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>17 439</td>
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<tr>
<td></td>
<td>2010</td>
<td>19 749</td>
<td></td>
</tr>
<tr>
<td>Ru1</td>
<td>1990</td>
<td>3 221</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>3 64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>3 91</td>
<td></td>
</tr>
<tr>
<td>Ru2</td>
<td>1990</td>
<td>9 49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>17 49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>19 749</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>1990</td>
<td>20 136</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>17 113</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>14 311</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>1990</td>
<td>32 62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>17 62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>15 17</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>1990</td>
<td>43 591</td>
<td>4,367</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>61 508</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>93 368</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>1990</td>
<td>70 316</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>14 672</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>19 862</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>1990</td>
<td>863 388</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>1119 2603</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>4518 4888</td>
<td></td>
</tr>
</tbody>
</table>

track segments illustrate positive percentage changes in population and housing units impacted from 1990 to 2010, although results are tempered by the low affected counts. The amplification in tornado exposure for the T1 and T2 segments is due to increased development and affiliated sprawl apparent in these areas over the past two decades. Areas that were once largely row-crop farmland have since transitioned to exurban development, incrementally increasing hazard targets and the expanding bull’s-eye effect. Tornado scenario segments T3, T4, and T5 are characterized by areas that have transitioned from exurban to suburban land use classifications. All three of these tornado scenario segments exemplify extremely large (>150%) positive percent increases in population and housing units impacted from 1990 to 2010. Indeed, these segments contain collectively the largest percentage increases found in any of the segment scenarios suggesting that it is this particular development change that has led to the greatest expansion in the exposure to weather hazards in this region.

5. Discussion and conclusions

We have employed the contextual argument that exposure is a “condition sine qua non for disaster risk to exist” (UNDP 2004). Moreover, population growth is not
spatially uniform and, therefore, exposure is not distributed evenly across the landscape. For instance, cities and suburbs grow directionally and, consequently, the evaluation of the spatial character of exposure is as important as other interrogatives. Because of data, computational, and methodological restrictions, research quantifying _changes_ in hazard exposure has been relatively limited. Using conventional spatiotemporal change methods on standard, relatively large, enumeration units, previous works (e.g., Hall and Ashley 2008; Paulikas and Ashley 2011) have investigated shifts in weather-related exposure at the metropolitan scale. These methods lacked the sophistication necessary to assess a spectrum of geographic extents and generate more substantial conclusions regarding exposure’s culpability in augmenting tornado disaster consequences. Preceding evaluations of exposure tend to aggregate at spatial extents far larger than the hazard footprint, especially for micro-scale hazards spawned by severe thunderstorms. The incongruence of spatial scales of analysis often precluded an assessment of the relationship between the underlying constituents requisite for disaster. This investigation offered an initial step toward rectifying these perceived deficiencies, fostering a homogenized approach for assessing and quantifying changes in finescale weather hazard exposure and providing a framework for future work exploring exposure and vulnerability’s contribution to disasters.

Specifically, through a geographic lens, we assessed how an increasing and spreading population is leading to substantial growth in tornado hazard exposure rates, appearing to offset, or counteract, contemporary scientific and technological advances in mitigation (e.g., warning systems, Doppler radar, etc.) as exemplified in recent tornado disasters. We employed spatial data modeling and spatial analytic approaches that appraised contemporary changes in the relationship between tornadoes and the distribution of people and their residences for the case of Chicago. Results proved that, generally, the number of people and their housing continues to grow and geographically expand, promoting an increasing hazard target, or what we termed the expanding bull’s-eye effect. Metropolitan-scale assessments of Chicago’s demographic, housing unit, and land-use types confirm that, simply, more people and their possessions are in the potential path of tornadoes. This finding is not entirely unexpected, but we illustrate specifically how differing development types lead to varying exposure rates that contribute to the unevenness of potential weather-related disasters across the landscape. For instance, suburbanization development character associated with high-density sprawl has led to the greatest change in exposure landscape in the Chicago area. Conversely, along the periphery of the urban core, long-term population loss has led to decreasing amounts of people to be affected; however, those that remain may be highly vulnerable due to enhanced sensitivity/susceptibility and reduced adaptive capacity (e.g., see Klinenberg 2002)—components of vulnerability we did not examine in this study. More recently, inward migration to CBDs (Census Bureau 2012b; Ehrenhalt 2013) has promoted a very dense exposure in the urban core with concentrated catastrophic disaster potential that could potentially overwhelm the critical infrastructure sectors (Homeland Security 2009) of most, if not all, cities, including Chicago.

