Rapid growth of the US wildland-urban interface raises wildfire risk

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The wildland-urban interface (WUI) is the area where houses and wildland vegetation meet or intermingle, and where wildfire problems are most pronounced. Here we report that the WUI in the United States grew rapidly from 1990 to 2010 in terms of both number of new houses (from 30.8 to 43.4 million; 41% growth) and land area (from 581,000 to 770,000 km²; 33% growth), making it the fastest-growing land use type in the conterminous United States. The vast majority of new WUI areas were the result of new housing (97%), not related to an increase in wildland vegetation. Within the perimeter of recent wildfires (1990–2015), there were 286,000 houses in 2010, compared with 177,000 in 1990. Furthermore, WUI growth often results in more wildfire ignitions, putting more lives and houses at risk. Wildfire problems will not abate if recent housing growth trends continue.


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of WUI growth. The decennial US Census provides fine-resolution housing data for 1990, 2000, and 2010, but the boundaries of the smallest units for which housing units are reported (i.e., census blocks) often shift between decades, precluding direct change analyses (27). We have developed algorithms to convert the decennial Census data at census block resolution into a consistent dataset on housing growth across the conterminous United States (Methods), which we combined with 1992, 2001, and 2011 National Land Cover Data (NLCD) on wildland vegetation: forests (classes 41–43), shrublands (classes 51 and 52), grasslands (class 71), and woody wetlands (class 90). We mapped decadal WUI change from 1990 to 2010 within 2010 census block boundaries, based on the WUI definitions in the Federal Register and our previously developed WUI mapping algorithms (1, 14), and conducted several robustness checks of our new dataset (Supporting Information). Because of concerns about housing growth and wildfire management, we calculated housing growth for 1990–2010 within WUI burned areas identified in Landsat imagery between 1990 and 2015 (22).

We found that the WUI was widespread in 2010, covering 9.5% of the conterminous United States (Fig. 1), and that the WUI grew rapidly from 1990 to 2010 in all its aspects (Fig. 2).

Fig. 1. The WUI in the United States was widespread in 2010 (A), as were changes in WUI area (B), for example, in and around Santa Rosa, California (1, 3), and Gatlinburg, Tennessee (2, 4), areas where wildfires destroyed many homes in 2017 and 2016, respectively.
The number of housing units ("houses" hereafter) in the WUI grew fastest, followed by the number of people in the WUI and then WUI area (Fig. 2B and Table S1). New WUI area totaled 189,000 km², an area larger than Washington State. At 33%, WUI area growth was faster than that of any of the level I land cover categories included in the NLCD (28). Increases in houses and people were also strong, with 12.7 million more houses and 25 million more people in the WUI in 2010 compared with 1990. The overall combination of more WUI area (7.2% of the conterminous United States in 1990 vs. 9.5% in 2010; Fig. 2C) and higher growth rates for both houses and people in the WUI, compared with the nationwide averages (Table S1), increased the percentage of houses (from 30.3% to 33.2%) and people (from 29.4% to 31.9%) in the WUI from 1990 to 2010 (Fig. 2C). Even though the WUI occupies less than one tenth of the land area of the conterminous United States, 43% of all new houses were built there, and 61% of all new WUI homes were built in areas that were already in the WUI in 1990 (and remained in the WUI in 2010) (Tables S1 and S2).

There are two main types of WUI: intermix WUI, the area where houses and wildland vegetation directly intermingle, and interface WUI, where settled areas abut wildland vegetation (1). We found that intermix WUI was both more extensive and expanded much more rapidly in area (from 5.6% to 7.5% of the conterminous United States from 1990 to 2010) than interface WUI (from 1.6% to 2.0%). However, interface WUI had higher housing growth rates (43% from 1990 to 2010) than intermix WUI (38%) and non-WUI areas (23%; Table S1). In absolute numbers, there were 4.7 million more houses in the intermix WUI and 8.0 million more in the interface WUI in 2010 than in 1990.

Regional differences in WUI growth were striking (Fig. 3). The highest absolute gains in WUI area occurred in the East, whereas high gains in houses and people in the WUI were most common in the South and Southwest. Absolute gains are most relevant for management agencies, because they indicate how much area and how many people and houses may require management actions; however, rapid growth often garners the most attention. Across the United States there is an interesting dichotomy in that states in the East had large absolute gains, but relatively low WUI growth rates, largely because WUI was already so widespread in 1990. In contrast, states in the northern Rockies saw much smaller absolute gains in WUI area and houses, but rapid WUI growth rates.

New WUI areas arise either when new houses are built in or near wildland vegetation or when wildland vegetation regrows in or near settled areas. Between these two possible causes, housing growth was unambiguously the main cause for new WUI areas, with increases in vegetation contributing minimally. Of all new WUI areas, 97% were caused by housing growth in sparsely settled areas, pushing these areas over the threshold of 1 house per 40 acres (6.17 homes/km²). Only 2% of new WUI area was due to vegetation growth alone, and 1% was due to the combination of both housing and vegetation growth (Table S2). Similarly, new houses were the cause of >80% of WUI growth in all states except Delaware, the District of Columbia, Maryland, and New Jersey (Fig. S1).

