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Spatiotemporal changes in conterminous US wildfire exposure from 1940 to 2010

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Abstract This study utilizes fine-scale, built-environment data in conjunction with past wildfire events to assess historical spatiotemporal changes in wildfire likelihood and societal exposure to wildfires for the conterminous USA. Results indicate that conterminous US wildfire exposure has increased substantially over the past 70 years due to escalating wildfire likelihood and an expanding human-developed footprint. Although wildfire exposure has increased as a whole throughout the conterminous USA, the relative contributions of wildfire likelihood and the built environment to exposure vary from region to region. Wildfire likelihood plays a larger role in exposure in the western USA due to a greater frequency of large wildfires. Conversely, built-environment density has a stronger influence on exposure than wildfire likelihood within the eastern and central USA. In all, the total number of homes and total developed land area prone to wildfire impacts has increased by nearly 1350% since 1940 throughout the conterminous USA. Findings presented in this study highlight the importance of considering both hazard likelihood and built-environment magnitude when assessing wildfire exposure. Given the rapid historical amplifications of both wildfire likelihood and societal exposure, communities in wildfire-prone areas should implement and/or continually evolve their existing wildfire prevention strategies to include the effects of expanding development to reduce future damages and losses. The continual enactment and adaptation of wildfire suppression and mitigation strategies will ultimately result in more disaster-resilient communities as climate and society continue to influence the future US wildfire exposure.

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1 Introduction and background

When adjusting for inflation, there have been 16 billion-dollar wildfire disasters in the USA since 1980 (NCEI 2017). Of note, the 1991 Oakland, CA wildfire was the costliest on record with 25 fatalities, over 2500 homes destroyed, and 1.5 billion USD (6.0 billion adjusted by the consumer price index) in losses (Parker 1992). A majority (9 of 16) of billion-dollar wildfire disasters have occurred over the last 10 years with an inflation-adjusted mean loss of 2.3 billion USD per event (NCEI 2017). Six of these billion-dollar wildfires transpired in the western USA throughout states such as California, Colorado, Idaho, Oregon, Washington, Wyoming. Most notably, the 2007 US drought and high winds resulted in wildfires across much of the western USA leading to 3.3. billion USD in losses and 12 fatalities from June to September (NCEI 2017). Comparable to the 2007 wildfires, the October 2017 Northern California wildfires burned over 990 km^2 (245,000-ac), generating estimated losses greater than 3.3 billion USD, destroying over 8900 homes, and resulting in 43 fatalities (Cal Fire 2017). Some reinsurance brokers have estimated that the 2017 Northern California wildfire will ultimately result in over 8 billion USD in insured losses making it the costliest wildfire disaster in recorded history (Jacob 2017). Consequently, the 2017 Northern California wildfire is exemplar of potential future wildfire disasters and impacts on society given projected future changes in climate (e.g., precipitation and temperature patterns) and a growing built environment.

In general, wildfire frequency and the associated burned area that is produced as a result have increased over time in the conterminous USA (hereafter, USA; Westerling et al. 2006; Dennison et al. 2014). Although the availability of data associated with wildfire activity, landscape flammability, ecosystem fuel structure is limited, the escalation in wildfire likelihood[1] has been largely driven by changes in climate that affects natural wildfire landscapes (Westerling et al. 2006; Ager et al. 2014; Dennison et al. 2014). As wildfire total burned area and frequency have magnified throughout the twentieth century, the number of homes burned annually has also risen (Whitlock 2004; Syphard et al. 2013).

Consequently, local, state, and federal agency fire-fighting expenditures now regularly surpass 1 billion USD per year in the USA (Whitlock 2004; Westerling et al. 2006). Complicating the wildfire–society interaction further, recent research has indicated that humans are responsible for 84% of all wildfire ignitions, compared to natural phenomena such as lightning (Balch et al. 2017). Nevertheless, little research attention has been given to quantifying the *interaction* between amplifying US wildfire likelihood and a growing human-developed footprint within the USA.

As wildfire likelihood has increased over the last few decades, the USA has transitioned from a largely rural development pattern to progressively urban, suburban, and exurban land use (Ashley and Strader 2016). During this same time period, the US population has more than doubled and the built environment (as measured by housing units, land use, and land cover) has grown by over 600% (Strader et al. 2015). This rapid escalation in development has led to an increased number of people and their possessions being placed in harm's way. Previous studies have examined the effects of an increasing population and the ensuing built environment (i.e., urban sprawl) on hazard exposure for events such as urban flooding (e.g., Pottier et al. 2005; Shepherd 2005; Brath et al. 2006; O'Connell et al. 2007; Haberlie et al. 2015; Ferguson and Ashley 2017), landslides (e.g., Leighton 1976; Sidle and Ochiai 2006), coastal inundation (e.g., Tralli et al. 2005; Wheater and Evans

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[1] In this study, wildfire *likelihood* is defined as the probability of a wildfire occurring in space and time (Paul 2011).

2009), tropical storms (e.g., Freeman and Ashley 2017), volcanic eruption-induced floods, lahars, and debris flows (e.g., Diefenbach et al. 2015; Strader et al. 2015), tsunamis (e.g., Wood et al. 2015; Sleeter et al. 2017), and tornadoes (e.g., Ashley et al. 2014; Rosencrants and Ashley 2015; Ashley and Strader 2016; Strader et al. 2017). By combining historical hazard event data and metrics of population and development within spatiotemporal analyses, these studies have found that increasing societal exposure[2] has a large influence on the consequence and frequency of hazard impacts. This process of a spatiotemporally increasing societal footprint and enhanced odds of hazard impact on populations and the built environment has been described as the "expanding bull's-eye effect" (Ashley et al. 2014; Strader and Ashley 2015).

2 Data and methods

In this investigation, the interaction between human development and wildfires in the USA is assessed over a historical period of 70 years. How has human development and wildfire exposure changed in the USA from 1940 to 2010? To what degree has the interaction of wildfire likelihood and built-environment exposure created a more disaster-prone society? And, to what extent have historical regional trends in housing, developed land use, and wildfire likelihood altered wildfire exposure? These questions are assessed by employing historical wildfire and built-environment data (i.e., housing, land use, and land cover) within a geospatial framework. The most accurate wildfire occurrence dataset (i.e., Fire Program Analysis-Fire Occurrence Database; **FPA-FOD;** Short 2017) compiled to date is utilized to quantify wildfire likelihood from 1992 to 2015, while housing unit (**HU**) density and land use–land cover (**LULC**) models are employed to assess historical trends in the human-built environment. Together, wildfire and built-environment data derived from these sources are utilized to analyze US spatiotemporal trends in wildfire exposure from 1940 to 2010. In addition to the USA, a threefold regional approach is applied to investigate wildfire likelihood, built-environment changes, and exposure for geographic regions: (1) east of the Mississippi River (East region), (2) east of the Continental Divide and west of the Mississippi River (Central region), and (3) west of the Continental Divide (West region; Fig. 1). This research aims to improve the understanding of how alterations in the built environment influence wildfire consequences and frequency.

