WILDFIRES

Rising wildfire risk to houses in the United States, especially in grasslands and shrublands

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Wildfire risks to homes are increasing, especially in the wildland-urban interface (WUI), where wildland vegetation and houses are in close proximity. Notably, we found that more houses are exposed to and destroyed by grassland and shrubland fires than by forest fires in the United States. Destruction was more likely in forest fires, but they burned less WUI. The number of houses within wildfire perimeters has doubled since the 1990s because of both housing growth (47% of additionally exposed houses) and more burned area (53%). Most exposed houses were in the WUI, which grew substantially during the 2010s (2.6 million new WUI houses), albeit not as rapidly as before. Any WUI growth increases wildfire risk to houses though, and more fires increase the risk to existing WUI houses.

Wildfires pose substantial risks to people and their homes (*1*), and that risk is concentrated in the wildland-urban interface (WUI), where wildland vegetation and houses are in close proximity (*2*, *3*). Concerns about wildfire risk have grown rapidly in the US over the past several decades, with more than 55,000 houses burned from 2010 to 2022 (*4*) as a result of rapid increases in both the area that burns annually (*5*, *6*) and the number of houses in the WUI (*7*). However, despite widespread concerns about wildfire risk, patterns of wildfire extent and building exposure in different types of vegetation and WUI are unknown. In this work, we drew upon three decades of data on wildfire occurrence and WUI growth in the US, from 1990 to 2020, to examine these trends.

Wildland vegetation type greatly affects fire behavior (*8*). Crown fires in forests have the highest fire intensity and can produce many embers (*9*) that can ignite houses that are far from a fire front. However, grassland and shrubland fires can spread rapidly when wind is strong, such as in the 2021 Marshall Fire near Boulder, Colorado, which destroyed more than a thousand houses. Furthermore, fuels recover quickly in grasslands and shrublands, such that areas can reburn within a few years, and these areas require different risk management strategies than forests (*10*). Our first goal was to assess which vegetation types dominated (i) fires, (ii) the vicinity of buildings destroyed by fires, and (iii) the WUI at-large.

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The exposure of houses to fires represents realized risk and can rise either as a result of housing growth or increases in burned area. Over the past 50 years, housing growth has far outpaced population growth in the US, owing to smaller household sizes and more second homes (*11*). Concomitantly, burned area has increased substantially (*5*, *6*) as a result of fuel accumulation (*12*, *13*), human ignitions (*14*, *15*), and, in the West, earlier spring snowmelt and extended droughts (*16*, *17*). Our second goal was thus to determine (i) how much the exposure of houses to fires has grown, (ii) whether that increase was due mainly to housing growth or an increase in burned area, and (iii) how many houses were built within fire perimeters after the fires occurred.

Although many houses have already been exposed to fires, many more are at risk, which is why WUI growth at-large is a concern. Indeed, during the 1990s and 2000s, the WUI was the fastest-growing land cover type in the US (*7*). However, housing construction plummeted after the 2008 economic recession, and an increase in fires may have slowed WUI growth if homeowners decided to build in non-WUI areas in response or local planners limited development in the WUI. Our third goal was to (i) quantify overall growth in WUI areas and houses, (ii) compare regional patterns, and (iii) assess the effects of the 2008 housing market downturn.

Vegetation type within wildfire perimeters and in the WUI

News coverage of wildfires and discussions about fire-management efforts, such as fuel treatments, tend to focus on forest fires (*18*, *19*). However, we found that within the perimeters of the wildfires that burned from 1990 to 2020 in the conterminous US, grassland and shrubland covered 64.0% of the area burned (33.7 million ha), whereas only 27.3% was forest (14.4 million ha) and 8.7% was other land cover (4.6 million ha) (Fig. 1A) (*20*).