Among areas that were WUI in 1990, the vast majority were still WUI in 2010, and both homes and population increased in those areas over that time (Table S2). A small proportion (6%) of the 1990 WUI area was dropped out of the WUI by 2010. Among all WUI changes (i.e., gains and losses combined), 13% of the changes in WUI area and 25% of the changes in WUI houses from 1990 to 2010 were losses. In terms of the causes of WUI area loss, reduced housing density was the most important (65.0%), whereas the loss of vegetation accounted for 32.6%. Housing density may have declined due to actual removal of housing units, or possibly due to enumeration errors in the Census data. Loss of vegetation was the dominant driver of loss of homes from the WUI (65.0%), which occurred largely in densely settled areas where additional housing development, deforestation, or fuel management may have removed wildland vegetation.

The number of houses within burned areas in the different decades is a strong indication of how much WUI growth can exacerbate wildfire problems. In 1990, there were 177,000 houses within the perimeters of the fires that occurred in the subsequent 25 y. By 2010, there were 286,000 housing units in the same fire perimeters, i.e., 109,000 more, which corresponds to 62% growth (far outpacing the average US housing growth rate of 29%). Of these new houses, those built before the wildfires occurred complicated firefighting because more houses had to be protected and more residents had to be evacuated. Similarly, houses built after fires occurred are of concern because new development in areas that burned recently, and thus are known to have a high fire risk, suggests that there is little adaptation to fire risk (2).

Our results provide compelling evidence that the WUI in the United States has grown rapidly, despite the risks that wildfires pose to homes and lives (3) and despite the other environmental problems caused by housing development in or near wildland vegetation (9). Our findings are generally in alignment with previous studies that found rapid previous WUI growth (24) and widespread potential for future WUI growth (25, 29), even though absolute numbers are not comparable because of differences in WUI definitions, datasets, and time periods (30). Furthermore, the WUI is not unique to the United States, but is widespread in many other countries as well (15, 16, 18–20). Rampant WUI growth demonstrates that the social and economic factors that together propel WUI growth are strong, WUI areas are attractive places to live because of affordability and ready access to natural settings and recreation (31). As WUI areas attract new residents, the number of houses per capita often increases as well, due to increasing rates of seasonal homeownership and declining family size (32). Indeed, despite the economic downturn after 2008, the absolute number of

![Fig. 2. WUI growth was rapid in terms of the absolute numbers of the area, houses, and people in the WUI in 1990, 2000, and 2010 (A); WUI growth rates during the 1990s and the 2000s (B); the proportion of all houses and people, as well as the land area in the WUI in 1990, 2000, and 2010 (C); and the absolute number of all new housing units within and outside the WUI during the 1990s and 2000s (D).](https://www.pnas.org/cgi/doi/10.1073/pnas.1718850115)
houses built in the WUI, and in the United States as a whole, was higher between 2000 and 2010 than between 1990 and 2000 (Table 1). Demographic trends do not suggest slower future WUI growth. Furthermore, climate change projections indicate that conditions favorable for wildfires will occur more frequently in the future (8). Thus, increased wildfire ignition rates due to WUI expansion will initiate more wildfires in vegetation that is more susceptible to fire spread, leading to more widespread fires and possibly more severe fire behavior (33). This suggests that WUI growth and climate change together will compound the existing problems with wildfires in the WUI.

As WUI growth continues, there are many management options and policy tools to consider for addressing both wildfire and other environmental problems. Just as WUI-related problems involve actors (e.g., homeowners, community leaders) at many levels, so too must their solutions involve actors at multiple levels (i.e., local, regional, state, and national) (3, 8). Homeowners can reduce their individual fire risk by removing vegetation directly adjacent to their house (i.e., the home ignition zone; refs. 3 and 34), changing roofing and building materials, and following additional Firewise recommendations (35). To limit some of the other environmental problems associated with living in the WUI, homeowners can keep cats inside and dogs on a leash, limit fertilizer and pesticide use, and landscape with native plants (9). To reduce wildfire impacts, communities can coordinate fuel reduction efforts, educate homeowners, train firefighters, and establish wildfire management plans. Insurance companies can offer reduced premiums for communities taking mitigation action to incentivize community-level efforts to reduce wildfire losses. Communities and local jurisdictions could anticipate wildfires and environmental impacts more explicitly when planning future land use to avoid housing expansion in high-risk wildfire areas and other environmentally sensitive areas (36). State and federal agencies typically do not regulate development directly, but can allocate resources to areas experiencing rapid WUI growth, support local and regional planning efforts, and provide important research data and information to help communities adapt to fire-prone environments. Agencies managing public lands could consider targeted purchases of private inholdings to limit future housing growth within the administrative boundaries of public lands, which has been particularly rapid (37). In summary, there are many concrete management actions and policy responses that can limit the negative effects of WUI growth on wildfire risk and other environmental problems, but changes will require efforts at all levels by homeowners and community leaders, local and county governments, and state and federal agencies.