2.1 Wildfire data

To assess historical spatiotemporal trends in wildfire likelihood, the FPA-FOD was utilized. The FPA-FOD is a publicly available wildfire occurrence dataset from the US Department of Agriculture and Forest Service (Short 2017). Because there is no single, unified system of wildfire record keeping in the USA, the FPA-FOD was created by compiling wildfire records from multiple federal, state, and local entities. The FPA-FOD contains wildfire attributes such as location (latitude and longitude), burned area (acres), reporting agency, discovery date for the USA from 1992 to 2015 (Short 2017). As a result, the FPA-FOD is the most temporally accurate and comprehensive historical wildfire

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[2] As outlined in Morss et al. (2011), *exposure* is a vital part of vulnerability and defined as people, assets, or characteristics of the natural and/or built environment that position a system to be affected by a hazard. Exposure is influenced by both the hazard magnitude and frequency as well as the people, assets, and/or characteristics subject to loss in a hazard event.
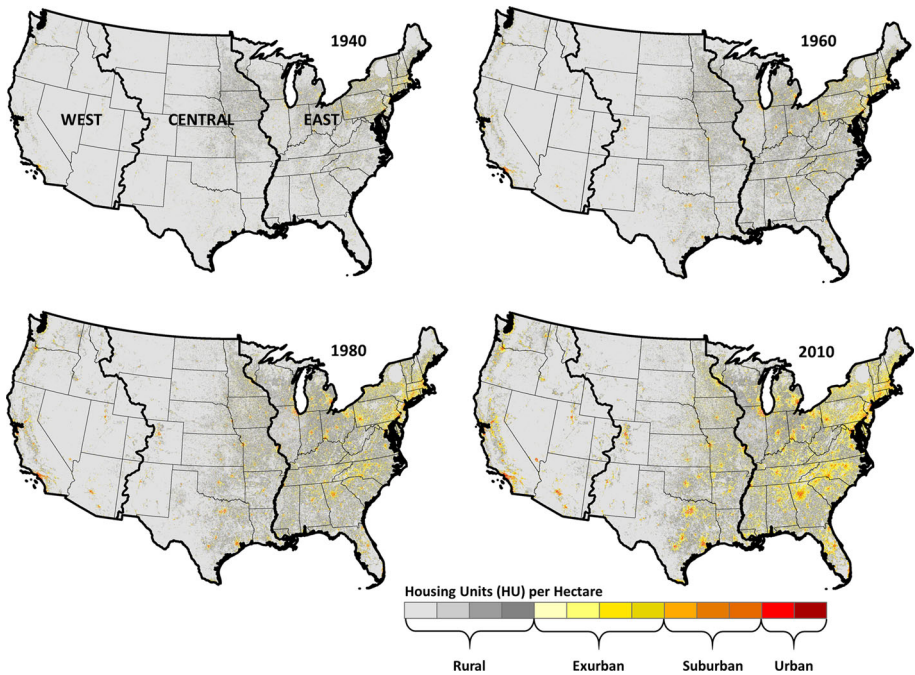
Fig. 1 Total housing units (HU) per hectare for 1940, 1960, 1980, 2010 with the Central, East, and West study regions depicted

database available (i.e., substantial effort was taken to assure temporal consistency with no missing wildfire records or duplications of wildfire occurrences during the FPA-FOD data creation process; Short 2017). Although wildfire perimeter occurrence datasets such as the Monitoring Trends in Burn Severity (**MTBS**), Geospatial Multi-Agency Coordination (**GeoMAC**), and Wildland Fire Decision Support System (**WFDSS**) contain more accurate spatial representations of historical wildfire-burned areas, the FPA-FOD was chosen for this particular study because the associated historical data represent the best combination of length of record (i.e., 1992–2015), spatial coverage (i.e., conterminous USA), and completeness (i.e., few missing historical fires on record) for examining spatiotemporal changes in wildfires.

2.2 Housing and developed land use–land cover data

Previous research has developed models to represent historical population, built-environment variables, development, LULC, etc., for the USA (e.g., Landis and Zhang 1998; Irwin and Bockstael 2002; Waddell 2002; Theobald 2005; Sohl and Sayler 2008; U.S. EPA 2009; Homer et al. 2015). Similar to Strader et al. (2015, 2017), and Freeman and Ashley (2017), this study uses the Spatially Explicit Regional Growth Model (**SERGoM**; Theobald 2005) to assess historical spatiotemporal changes in HUs and development. The SERGoM comprises decadal HU estimates for the USA within a 100-m resolution gridded framework from 1940 to 2010. Data accuracy for the SERGoM was measured at 80 to 91% using hindcast techniques coupled with historical US Census Bureau population and HU estimates (Theobald 2005).

In addition to the SERGoM HU estimates, historical LULC data from the United States Geological Survey (**USGS**) and Earth Resources Observation and Science Center (**EROS**) are employed in the study to examine historical changes in the human-built environment. The FOREcasting SCEnarios of Land-use Change (**FORE-SCE**) modeling framework was developed to produce historical and future LULC scenarios for the USA from 1938 to 2100 (Sohl and Sayler 2008). Specifically, the FORE-SCE model provides 250-m resolution historical gridded LULC estimates involving 17 primary LULC classifications including open water, urban/developed, mining, barren, cropland, deciduous forest, pasture using hindcast techniques. These data are modeled using statistical and tabular data from historical agricultural censuses, population censuses, and USGS land cover trends (Sohl and Sayler 2008). The FORE-SCE-developed LULC estimates are utilized in conjunction with the SERGoM HU approximations to better capture spatiotemporal trends in the historical built environment. For instance, HUs only represent a single type of developed land use, while the FORE-SCE combines a variety of developed LULC types such as residential areas, commercial locations, industrial districts to provide a more inclusive representation of the human-built environment. Overall, the FORE-SCE defines the developed LULC category as areas that have a high percentage ($> 20\%$) of constructed material such as concrete, asphalt, buildings, homes.

While there may be some spatial discrepancies among the built-environment data and historically burned areas associated with wildfires, the SERGoM and FORE-SCE model estimates are sufficient for examining changes in wildfire exposure due to the relatively large regional areas examined. As an example of this spatiotemporal mismatch, the FORE-SCE model could potentially highlight an historical increase in developed land area within a region that was actually destroyed by a past wildfire. Additionally, societal exposure to wildfires is analyzed using HU and LULC metrics rather than population because the counts and trends in HU and LULC are much more stable over time and across geographic space. For instance, the potential number of people in the path of a wildfire varies greatly depending on the time of day, date, warning lead time, etc., while the HU counts and LULC types are less variable.

3 Methods

Spatiotemporal analyses of US wildfire likelihood, built-environment changes, and exposure were conducted using a geographic information system (**GIS**). Historical changes in wildfire likelihood and societal exposure were assessed using a GIS by employing decadal SERGoM HU and FORE-SCE LULC development data from 1940 to 2010 and FPA-FOD wildfire events from 1992 to 2015.

To examine FPA-FOD-derived wildfire likelihood (i.e., frequency and total burned area) within the USA and subregions, wildfires were first grouped into two primary total burned area categories: wildfires greater than or equal to (1) 0.202 km^2 (50-ac) and greater than or equal to (2) 20.23 km^2 (5000-ac). Although FPA-FOD does not contain wildfire perimeters, it does record the total burned area associated with all wildfires from 1992 to 2015. The wildfire geospatial point locations (latitude and longitude) for each wildfire were buffered by the reported FPA-FOD wildfire total burned area to create a spatial representation of total wildfire-burned area per event. The buffered total burn area of fires from 1992 to 2015 was then aggregated to a 20-km grid for the USA to determine spatiotemporal trends in wildfire likelihood (i.e., total burned area (km^2) per 20-km grid cell) over

the 24-year historical wildfire data period for fires greater than 50-ac and 5000-ac. An emphasis was placed on fires greater than 50-ac and 5000-ac to distinguish spatiotemporal differences between relatively small and large wildfires within each geographic study region. After aggregating the greater than or equal 50-ac wildfire 20-km grid to 40-km grid, a smooth wildfire likelihood surface was generated using a GIS and applying a 3×3 low-pass filter and spatial contouring techniques on the 40-km grid cell values. The 40-km wildfire-burned area contour lines were also smoothed using a GIS line smoothing tool to generate the regions of wildfire likelihood in the USA. The greater than 50-ac smoothed wildfire likelihood surface was then split into seven qualitative categories or wildfire likelihood zones (**WLZ**): very low, low, low–medium, medium, medium–high, high, and very high to provide a categorical likelihood of wildfire occurrence. Each WLZ was then intersected with the decadal SERGoM HU and FORE-SCE LULC development estimates from 1940 to 2010 to determine wildfire exposure for the US, East, Central, and West study regions over time. Graphical and spatial analyses were then conducted to quantify spatiotemporal trends in wildfire exposure.