A simple conceptual model (Fig. 4) is provided to illustrate how spatiotemporal development changes found in metropolitan regions have led to and will continue to foster an expanding bull’s-eye effect, placing ever increasing amounts of “targets”—people, built environments, and infrastructure—in harm’s way of tornadoes and other geophysical and technical hazards. We have argued it is not solely the population magnitude that is important in creating disaster potential; rather, it is how the population, and its affiliated built environment, is distributed across the geographical landscape that defines how the fundamental components of risk and vulnerability are realized in a disaster. The model proposed reveals the broad concept of the expanding bull’s-eye effect with the inferred understanding that each city and/or regional development footprint will be constrained by a diverse set of social, economic (Hardaway 2011), political (e.g., land-use planning, park designation, etc.), and physical (e.g., Lake Michigan in Chicago’s case) elements.

In addition, our research appraised the viability of using a gridded framework for assessing the changes in census-derived exposure data. The gridded methodology removes the spatial unit variation problem found when using two or more census time stamps (Cai et al. 2006) and promotes an evaluation of temporal changes in the underlying vulnerability, a dimension often excluded from exposure studies. Results revealed that the modifiable unit problem (MAUP; Openshaw 1984) was still influential. MAUP occurs when spatial aggregations of data (e.g., changing census enumerations, differing grid resolutions) lead to dissimilar results, a prevalent analysis obstacle in studies employing spatial enumerations of aggregated data (Mennis 2002; Holt et al. 2004; Cai et al. 2006). The difference between gridded county-, tract-, and block-level data in the estimation of potentially affected exposure units by the same tornado scenario exemplifies the effect of different areal unit sizes (Tables 6 and 7). Since tornadoes have relatively small hazard footprints, the finest analysis resolution provides the most precise results (Schlossberg 2003).
The investigation also assessed tornado dimensions employed in previous scenario-based research. An analysis of historical significant and violent tornado events found that the high-end width scenarios in WUR are not likely representative of even the most extreme potential tornadoes. We offer a structure for synthetic development based on observed damage indicators for a modern catastrophic event (2011 Joplin EF5). This methodology promoted a flexible, yet observationally constrained framework for developing tornado synthetics that can be used in models to assess potential social, physical, and economic losses from tornadoes. Additional work conflating damage indicators, mobile Doppler radar data, and in situ observations is required to build a more robust and realistic tornado scenario model.

While climate change may amplify the risk of certain hazards, the root cause of escalating disasters is not necessarily event frequency, or risk, related. Rather, as affirmed by previous research (e.g., Changnon et al. 2000; Cutter 2010; Bouwer 2011; Barthel and Neumayer 2012; Simmons et al. 2013) and illustrated herein, the growing trend in disasters is likely due to 1) the increasing density and spread of humans and property in harm’s way, or exposure, and 2) the increasing vulnerability of the population. We have focused explicitly on the physical exposure components of population and their residences to tornadoes in the third largest metropolitan area in the United States—a region that has a relatively elevated risk of tornado risk (Brooks et al. 2003). This research methodology could be replicated across a variety of spatiotemporal domains, as well as for other hazards. Recent tornado catastrophes (e.g., the 27–28 April 2011 tornado outbreak, 22 May 2011 Joplin tornado, 20 May 2013 Moore, etc.) reveal that there is much to be learned about how hazards interact with society and, perhaps more importantly, how society interacts with hazards. Studies engaging a worst-case hazard scenario approach using representative hazard models on high-spatial-resolution datasets of historical or forecast vulnerability constituents could spur mitigation activities and policy changes with the goal of reducing hazard impacts. An essential part of that research must focus on understanding how the exposure landscape has transformed over time and how those spatiotemporal changes may influence the tasks of warning, rescue, and recovery should a catastrophic scenarios come to fruition. Discovered spatiotemporal trends of hazard exposure will assist policy makers, hazard scientists, and the public by illustrating the role amplifying exposure has on the increasing hazard impacts.

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