Wildfires are most destructive in the WUI, of which there are two types: intermix and interface. Intermix WUI is the type in which houses directly intermingle with wildland vegetation, and so vegetation has a more direct effect on wildfire risk to houses because many are ignited by nearby burning vegetation (*21*). In the intermix WUI areas that burned, the majority burned as a result of grassland and shrubland fires (44.5 versus 41.2% as a result of forest fires; Fig. 1B) but not by as wide a margin as for the entire wildfire area (Fig. 1A). Interface WUI contains less wildland vegetation than intermix WUI but is in close proximity to a large wildland vegetation area. Although wildfires do destroy many houses in interface WUI (*8*), they are typically ignited by fire brands originating from afar or when nearby houses burn, and so we present vegetation results for interface WUI in the supplementary materials (fig. S6).

In the entire intermix WUI, not just in the intermix WUI that burned, grasslands and shrublands were also widespread (Fig. 1C). Especially in those western states where wildfires are most prevalent, grasslands and shrublands dominate the intermix WUI (Fig. 1G). For example, in California, 52.3% of the intermix WUI is grassland and shrubland and only 30.1% is forest. In Colorado, grasslands and shrublands also dominate (45.7 versus 35.2% forest), and in Arizona, shrublands alone cover 74.1% of the intermix WUI. However, across the US, forest is the most common wildland vegetation type in intermix WUI, covering a little more than half of the area (53.8%; Fig. 1C), because grasslands and shrublands are uncommon in the large intermix WUI areas of the eastern US. Over time, grasslands and shrublands dominated burned areas in most years from 1990 to 2020 (Fig. 1D), and also the intermix WUI that burned (Fig. 1E), but there was no trend of increasing dominance over time, whereas both wildfire area and the number of houses in wildfires increased markedly from 1990 to 2020 (Fig. 1F).

Vegetation type affects fire intensity and behavior, and we asked whether vegetation type also affects the rate at which houses are destroyed. Of the 151,725 buildings (houses and other structures) that were exposed to wildfires from 2000 to 2013 (Fig. 1H), 11.3% were destroyed. However, buildings in evergreen and in mixed forests were almost twice as likely to be destroyed (20.1 and 22.9%, respectively). By contrast, the destruction rate for shrublands was similar to the average (12.7%), and rates for grasslands and deciduous forests were considerably lower (8.0 and 3.3%, respectively). Accordingly, logistic regression results showed that the proportion of these vegetation types within 1 km of buildings were all significant predictors of building loss ($p < 0.0001$; table S1). However, because the total area of grassland and shrubland fires is much larger than that of forest