A wildfire likelihood-societal exposure index was also developed to highlight locations in the USA that have experienced *both* rapid spatiotemporal increases in wildfire likelihood *and* societal exposure over time. To determine how quickly wildfire likelihood has amplified across the USA, the mean annual rate of change in total burned area (km^2) was calculated for individual 40-km grid cells using wildfires greater than or equal to 50-ac from 1992 to 2015. Similar to wildfire likelihood, the 40-km gridded mean annual rate of change in total HUs was calculated to provide a measure of increasing trends in the built environment within the study domains. The rate of change in total burned area for each 40-km grid cell was first calculated from year-to-year starting in 1992 and ending in 2015 using wildfires greater than or equal to 50-ac (e.g., 1992–1993, 1993–1994, 1994–1995). Following this annual measurement of total burned area change, map algebra was employed to find the average (mean) annual rate of change in total burned area per 40-km grid cell from 1992 to 2015. Similarly, this method was used to calculate mean annual rate of change in HUs on a 40-km grid from 1940 to 2010. Finally, the wildfire likelihood-societal exposure index was created using map algebra and multiplying the wildfire total burned area (km^2) and the total number of HUs on a 40-km grid to provide an estimate of where wildfire exposure has changed and is increasing the fastest.

4 Results and discussion

4.1 Trends in the built environment and HUs

The total number of HUs in the USA increased approximately 601% (106.4 million HUs) from 1940 to 2010 (Table 1; Figs. 1, 2). A majority of this built-environment escalation occurred in the eastern USA where there was a 64.2 million HU increase over the 70-year historical period of analysis. During this same time frame, the West study region underwent the greatest relative growth with a 1150% amplification in total HUs. This finding indicates that HU totals in the West region escalated at a faster rate than all other regions in the USA. The Central study region represents a higher percentage growth rate in total HUs (643%) compared to both the US and East study regions. A primary contributor to the more rapid HU growth found in the Central and West regions was the post-World War II economic boom that allowed populations to swell and people to migrate from the East to

Table 1 Absolute and relative changes in housing units (HU) and total developed land area (km²) by East, Central, West, and conterminous US study regions

Regions	1940	2010	Abs. change	% Change
Housing units (HU)				
East	12,557,576	76,814,445	64,256,869	511.7
Central	3,408,628	25,338,469	21,929,841	643.4
West	1,758,909	21,985,545	20,226,636	1,150.0
Cont. USA	17,725,113	124,138,459	106,413,346	600.9
Developed area (km²)				
East	43,892	133,250	89,358	203.6
Central	21,524	52,813	31,289	145.4
West	9170	32,650	23,480	256.1
Cont. USA	74,586	218,713	144,127	193.2
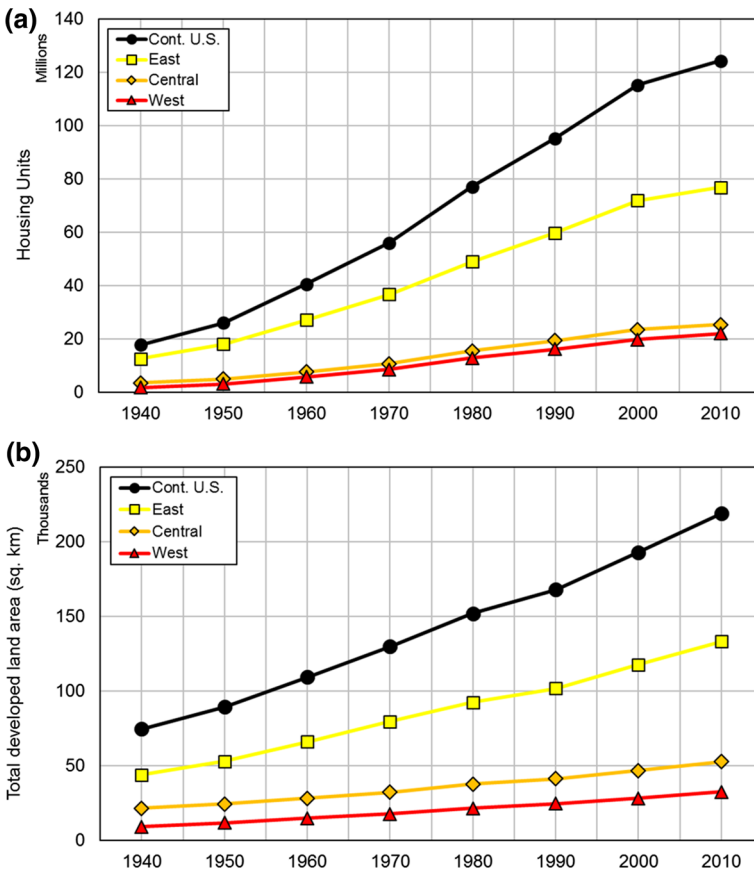
Fig. 2 Total change in **a** housing units (HU) and **b** developed land area (km²) within the conterminous US, Central, East, and West study regions from 1940 to 2010

Central USA in search of jobs, land, and prosperity (Marglin and Schor 1990). Most notably, the creation of the US Interstate Highway System and affordable automobiles made it possible for middle class populations to migrate more easily across the USA (Greene and Pick 2013).

Along with increasing HUs, developed land area in the USA has increased approximately 193% since 1940 (Table 1). Again, the East study region contained the greatest historical amplification in the built environment where developed land area expanded 89,358 km^2 over the 70-year period. Similar to the changes in total HUs, the West region represents the largest relative growth in developed land area with a 256% increase. In all, the Central and West regions contained increases of 31,289 and 23,480 km^2 in developed land area from 1940 to 2010. While the historical LULC estimates indicate that developed land area in the US and East region has increased threefold since 1940, developed land area in the West study region has nearly quadrupled over the same time period.

In general, all study regions are characterized by a growing built environment and expanding developed footprint. Regional trends in HUs and LULC also highlight important spatiotemporal differences among the three study domains. For example, although a majority of the built-environment growth during the 70-year study period occurred in the East study region, the built environment is enlarging at a much faster rate west of the Mississippi River. In the eastern USA croplands were exchanged for developed LULC, primarily in the form of urban areas and cities (i.e., urban sprawl; Duany et al. 2000; Gillham 2002). This same development process took place in the Central and West study domains. However, most of the natural land replaced by development in the West domain was not croplands but rather forests and shrubland.

4.2 Trends in wildfire likelihood

The assessment of wildfire likelihood is split into two primary fire total burned area categories: *moderate–large* fires (greater than or equal to 50-ac) and *large* fires (greater than or equal to 5000-ac; Fig. 3). Moderate–large wildfire frequency in the USA has increased approximately 36 fires per year on average (mean) since 1992 (Tables 2, 3; Fig. 4). Correspondingly, large wildfires in the USA have also had a mean annual frequency increase of 3.5 fires over the 24-year historical period. As US wildfire frequency has amplified over the previous two decades, the total area burned by wildfires has also expanded. For moderate–large wildfires, the total annual burned area escalated nearly 153,000-ac per year in the USA since 1992. Although large wildfires only represent 3.5% of all fires greater than 50-ac in the USA, the total burned area associated with large wildfires broadened approximately 136,000-ac per year. Overall, trends in wildfire likelihood using the FPA-FOD data support prior research (Westerling et al. 2006; Marlon et al. 2009; Miller et al. 2009; Dennison et al. 2014; Westerling 2016) that has indicated increasing US wildfire occurrence and associated total burned area.