Housing development in the WUI greatly exacerbates wildfire problems and other environmental issues in the United States (1, 5, 8), and globally (16, 18–20). Our results highlight the magnitude and rapid rates of WUI growth in the US, underscoring the urgency of identifying what can be done to address WUI growth and its associated wildfire challenges (3). Past federal fire policy has focused largely on fighting and preventing wildfires and on fuel reduction, public outreach campaigns, and other actions (38). Although laudable, such efforts are unlikely to be successful by themselves, because housing growth is clearly the dominant cause of WUI growth, as well as a major factor contributing to wildfire occurrence and cost. As long as WUI growth is unchecked, wildfire problems will likely worsen. On a more hopeful note, to the extent that WUI growth reflects a affinity for nature, the evident consequences and costs of growth could prompt discussions on how to sustain those highly valued ecosystems in which so many people have chosen to live.

Materials and Methods
Our WUI definition is based on the definition published by the US government in the Federal Register (39) and that has been widely used for WUI assessments in the past (1, 14, 40). It specifies two types of WUI, intermix and interface. Intermix WUI is where houses and wildland vegetation intermingle, with both a housing density of >1 house per 40 acres (6.17 houses/km²) and >50% of the area in wildland vegetation. Interface WUI represents settled areas that have <50% vegetation, but lie within
Based on the Census Bureau relationship files, we first allocated 1990 housing units to 2000 block boundaries by identifying the type of relationship for each 1990 block to 2000 block(s), classifying the relationship as one-to-one, one-to-many, or many-to-one. For one-to-one and many-to-one relationships, 1990 housing units were allocated directly to 2000 blocks. For one-to-many relationships, 1990 housing units were allocated proportionally based on the number of housing units in the 2000 blocks. For many-to-many relationships, we identified the least common denominator polygons that fully contained groups of both 1990 and 2000 housing units. Then, we assigned the number of 1990 and 2000 housing units for the boundaries for each 1990 block to 2000 block(s), classifying the relationship as many-to-many. To minimize instances of many-to-many relationships and maximize direct relationships, we removed blocks that were classified as water in 1990 and as vacant in 2000, as well as all 1990 and 2000 blocks that intersected by <1% of their area. Once 1990 housing units were allocated to 2000 census block geometry, we repeated the process using the 2000–2010 relationship files to allocate 2000 housing units to 2010 block boundaries. We then joined the 1990 housing units allocated to 2000 block boundaries with the 2000–2010 relationship files, and repeated the process to allocate 1990 housing units to 2010 block boundaries. The end result of our algorithms are 1990 and 2000 housing units allocated to the 2010 block geometry across the conterminous United States, i.e., a dataset that permits valid analyses of housing growth across the United States at fine spatial resolution and that minimizes erroneous changes due to changing census block boundaries.

We further refined census block boundaries by integrating them with information on the protected areas of the United States. The boundaries of protected areas were provided by the Protected Area Database, version 2. Where protected areas intersected census block boundaries, we assumed that the houses in that block were located in nonprotected areas only. However, where census blocks with houses were entirely within a protected area, we made no changes, and assumed a uniform housing density throughout the block.

The 30-m resolution NLCD provided us with data on wildland vegetation. We analyzed both the 1992/93–2001 and the 2001–2011 land cover change products and calculated the percentage of each NLCD land cover class within each census block after refinement by the protected area boundaries. We included forest and grass/shrub land cover classes as wildland vegetation and excluded open water, urban, barren, wetlands, and ice/snow.

For each decade, we mapped the WUI separately, by combining 1990 Census data with 1992/93 data from the 1992/93–2001 land cover change product, and 2000 and 2010 Census data with 2001 and 2011 data from the 2001–2011 land cover change product. We first identified all intermix WUI areas based on the housing and vegetation thresholds. We then identified contiguous vegetation areas that were at least 5 km² in size and had >75% wildland vegetation, selecting areas within 2.4 km that were above the housing threshold (but below the 50% vegetation threshold), and labeling these as interface WUI. When census blocks were only partly within this distance, we split them.

The NLCD change products are not fully consistent, in that the 2001 land cover in the 1992/93–2001 change product differs from the 2001 land cover in the 2001–2011 change product. Thus, we conducted a sensitivity analysis and mapped the 2001 WUI twice, based on the two representations, and then compared the resulting WUI maps. The differences between the two WUI maps were very minor.

To calculate the number of homes within fire perimeters over time, we analyzed all fire perimeters of fires that burned between 1990 and 2015 according to the Monitoring Trends in Burn Severity (MTBS) dataset, which includes all fires >404 ha (1,000 ac) in the West and 202 ha (500 ac) in the East. We then assessed which census blocks were at least partially within these fire perimeters and calculated an area-weighted estimate of the number of housing units within the fire perimeters in 1990 (177,000), 2000 (210,000), and 2010 (286,000). We note that this is a conservative estimate of the number of homes affected by wildfires because the MTBS dataset does not include small fires.

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