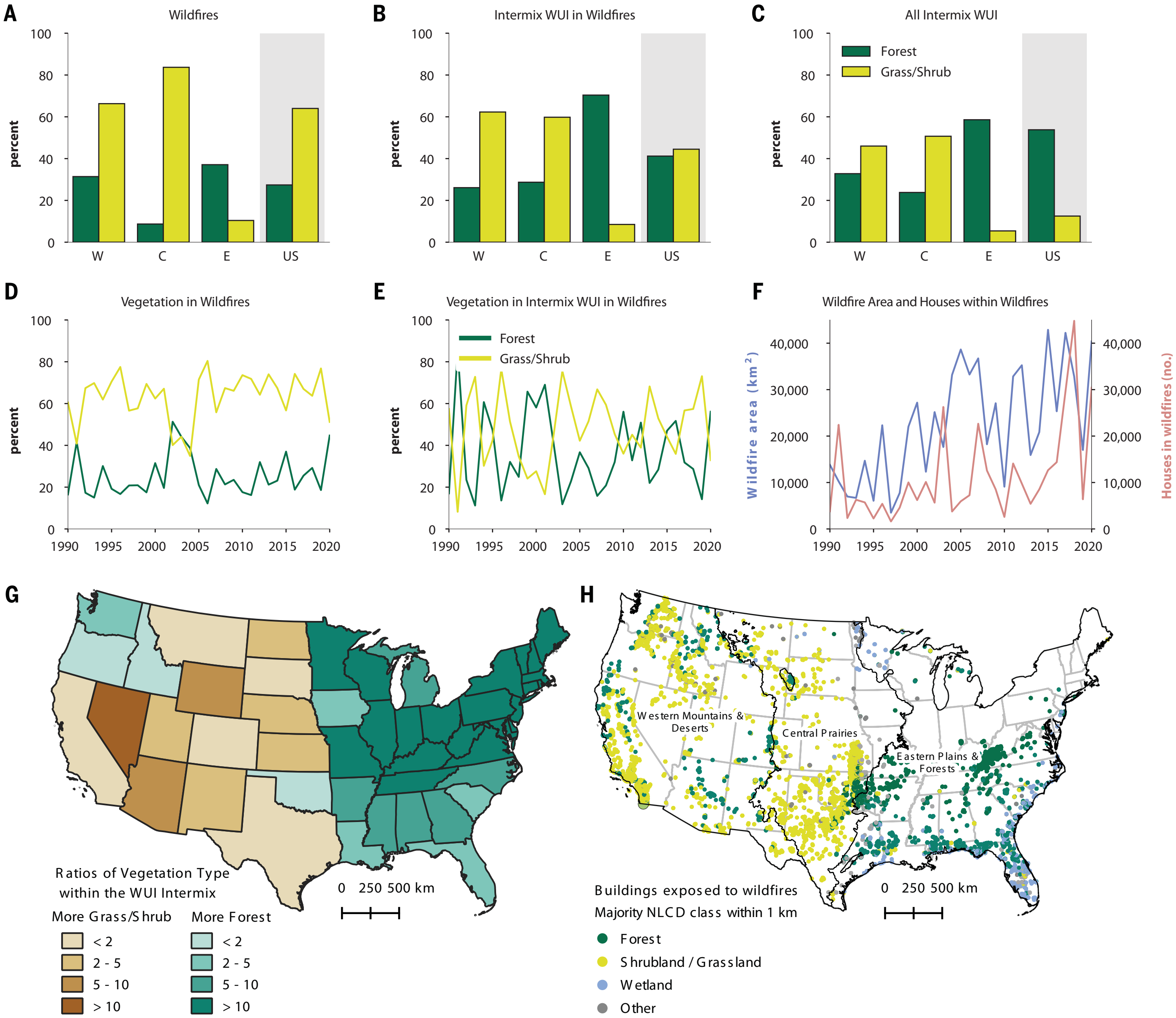

Fig. 1. The main vegetation types within wildfires, within the WUI, and near houses destroyed by wildfires. (**A** to **C**) The average percentage of forest, grassland, and shrubland land cover within the 1990–2020 wildfire perimeters in the western (W), central (C), eastern (E), and conterminous US (US, highlighted with gray shading) (A), within the portion of those wildfire perimeters that is 2020 intermix WUI (B), and within all (burned and unburned) 2020 intermix WUI (C). (**D** to **F**) The percentage of forest versus grassland and shrubland land cover within the entire 1990–2020 wildfire perimeters in the conterminous US over time (D) and within the portion of those wildfires that occurred in 2020 intermix WUI (E), and the annual wildfire area and the number of houses within wildfire perimeters over time (F). (**G** and **H**) The ratio of forest versus grassland and shrubland in the 2020 intermix WUI in each state (G) and the primary vegetation type surrounding buildings that were exposed to wildfires plus the boundaries of the three major ecoregions (H). Grasslands and shrublands dominate the intermix WUI in the Plains and the West, whereas forests dominate WUI in the East; however, because intermix WUI is far more widespread in the East, most intermix WUI in the US is dominated by forest, but intermix WUI within wildfires is dominated by grasslands and shrublands. Both burned area and the number of houses within wildfire perimeters have increased markedly since 1990, albeit with strong fluctuations from year to year. Most of the buildings that were destroyed by wildfires were also within grasslands and shrublands, especially in Texas, Oklahoma, and states of the West Coast. Data are provided in tables S2 and S3. NLCD, National Land Cover Database.