While trends in US wildfire frequency and total burned area indicate that wildfire likelihood has increased over the last two decades, analyzing wildfire likelihood by sub-regions provides greater insight to where wildfire frequency and total burned area are changing the most within the USA. There are notable differences in moderate–large wildfire counts among the East, Central, and West study regions. Although 75% of all moderate–large wildfires occurred in the East and Central US study domains, moderate–large fires in the East and Central regions were responsible for 38% of the total burned area in the USA (Table 3). This result implies that 62% of the total moderate–large wildfire-burned area (for wildfires > 50-ac) is associated with moderate–large wildfires in the West
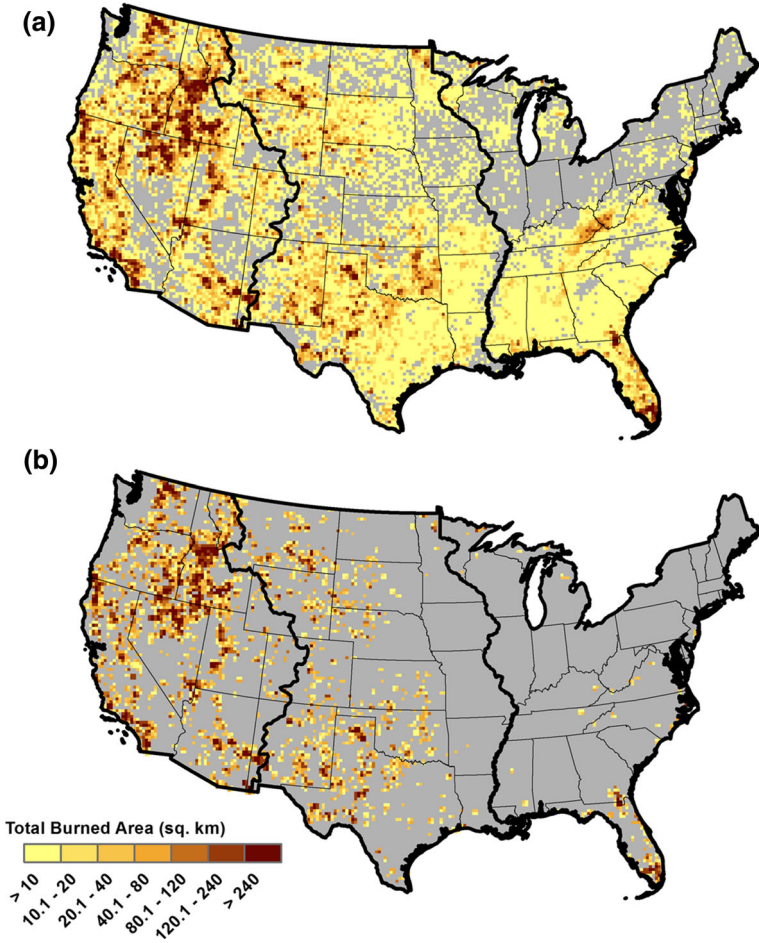
Fig. 3 Total area (km^2) burned by wildfires greater than **a** 0.202 km^2 (50-ac) and **b** 20.23 km^2 (5000-ac) from 1992 to 2015 within a 20-km grid

Table 2 The regional (East, Central, West, and USA) mean change in wildfire counts and total burned area (km^2) from 1992 to 2015 by greater than 50-ac and 5000-ac wildfire-burned area categories

Region	Mean change in wildfire counts from 1992 to 2015		Mean change in total wildfire-burned area (km^2) from 1992 to 2015	
	$\geq$ 50-ac	$\geq$ 5000-ac	$\geq$ 50-ac	$\geq$ 5000-ac
East	$-$ 3.8	0.12	6355.5	6547
Central	54.3	1.8	67,123	47,263
West	$-$ 14.4	1.6	78,991	82,076
USA	36	3.5	152,395	135,796

Table 3 Mean wildfire count and total burned area (km^2) for the East, Central, West, and US regions by wildfire total burned area categories greater than 50-ac, 1000-ac, 5000-ac, and 10,000-ac

Region	Mean wildfire count				Mean total burned area (km^2)			
	≥ 50-ac	≥ 1000-ac	≥ 5000-ac	≥ 10,000-ac	≥ 50-ac	≥ 1000-ac	≥ 5000-ac	≥ 10,000-ac
East	1282	47	8	4	404,410	229,138	153,994	130,828
Central	1474	156	39	19	1225,463	985,613	746,655	613,767
West	935	231	83	48	2,607,928	2,442,965	2,113,828	1,868,573
USA	3692	435	130	71	4,239,011	3,658,482	3,014,853	2,613,170
Region	% Total US wildfire count				% Total US wildfire-burned area (km^2)			
East	34.7	10.7	5.8	5.7	9.5	6.3	5.1	5.0
Central	39.9	36.0	29.8	26.5	28.9	26.9	24.8	23.5
West	25.3	53.3	64.3	67.8	61.5	66.8	70.1	71.5

Also illustrated is the percentage of total US wildfire counts and burned area by total burned area wildfire categories and East, Central, and West subregions

domain. In addition, there were 1821 fewer moderate–large wildfires in the western USA compared to the Central and East regions. Together, these results indicate that although moderate–large wildfires are more common in the Central and East US regions, moderate–large wildfires in the West region are likely to burn a greater amount of land area per event.

Moderate–large wildfire frequency in the Central region has increased by approximately 54 fires per year over the last 24 years. However, mean annual moderate–large wildfire occurrence has decreased in the East and West study regions over time. These slight decreases are attributed to the installation of more effective wildfire suppression techniques (e.g., Butry 2009; Noonan-Wright et al. 2011; Calkin et al. 2015). The largest decrease in mean annual moderate–large wildfire frequency is associated with the western USA where wildfire counts have declined approximately 15 fires per year. Although the Central USA is the only region that illustrates an increase in mean annual wildfire occurrence, the mean annual total burned area by moderate–large wildfires has enlarged in all three study domains throughout the 24-year historical period (Fig. 4). Moderate–large mean annual wildfire total burned area for the western USA has amplified 79,000-ac per year with the Central USA experiencing a 67,000-ac per year increase since 1992. Moderate–large wildfires in the Central and West US study regions represent a combined 90% of all moderate–large wildfire total burned area in the USA from 1992 to 2015. The West region is responsible for 62% of the total moderate–large wildfire-burned area, supporting prior research that has indicated that larger wildfires are more common in the western USA (Dennison et al. 2014). The mean annual escalation in wildfire-burned area associated with the eastern USA is less than that of the Central and West regions, amplifying 6400-ac per year.

Similar to the moderate–large wildfire mean annual frequency trends, mean annual large wildfire counts have also increased over time (Fig. 4). Although there are fewer large wildfires within the historical FPA-FOD fire record, the Central and West regions have experienced an approximate doubling in large wildfires on average (mean) each year from 1992 to 2015. This amplification has resulted in an estimated 35 to 40 more large wildfires
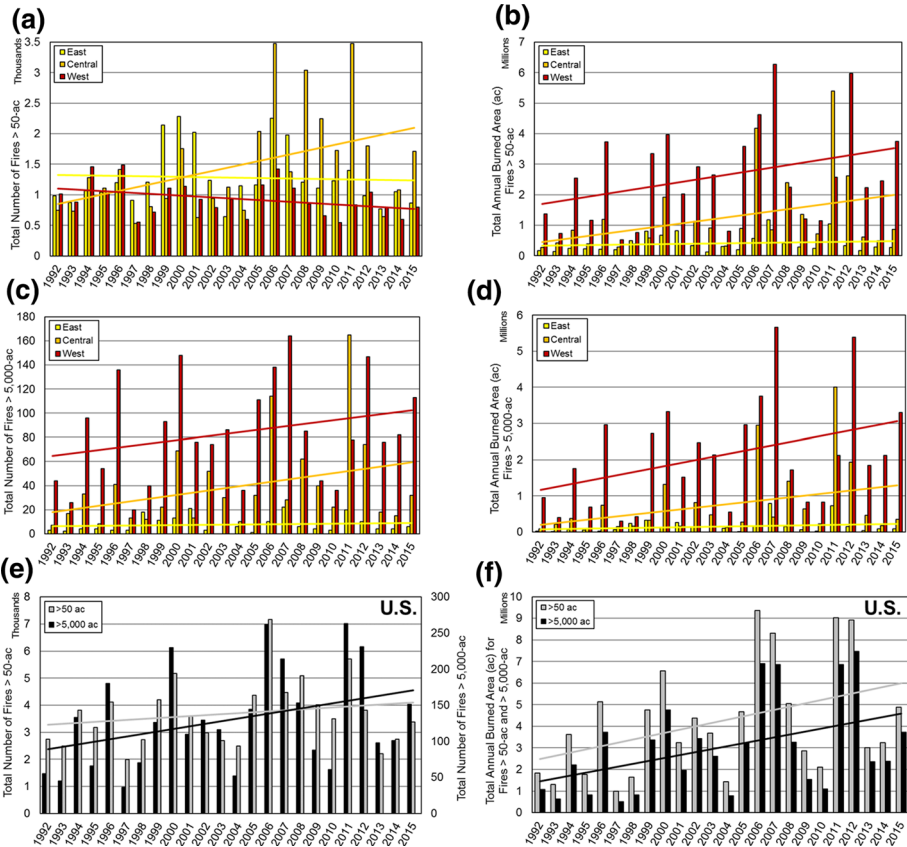
Fig. 4 The change in Central, East, and West study region annual number of wildfires (**a** and **c**) and total burned area (km^2; **b** and **d**) for wildfires greater than 0.202 km^2 (50-ac) and 20.23 km^2 (5000-ac) from 1940 to 2010. The change in conterminous USA **a** annual number of wildfires and **b** total burned area (km^2) associated with wildfires greater than 0.202 km^2 (50-ac) and 20.23 km^2 (5000-ac) from 1940 to 2010 is also highlighted

occurring in the West region and 40 to 45 more large wildfires in the Central US region in 2015 compared to 1992. The Central and West study domains comprised 95% of all large wildfires within the USA, while the West study region contained 68% of all large wildfires from 1992 to 2015. Although large wildfires are less common in the eastern USA, mean annual large wildfire frequency trends in the East study region have also increased over the 24-year period.

As expected, trends in mean annual large wildfire total burned area for the three sub-regions have increased substantially over the previous 24 years. Again, the largest increase in mean annual burned area coincides with the West region, where large wildfire total burned area swelled approximately 82,000-ac per year. This amplification in total burned area is nearly double the escalation found in the Central region where large wildfire total burned area increased 47,000-ac per year on average. Although the Central and West domains make up 75% of the total large wildfire-burned area in the USA per year, large wildfire total burned area has also increased 6500-ac per year in the eastern USA.

In all, the quantitative and spatial analysis of moderate–large and large wildfire counts, frequency trends, and total burned area indicates that wildfire likelihood is increasing throughout the USA over time. Although moderate–large wildfire frequencies in the West and East study regions have decreased in recent years, the total area burned has grown within these same regions. In addition, large wildfire annual counts and total burn area have amplified throughout the previous 24 years for the USA and all subregions. Together these findings suggest that large wildfires are becoming *more frequent* throughout the USA, especially for areas east of the Mississippi River.

4.3 Spatiotemporal trends in US exposure by contemporary wildfire likelihood zones (WLZ)

Combining the HU-LULC and wildfire likelihood findings, changes in US wildfire exposure by contemporary WLZ were examined from 1940 to 2010. Again, wildfire likelihood is represented by a smoothed wildfire likelihood surface derived from a 40-km grid denoting total burned area by fires greater than 50-ac from 1992 to 2015 (Fig. 5b). The smoothed wildfire likelihood surface and associated WLZ were intersected with the historical SERGoM HU and FORE-SCE LULC-developed gridded surfaces by decade from 1940 to 2010 to determine changes in wildfire exposure by contemporary wildfire region for the USA and study subregions. Because wildfire likelihood was divided into varying likelihood categories or WLZ (i.e., very low through very high likelihood), alterations in wildfire exposure are described using both absolute and normalized area measures of HUs and developed land area.

In all of the categorized US WLZ (very low to very high), the total number of homes to be potentially damaged by wildfires has increased nearly 106.4 million HUs (Fig. 6). Together, the total number of HUs in the three greatest likelihood areas (medium–high to very high) has increased 356,000 HUs since 1940. During this same time period, the total developed land area in the US medium–high to very high WLZ escalated 578 km^2. Of the three greatest WLZ (medium–high, high, and very high), the very high WLZ experienced the greatest historical increase in HUs (+ 235,000) and developed land area (+ 387 km^2).

Controlling for the different size WLZ, the medium WLZ represents the region that had the greatest area-normalized increase in wildfire exposure amplifying 17.2 HUs per km^2 from 1940 to 2010 (Fig. 6). Similarly, the very low and low–medium categories contained HU density increases of 16.4 and 10.6 HUs per km^2 over the same time frame. While the medium–high and high WLZ both experienced amplifying HU density from 1940 to 2010, HU density escalated the most at 2.2 HUs per km^2 in the very high WLZ. The percentage of total land area that is developed also increased in all WLZ within the USA. The largest percentage change in total developed land area occurred in the very low WLZ (+ 2.2%), followed by the low–medium (+ 1.5%) and low (1.4%) WLZ. Analogous to the increase in HU density results, the very high WLZ contains a larger percentage change in developed land area compared to the medium–high and high WLZ. Together, the medium–high to very high percentage developed land in the USA enlarged nearly 0.20 km^2 from 1940 to 2010.

4.4 Spatiotemporal trends in regional exposure by contemporary wildfire likelihood zones (WLZ)

Although wildfire exposure in WLZ has increased over time throughout the USA, there are substantial spatiotemporal differences among WLZ exposure for the East, Central, and
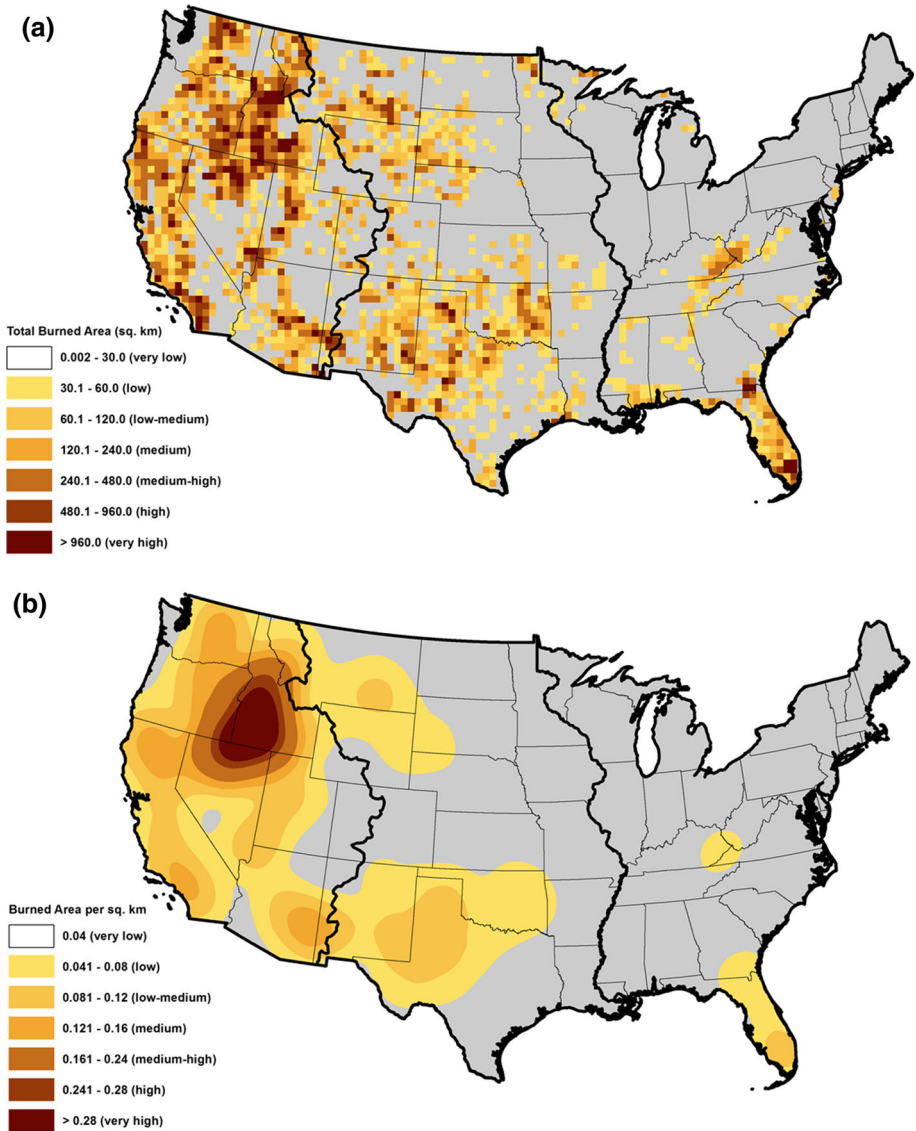
Fig. 5 Wildfire risk zones represented by **a** total burned area (km^2) within a 40-km grid and **b** smoothed (3 × 3 low-pass filter and spatial smoothing techniques) burned area per km^2 for wildfires greater than 0.202 km^2 (50-ac) from 1992–2015