fires, 63.7% of houses destroyed in wildfires (10,890) were located in grasslands and shrublands, compared with only 33.1% in forests (5655). This pattern was most pronounced in the western US, which encompassed 69% of all the buildings destroyed by wildfires. There, 79.5% of all destroyed buildings were lost in grassland and shrubland fires. In the East, by contrast, 82.1% of destroyed buildings were lost in forest fires. In the West, even though forests had a high destruction rate (21.3%), only 2367 buildings were destroyed by forest fires compared with 9402 in grassland and shrubland fires. On average, a wildfire in an evergreen or mixed forest poses a considerably larger threat to an individual home than a wildfire in other vegetation types. We suggest that this is likely due to higher fire intensity but cannot rule out that houses near forests are built differently or that weather patterns associated with forest fires are inherently different. However, grassland

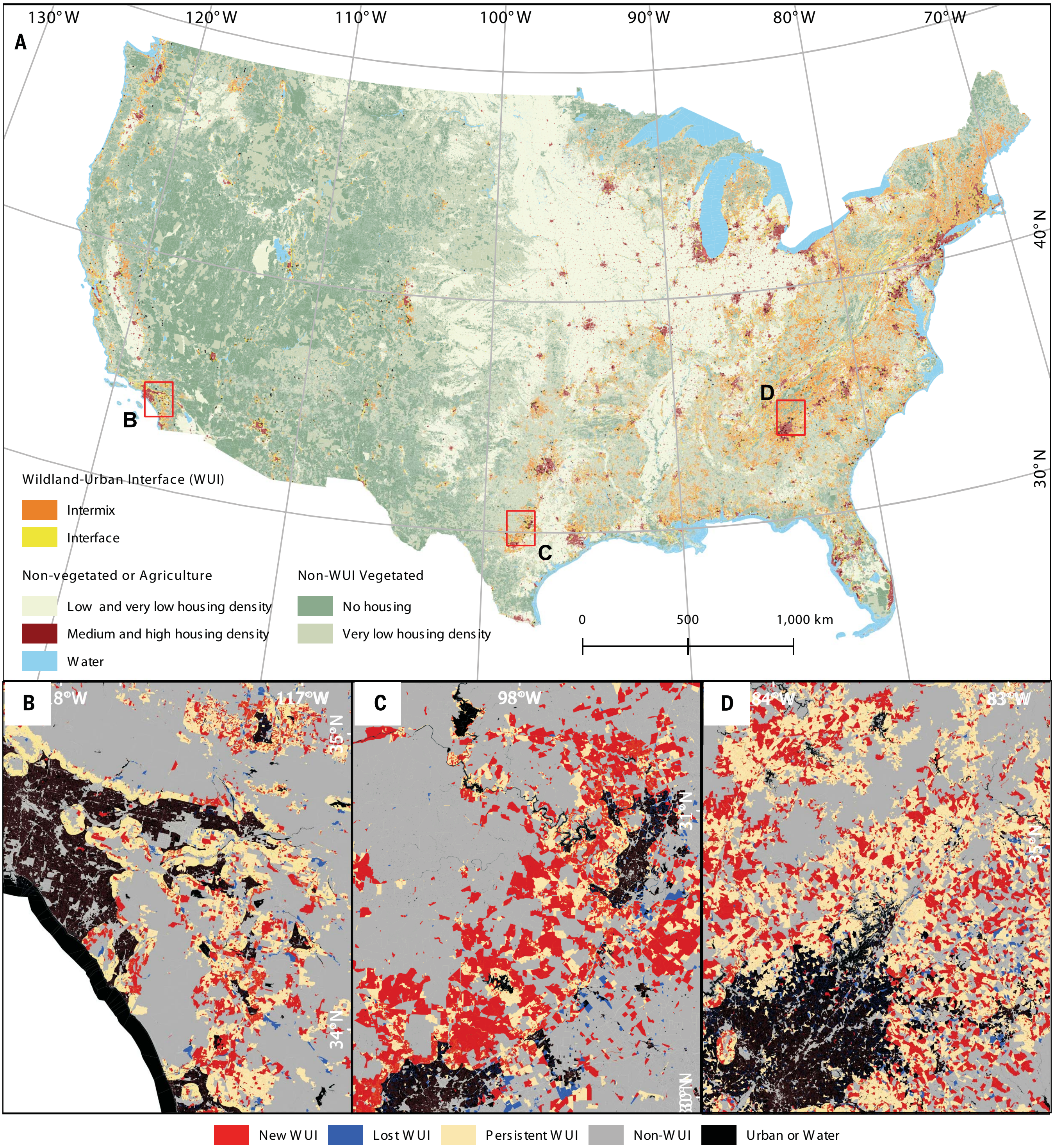

Fig. 2. The 2020 WUI and WUI change. (**A** to **D**) The WUI in 2020 across the conterminous US (A) and changes in WUI area from 1990 to 2020 near Los Angeles (B), San Antonio (C), and Atlanta (D).