West study regions. These dissimilarities exist because of the unique combinations of built-environment growth and increasing wildfire likelihood within each study region.
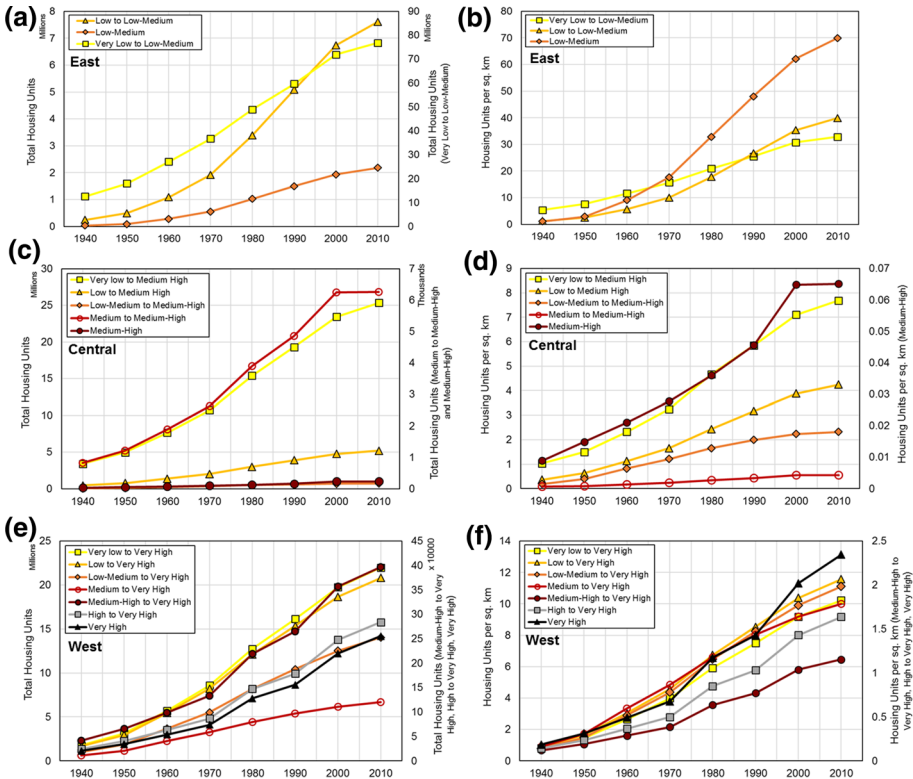
From 1940 to 2010, the total number of HUs within the East very low, low, and low–medium WLZ increased the most compared to any other zone due to the combination of a spatially larger very low wildfire likelihood area and a greater overall amount of development (Fig. 7). The total number of HUs within the East region increased 64.3 million, while the Central and West domains comprised HU escalations of 21.9 million and 14.1
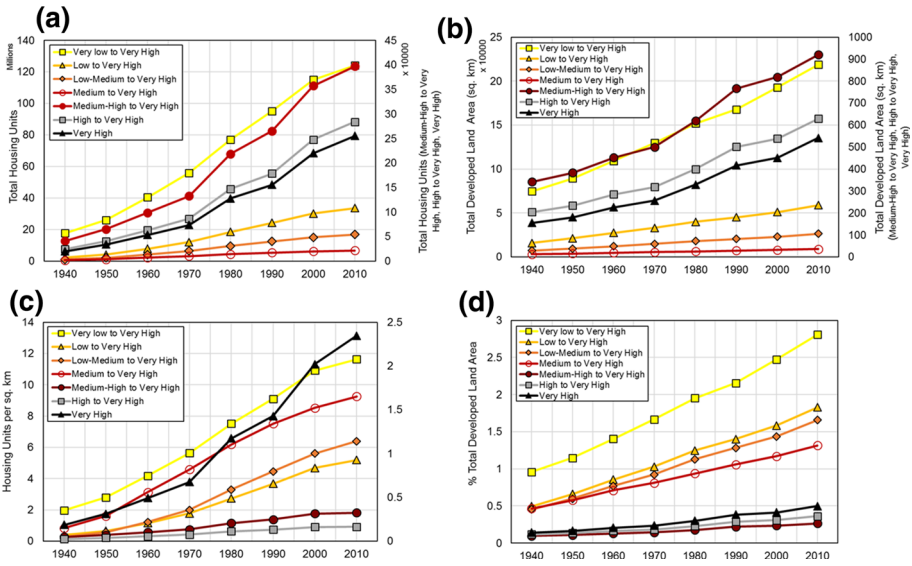
Fig. 6 Total absolute change in **a** housing units (HU) and **b** developed land area within wildfire risk zones (very low to very high) for the conterminous USA from 1940 to 2010. Total relative change in **c** HU per km^2 and **d** percentage developed land area by conterminous US wildfire risk zones from 1940 to 2010

million (Table 4). Further, developed land area in the very low to low–medium WLZ expanded 89,346 km^2 in the East and 31,285 km^2 in the Central USA (Fig. 8; Table 5). Developed land area within the very low through low–medium WLZ increased the least in the western USA where there was only a 17,697-km^2 expansion. Although the wildfire likelihood is higher in the western USA, the primary cause for the lower growth in wildfire exposure in the West region is the smaller spatial area of the very low WLZ. This finding stresses the importance of both WLZ intensity/magnitude and the built-environment concentration when assessing exposure.

Ignoring the very low WLZ in all regions, the western USA yields a much larger 70-year change in wildfire exposure compared to the other regions with an increase of 13.1 million HUs within the low to low–medium WLZ. Comparatively, the East region experienced a 7.4 million HU increase within the low to low–medium WLZ, while the total number of HUs in the Central domain low to low–medium WLZ grew by 4.8 million HU (Table 4). The increasing trends in total regional HUs within the low to low–medium WLZ correspond to developed land expansions of 13,598 km^2 (East), 7268 km^2 (Central), and 16,192 km^2 (West). Examining the medium through very high WLZ, the western USA comprises the greatest built-environment growth with a 6.1 million HU increase and 17,697 km^2 escalation in developed land area (Tables 4, 5). Although the Central study region does not contain WLZ with a magnitude greater than medium–high, the Central domain did experience an increase of 5426 HU from 1940 to 2010. Inversely, the West domain is the only study region to encompass WLZ of high and very high. The amplification in HU counts and developed land area for the high and very high WLZ in the West was 259,500 HU and 5778 km^2, respectively. A majority of built-environment growth within the high and very high WLZ has been associated with Boise, ID, and Ontario, OR-ID, metropolitan areas. Historically, this area of western Idaho has been a concentrated

Fig. 7 The change in total number of housing units (HU) and HU per km² for the East (**a** and **b**), Central (**c** and **d**), and West (panels **e** and **f**) study regions from 1940 to 2010

region where there has been substantial growth in the job market and employment opportunities compared to the rest of the states (Gabe 2006).

Taking all WLZ within each study region into account, wildfire exposure escalated greatest over the last 70 years in the East domain. The total number of HUs in the East has increased from 12.6 million HU to 76.8 million HU, and developed land area has swelled from 43,881 to 133,227 km². Examining the East domain further, the relative growth in societal exposure to wildfires is greatest in the low–medium WLZ. Within the eastern US low–medium WLZ, HU counts increased 6122% as developed land area swelled 627% from 1940 to 2010. Again, this greater eastern US absolute increase in wildfire exposure by contemporary WLZ is due to the larger area of very low wildfire likelihood and greater overall percentage (5.7%) of total developed land area compared to the other regions. Nevertheless, this larger relative increase in exposure is associated with the rapid development in the Miami-Fort Lauderdale-West Palm Beach metropolitan statistical area.