and shrubland fires destroy far more homes overall because these fires are more widespread.

More houses within wildfire perimeters, both before and after fires

Over time, the number of houses within wildfire perimeters in the conterminous US more than doubled from 64,000 houses within 1990s fire perimeters, to 109,000 in the 2000s, and then to 148,000 in the 2010s. Of the houses within wildfire perimeters, three-quarters were within either the intermix or the interface WUI (74.9%), and that proportion was stable (75.2, 76.4, and 73.1% in the 1990s, 2000s, and 2010s, respectively), which highlights why the WUI is a focal area for wildfire concerns.

Increases in the number of houses exposed to wildfires can stem from either housing growth or increasing burned area. One indication of the strong effect of housing growth is that 39,000 of the 148,000 houses within 2010s

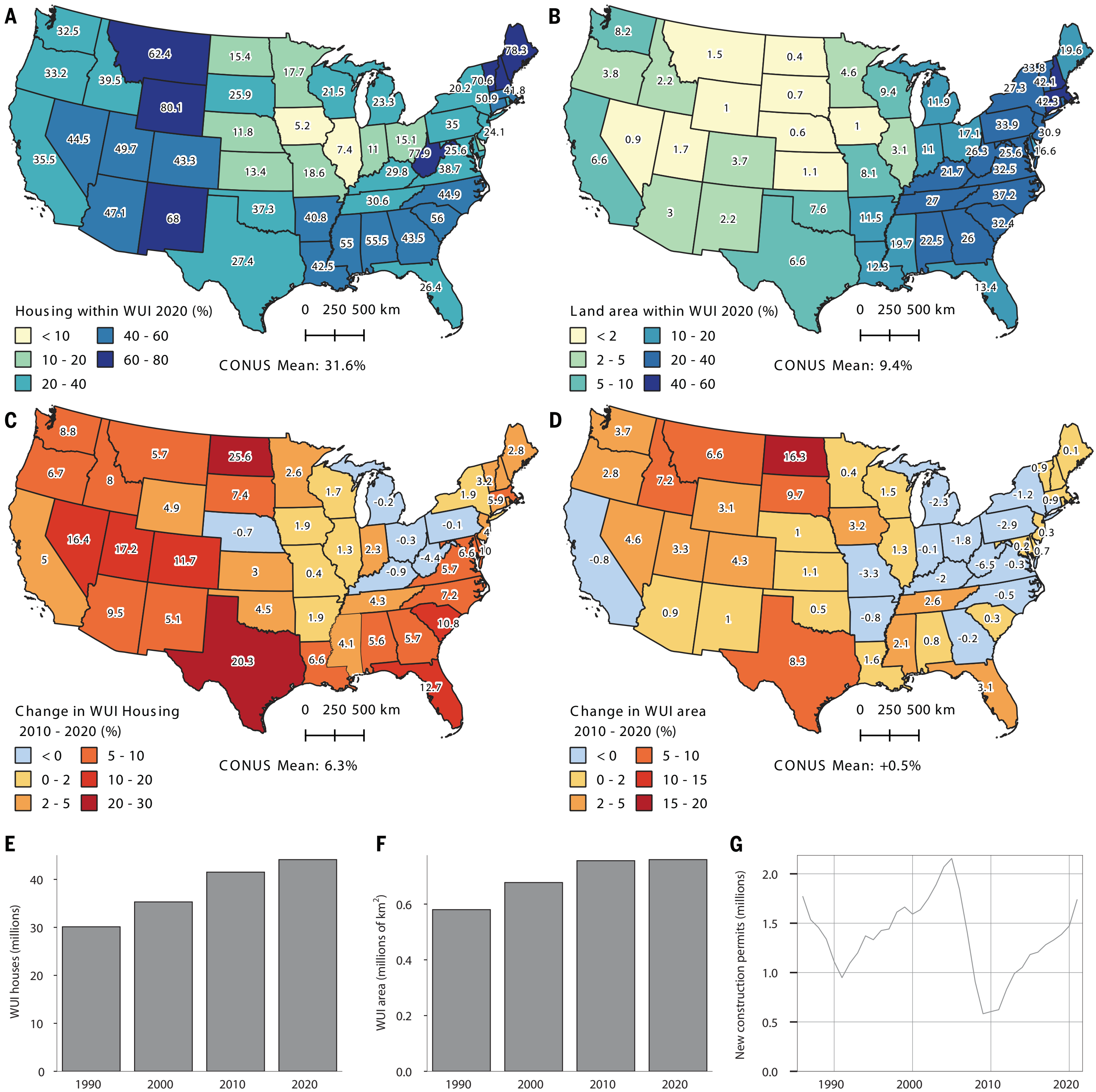

Fig. 3. The proportion of WUI and WUI change in each state and in each decade. (**A**) Proportion of houses within the WUI. (**B**) Proportion of the land area that is WUI. (**C** and **D**) Percentage growth of WUI houses (C) and WUI area from 2010 to 2020 (D). (**E**) Total numbers of WUI houses in 1990, 2000, 2010, and 2020. (**F**) WUI area in 1990, 2000, 2010, and 2020. (**G**) Number of new construction permits from 1990 to 2021. In many states, especially in the interior West and the Southeast, more than 40% of all houses are in the WUI. In the East, WUI also covers large proportions of most states. Growth in the number of WUI houses was highest in Texas and South Dakota and overall greater than growth in the amount of WUI area. WUI growth slowed after 2010, as indicated by the smaller increases in both WUI houses and WUI area from 2010 to 2020 than in prior decades. New construction permits peaked before the 2008 recession at about 2 million per year in 2004 to 2006, dropped to about 600,000 per year in 2009 and 2010, and recovered to 1.7 million in 2021. Data are provided in tables S4 and S5. CONUS, conterminous US.