Although the Central domain does not encompass WLZ of high and very high, the region does represent second largest absolute increase in exposure within contemporary WLZ with a 21.9 million HU and 31,290 km² built-environment amplification from 1940 to 2010. The greatest relative change in HUs and developed land area within the Central domain occurred within the low and low–medium WLZ. Built-environment growth associated with metropolitan areas such as Amarillo, TX, Lubbock, TX, Midland-Odessa,

Table 4 Absolute and relative changes in housing units (HU) by wildfire likelihood zone for the East, Central, West, and conterminous USA study regions

Likelihood	East (1940–2010)		Central (1940–2010)		West (1940–2010)		Cont. USA (1940–2010)	
	Abs. change	% Change	Abs. change	% Change	Abs. change	% Change	Abs. change	% Change
Very low	56,895,834	462	17,169,212	580	1,068,133	1013	75,133,179	489
Low	5,214,031	2424	4,103,576	1054	6,124,031	941	15,441,638	1230
Low–medium	2,147,004	6122	651,627	1161	6,939,258	1760	9,737,889	2005
Medium	–	–	5225	654	5,739,640	1013	5,744,865	1012
Medium–high	–	–	201	634	96,075	571	96,276	571
High	–	–	–	–	24,420	582	24,420	582
Very high	–	–	–	–	235,080	1165	235,080	1165
Total (low–very high)	7,361,035	2942	4,760,629	1067	19,158,504	1159	31,280,168	1331
Total (very low–very high)	64,256,869	512	21,929,841	643	20,226,637	1150	106,413,347	600

TX, Billings, MT, and Rapid City, SD is responsible for the larger relative increase in wildfire exposure within the low and low–medium WLZ.

The total number of homes in the West study region increased by 20.2 million HU and developed land area expanded 23,476 km^2 from 1940 to 2010. Although the western USA is the only study region that contains WLZ from very low to very high, it ranks third in absolute changes in wildfire exposure over the 70-year study period when considering all WLZ. Nevertheless, the West region does contain a greater concentration and frequency of large wildfires (Fig. 3). Due to a rapidly expanding built environment and relatively higher wildfire likelihood, the West region comprises the greatest relative or percentage increase in wildfire exposure from 1940 to 2010 with a 1150% increase in the total number HUs and 256% expansion in developed land area. Thus, although only 1.5% of the total land area in the West was developed by 2010 (compared to 5.7% in the East and 1.6% in the Central regions), wildfire exposure within contemporary WLZ escalated at a much faster rate in the western USA compared to the Central and East study regions.

Though wildfire exposure within fire zones historically may have amplified most in the eastern USA when considering all WLZ, this measurement of exposure in fire zones is somewhat misleading. For instance, absolute changes in the built environment are a product of both development magnitude and the size of the WLZ. Because the East USA contains few WLZ greater than the very low likelihood magnitude, changes in eastern US wildfire exposure within the very low WLZ are inflated. However, when excluding the very low WLZ, the West region comprises the greatest change in exposure with an increase of 19.2 million HU and nearly 20,000 km^2 in developed land area (Tables 4, 5).
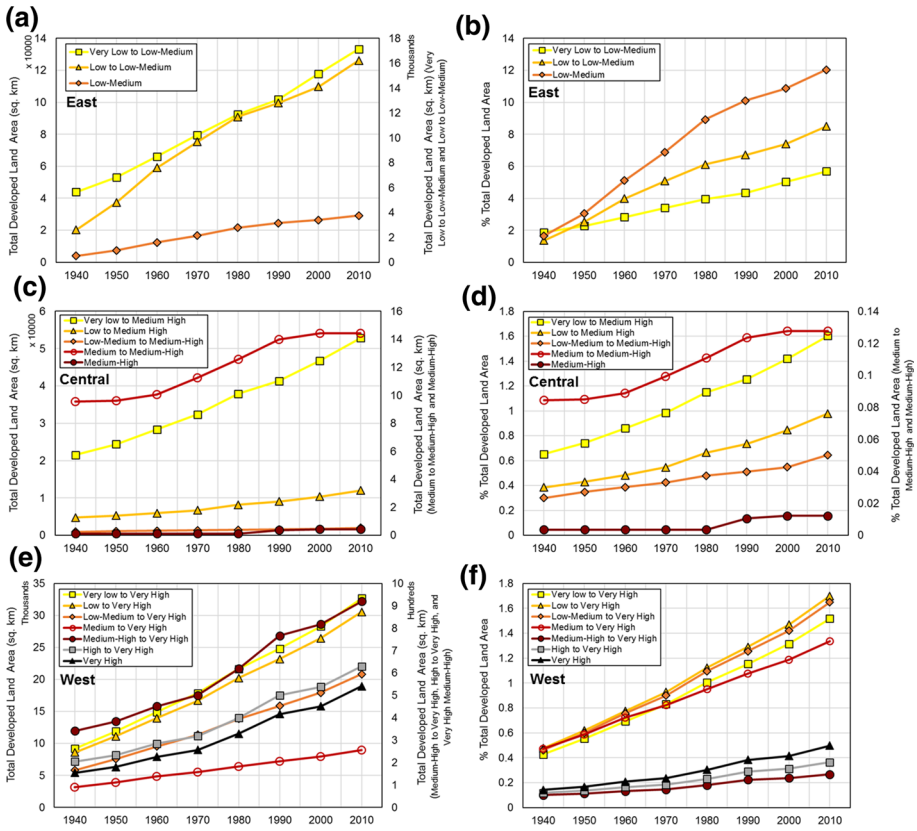
Fig. 8 The change in total developed land area (km²) and percentage total developed land area for the East (**a** and **b**), Central (**c** and **d**), and West (**e** and **f**) study regions from 1940 to 2010

4.5 Spatial rate of change in exposure to wildfires

Changes in wildfire exposure are a product of both alterations in the built environment and wildfire likelihood. To assess locations where rapid changes in wildfire likelihood and societal growth have coincided, a 40-km gridded metric that denotes the mean annual rate of change in both total HUs and burned area by wildfires greater than or equal to 50-ac was created (Fig. 9). Examining where wildfire frequency and total burned area have increased alongside sharp escalations in the built environment allows for the identification of regions and communities that may need to consider or reconsider existing wildfire mitigation and suppression strategies.

As expected, the greatest mean annual rate of change in total HUs occurred in heavily populated metropolitan statistical areas such as Atlanta, Chicago, Dallas-Fort Worth, Los Angeles, Miami, the Interstate 95 corridor (Washington D.C., Baltimore, Philadelphia, New York, Boston) (Fig. 9a). The location with the greatest mean annual rate of change in total HUs is New York City, NY, where total HU counts increased 26,000 HU per year from 1940 to 2010. Wildfire likelihood has increased the fastest in the upper Northwest USA, specifically the Columbia Basin and east of the Cascade Range (Fig. 9b). Other locations that have experienced large mean annual increases in wildfire likelihood from

Table 5 Absolute and relative changes in total developed land area (km^2) by wildfire likelihood zone for the East, Central, West, and conterminous US study regions

Likelihood	East (1940–2010)		Central (1940–2010)		West (1940–2010)		Cont. USA (1940–2010)	
	Abs. change	% Change	Abs. change	% Change	Abs. change	% Change	Abs. change	% Change
Very low	75,748	184	24,017	143	1505	250	101,233	173
Low	10,359	495	6214	163	6958	253	23,568	272
Low–medium	3239	627	1054	115	9234	349	13,519	332
Medium			5	48	5200	184	5205	183
Medium–high	–	–	0.3	250	153	112	154	112
High	–	–	–	–	38	77	38	77
very high	–	–	–	–	387	250	387	250
Total (low–very high)	13,598	521	7273	154	21,970	256	42,870	269
Total (very low–very high)	89,346	204	31,290	145	23,476	256	144,104	1398

1992 to 2015 are Eastern Oklahoma and Kansas, Northern California, parts of the Appalachian Mountains, and South Florida. These escalations in mean annual burned area are likely a result of climate change-driven alterations in drought, temperature, and precipitation (e.g., Piñol et al. 1998; Gillett et al. 2004; Giglio et al. 2013; Dennison et al. 2014) combined with society interacting more regularly with wildfire-prone landscapes (Balch et al. 2017). Nevertheless, intersecting the geospatial layers that represent rates of mean increases in HUs and total burned area reveals a number of regions communities and area that have experienced rapid amplifications in wildfire exposure (Fig. 9c). In the western USA, regions within the northern Columbia Basin, northern Coastal Range, southern Cascade Range, and mountain ranges surrounding Los Angeles, CA, and San Diego, CA (i.e., San Gabriel Mountains and Santa Ana Mountains) have undergone the most rapid increase in exposure to wildfires. The Central region also contains regions that have undergone combined rapid increases in wildfire exposure and wildfire likelihood. For example, the Flint Hills region in Kansas has undergone both a rapid increase in wildfire likelihood and built environment over the last half century. Lastly, in the eastern USA, areas of Florida and the Appalachian Mountains have witnessed the sharpest amplifications in wildfire exposure over the last 70 years.