wildfire perimeters were built after 1990, which is equivalent to 36% growth. However, burned area grew even more rapidly, from 114,000 to 274,000 km^2 during the 1990s and 2010s, respectively, which is equivalent to 240% growth, although most of this burned area contained few or no houses. Of the 84,000 additional houses located within 2010s fire perimeters compared with 1990s perimeters, we estimated that 47% were related to housing growth, a percentage that represents the proportion of the houses present in 2010 that were built after 1990 (see supplementary materials), and that the remaining 53% were related to increases in burned area. Overall, both housing growth and burned area increases contributed substantially to the rise in the number of houses exposed to wildfires.

The increasing number of houses exposed to wildfires has not deterred new construction in the areas that burned. Indeed, past wildfire areas had higher housing growth after wildfires than nonfire areas (120 and 33% housing growth, respectively, within the 1990s and 2000s wildfire perimeters compared with 37 and 21% growth for the conterminous US as a whole). Within 1990s burn perimeters, there were only 64,000 houses in 1990 before the fires, but by 2020, there were 142,000 houses within those same perimeters, suggesting that those past fires were not a major deterrent to new development. Similarly, within the 2000s burn perimeters, there were 109,000 houses in 2000 but 145,000 by 2020. These numbers suggest that wildfire occurrence is not discouraging development. Even if another fire is unlikely in the immediate aftermath of a wildfire because of a lack of fuel, past wildfire areas can burn again within years or decades, depending on the vegetation type.

Growth of the WUI at-large

Given strong increases in both burned area and the number of houses exposed to wildfires and given that three-quarters of all houses within wildfire perimeters are in the intermix WUI, we asked how much the WUI at-large has grown. From 1990 to 2020, the US total WUI (both interface and intermix) increased by 31% in area, and the number of total WUI houses increased by 46%, from 30 million to 44 million (Fig. 2). Across the conterminous US, there were 2.6 million more houses in the total WUI in 2020 than in 2010, and in California alone, there were 244,000 more. Furthermore, WUI growth was concentrated in the southern US. Texas added 534,000 total WUI houses during the 2010s, which is considerably more than the 336,000 added during the 1990s. As a result, by 2020, there were 44.1 million, 5.1 million, and 3.2 million houses in the total WUI in the conterminous US, California, and Texas, respectively.

However, total WUI increased more slowly in terms of both houses and area during the 2010s than in the two prior decades (Fig. 3, A to D, and figs. S1 to S5). The absolute number of additional WUI houses during the 2020s was lower by more than half (2.6 million from 2010 to 2020 versus 5.7 million per decade from 1990 to 2010; Fig. 1E), and the rate of total WUI housing growth decreased by almost two-thirds (6.3 versus 17.4%). Furthermore, there was only a very limited increase in total WUI area during the 2010s (3900 km^2; Fig. 1F) compared with 1990 to 2010 (88,000 km^2 per decade) because almost all new WUI houses were built in areas that were already WUI in 2010.

Concomitant with slower total WUI growth, the total WUI became less of a focal area for housing growth during the 2010s. The percentage of all new homes that were built in the WUI (29.9%) was lower than that in the prior two decades (38.9%). Similarly, in California, the percentage of new houses that were built in the total WUI dropped to 34.3% during the 2010s from an average of 48.3% during the prior two decades. However, this reversal was not uniform. In Texas, housing growth in the total WUI was almost double the growth in non-WUI (20.3 versus 10.6%) during the 2010s, and 93.3% of all new houses in Texas during this most recent decade were built in WUI.

One reason why total WUI growth slowed was that the 2008 housing market collapse in the US greatly limited how many houses were constructed in the subsequent decade. From a high of 2.2 million in 2005, the number of permits for new construction plummeted to 905,000 in 2008 and 583,000 in 2009, a 73% decline (Fig. 3G). However, permits for new construction have rebounded because of strong demand and high housing prices, and new construction permits are approaching their pre-2008 peak (1.7 million in 2021, or 81% of peak). Regionally, the South recovered fastest (88% of peak), which contributed to rapid total WUI growth there, and the Midwest slowest (64%). Two-thirds of all new permits are still for single-family housing units (64.2%), but that percentage is lower than it was before the recession (78% in 2005), and in the Northeast, single-family units dropped to 39.5% of new housing construction. A shift toward more multiunit housing may be one reason for slower growth in WUI area. COVID-19 may have also influenced the number of WUI homes. The US Census data that we analyzed do not capture COVID-19–related changes in housing patterns, owing to the 1 April 2020 enumeration date, but other evidence suggests that there was a substantial migration toward rural areas (*22*).

Discussion

Our results highlight that homeowners and communities in the WUI have experienced wildfires more frequently in recent years. In many WUI areas, it is not a question of whether a wildfire will occur, but when. Proactive efforts to limit the loss of lives and houses during fires are thus of paramount importance (*23*). Hardening homes, so that fewer are destroyed during a fire, is one option. Overall, only 11.3% of houses within fire perimeters burn, and the fact that most houses survive suggests that it may be possible to reduce the rate at which houses are lost even further. Building materials, landscaping, and landscape position of houses all affect which houses burn (*24*). Limiting ignitions, especially during high-wind events when fires can spread quickly, is also important, and this requires public education [e.g., Smokey Bear, (*25*)], improvements to the electrical grid, and occasional shutdowns. When fires do occur, predicting their likely direction is critical for alerting residents rapidly and managing evacuations. All of these efforts are costly, and they would need to be done continuously; however, they are proven solutions to limiting the effects of fires.