5 Conclusions

This study employed a spatiotemporal approach to examine how wildfire likelihood and the human-built environment have transformed wildfire exposure throughout the USA from 1940 to 2010. A bulleted list of conclusions is provided below:

- Wildfire likelihood and the built-environment exposure to wildfires have risen dramatically over the previous 70 years.
- The total number of homes in the three greatest likelihood areas (medium–high to very high) has increased 356,000 HUs over the previous 70 years.
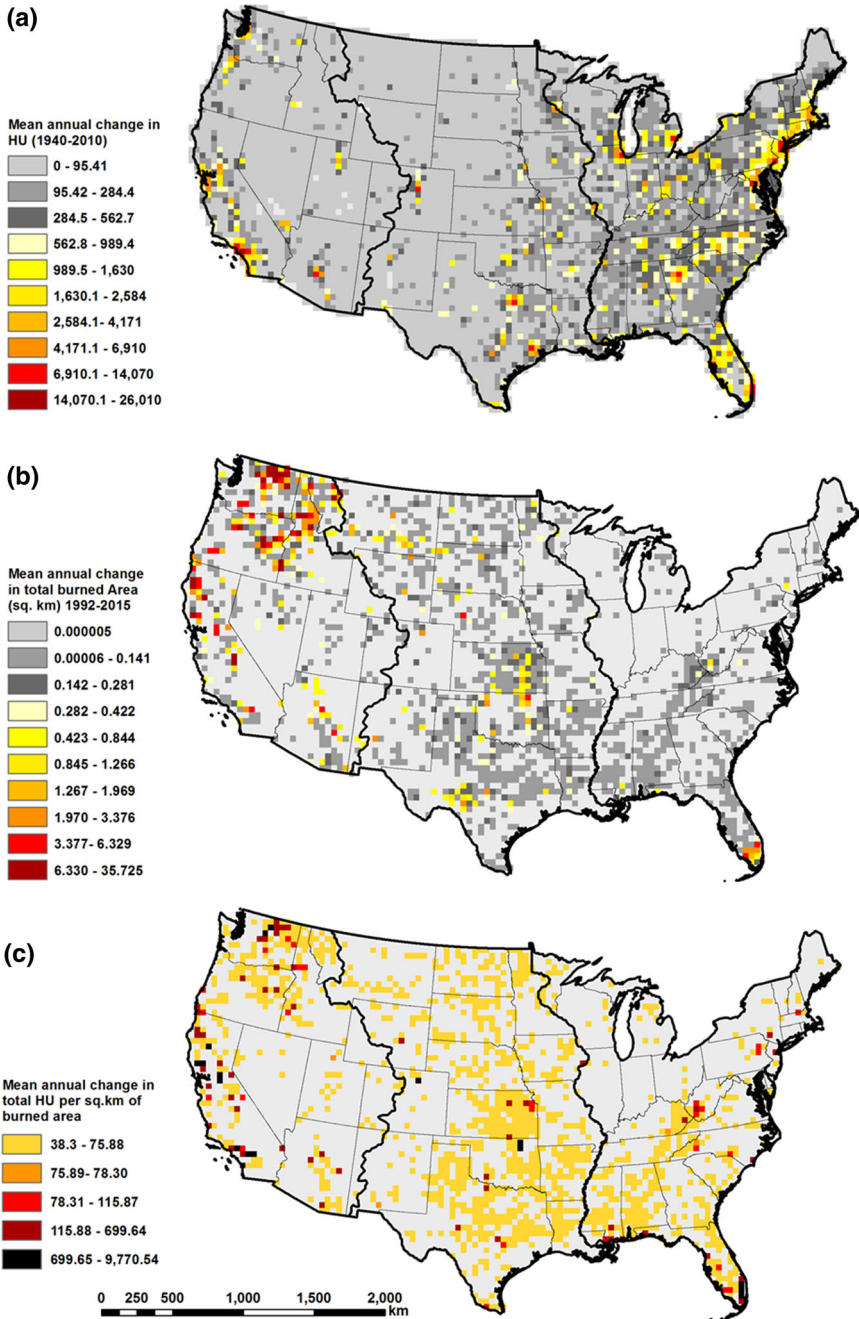
Fig. 9 Mean annual rate of change in **a** total housing units (HU) and **b** burned area (km²) associated with wildfires greater than or equal to 50-ac within a 40-km grid. Panels A and B are multiplied together (panel C) to highlight areas of the conterminous USA that have experienced rapid growth in total HUs and wildfire-burned area

- The total number of homes in the East study region WLZs has increased from 12.6 million to 76.8 million since 1940, and developed land area has swelled from 43,881 to 133,227 km^2.
- A primary driver for the increased exposure has been the escalation in the number of homes and the increased developed land area within wildfire-prone regions.
- There is a trade-off between wildfire likelihood and the built environment that ultimately dictates wildfire exposure magnitude. For instance, the eastern USA contained the greatest concentration of developed land area and total HUs throughout the 70-year study period, yet wildfire likelihood in the East is relatively low compared to the Central and West USA.
- Communities such as Boise, ID, serves as an exemplar in this regard. Boise, ID, has already dedicated interdepartmental wildfire mitigation teams that set building codes, treat wildfire fuels, and participate in community-driven wildfire education practices (City of Boise 2017).

Results from this study may provide insight on changes in wildfire exposure for similar communities with wildfire mitigation teams throughout the USA. Understanding the importance of how city development patterns have changed or may be altered in the future will help affected communities better assess wildfire vulnerability and improve their resilience. Additionally, locations prone to wildfires that experience a high number of tourists may need to reassess their wildfire mitigation practices more regularly, due to these locations' rapid developed land growths as compared to surrounding more stably populated areas and considering that this transient population may be less educated on wildfire safety. For example, the Pigeon Forge and Gatlinburg, TN wildfires in the fall of 2016 killed 14 people, injured 124, and destroyed more than 2400 structures (Associated Press 2006). Although there is no conclusive evidence that such a lack of education contributed to the Pigeon Forge and Gatlinburg, TN wildfires, it is worth considering the influence transient populations may have on wildfire exposure. While the Pigeon Forge-Gatlinburg, TN area, participates in Firewise USA (2017) and other community-based wildfire protection and mitigation plans, an emphasis should be placed on the rapid updating of these plans to keep pace with increasing built-environment growth.

Constantly adapting existing prevention measures or enacting new prevention, mitigation, and recovery strategies that take into account societal influences in wildfire exposure will ultimately reduce future damages and the loss of life. The continued development and implementation of building codes, standards, and practices that reduce the likelihood of homes, businesses, etc., being destroyed by wildfires is vital in creating a more wildfire-resistant society. In addition, the creation of new zoning ordinances and continual adaptation of existing that reduce the odds of wildfire ignition within populated areas will reduce wildfire exposure. Lastly, participation in community outreach programs such as the National Fire Protection Association (NWCP 2017) and the US Forest Service's Fire Adapted Communities project should continue to be encouraged in areas where wildfire exposure is increasing more rapidly. The application and reinforcement of wildfire suppression, mitigation, and recovery best practices is needed to create more disaster-resilient communities in the future.

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