One surprising result was that grassland and shrubland fires destroyed far more houses than forest fires, mainly because so much of the WUI in the West is dominated by grasslands and shrublands. The type of vegetation in the intermix WUI determines how quickly an area can reburn, which risk-management strategies are most appropriate, and how frequently they must be applied to reduce risk (*21*). In grasslands and shrublands, very different management approaches are needed to reduce risk in the intermix WUI than in forests (*26*). Prescribed fire can be an effective fuel treatment in grasslands and shrublands; however, fire needs to be applied frequently because fuel loads recover quickly (*27*, *28*). Further, fuel reduction and prescribed fires may not be advisable in all grasslands and shrublands (*29*), especially where fire-prone invasive species have replaced native vegetation, resulting in a positive-feedback loop and increased fire frequency (*30*–*32*). In some forests, thinning to reduce fuel loads, followed by prescribed surface fires, can reduce the likelihood of crown fires and revert the negative effects of past fire suppression (*33*). However, this strategy is only suitable for those forest types that are adapted to low-intensity surface fires, such as low-elevation forests in the mountainous West, where decades of fire suppression caused fuels to build up.

Irrespective of how much the total WUI grows in the future, the 44.1 million existing houses in the total WUI in 2020 mean that WUI wildfires will remain a major problem. Some future losses of houses due to wildfires are probably unavoidable and could be planned for by assisting affected homeowners and coordinating rebuilding efforts (*34*). If a policy goal is to limit risk to newly developed houses, this could be accomplished by both stricter building standards and land-use planning to avoid construction in the areas where fires are most likely to occur (*35*). California, for example, has comprehensive building requirements, but most states do not. For existing homes in the total WUI, risk could be reduced by hardening houses and other infrastructure (*36*) and by maintaining defensible space (*21*). Wildfire awareness of homeowners, as well as community involvement and actions, can be strengthened through outreach programs such as Firewise USA (*37*). Outreach, combined with enforcement, could also reduce unwanted ignitions, which cause most of the fires that lead to home losses (*15*, *38*). At the landscape scale, vegetation management, including fuel breaks, can reduce the potential for wildfires that have high intensity or that spread rapidly. Such efforts are most successful when facilitated by agency-agency partnerships and multistakeholder collaboration (*39*).

Maintaining wildfires in ecosystems where they are a natural disturbance is an important management objective but challenging because they also pose major threats to many people, including health problems stemming from smoke, and their homes (*28*). Similarly, prescribed burning is an important tool for both fuel-load reductions and ecosystem restoration (*27*, *28*), and indigenous cultural burning fosters social restoration and helps maintain traditional knowledge and spiritual values (*40*); however, both are difficult to implement safely in WUI areas. Furthermore, although wildfires are the most pressing concern, there are many other environmental problems in the WUI. These include biodiversity loss due to habitat fragmentation, introductions of exotic species, noise and light pollution, and pets acting as subsidized predators (*41*, *42*). Similarly, the WUI is where the risk of transmission of zoonotic diseases, such as Lyme disease, is highest (*43*). WUI growth is hence a concern for a range of issues in addition to wildfires.

Our findings of high numbers of existing homes combined with rapid increases in burned areas, plus predictions for even more fires (*44*), mean that wildfire problems in the US will at least continue at present levels and likely increase. Similarly, increasing numbers of construction permits suggest that discussions about, and solutions to, wildfire risks to homes are urgently needed. Coordinated actions among homeowners, builders, communities, and public agencies alike, and a greater focus on wildfires in grasslands and shrublands, can limit loss of lives and houses.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S6
Tables S1 to S5
References (*47*–*53*)

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Rising wildfire risk to houses in the United States, especially in grasslands and shrublands

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Editor's summary
Houses built near wildland vegetation are at greater risk of burning than those farther from the wildland-urban interface, a growing problem as housing developments expand and the climate becomes warmer. Radeloff *et al*. examined how the risk to houses within wildfire perimeters has changed in the US since 1990, finding that the number of homes within the wildland-urban interface and climate change are the most important factors controlling how many homes burn (see the Policy Forum by Boomhower). The number of homes destroyed by wildfires has doubled over the past 30 years, and most of them were in grasslands and shrublands, not near forests. —H. Jesse Smith

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