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Rebuilding and new housing development after wildfire

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Abstract. The number of wildland–urban interface communities affected by wildfire is increasing, and both wildfire suppression and losses are costly. However, little is known about post-wildfire response by homeowners and communities after buildings are lost. Our goal was to characterise rebuilding and new development after wildfires across the conterminous United States. We analysed all wildfires in the conterminous USA from 2000 to 2005. We mapped 42 724 buildings, of which 34 836 were present before the fire and survived, 3604 were burned, 2403 were post-fire new development, and 1881 were burned and rebuilt. Before the fires, 38 440 buildings were present within fire perimeters (surviving plus burned). Within 5 years post-fire, there were 39 120 buildings (surviving, rebuilt and new development). Nationally, only 25% of burned homes were rebuilt within 5 years, though rates were higher in the west, the south and Kansas. New development rates inside versus outside fire perimeters were similar. That the number of buildings inside fire perimeters within 5 years post-fire was greater than pre-fire indicated that homeowners are either willing to face wildfire risks or are unaware of them; or that economic incentives to rebuild in the same place outweigh perceived risks.

Additional keywords: building digitalisation, fire perimeters, fire-adapted communities, post-wildfire community response, rebuilding patterns, wildland–urban interface.

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Introduction

Wildfires are common in many parts of the United States. Every year, large areas burn and substantial efforts are made to prevent and suppress wildfire (Gorte 2011; National Interagency Fire Center 2011*a*, 2011*b*). Although unpopulated wildlands account for the majority of the burned area, fire prevention and firefighting focus on areas where human assets and lives are in danger (Hammer *et al.* 2009). These areas of housing development intermingled with – or adjacent to – vegetated areas are called the wildland–urban interface (WUI; Radeloff *et al.* 2005). Despite protection efforts, many WUI buildings are lost every year to wildfires, and these losses entail considerable social, economic and emotional costs.

Between 1999 and 2011, an average of 1354 residences were lost to wildfire each year in the USA (National Interagency Fire Center 2011*a*), and on average US$2 billion was spent annually to suppress wildfires (National Interagency Fire Center 2011*b*, 2012; USDA Forest Service 2011*a*). In the future, residential development is expected to further increase in rural wildland areas (Brown *et al.* 2005), and wildfires may become even more common owing to climate change (Dale *et al.* 2000, 2001; Westerling *et al.* 2006), increasing the threat posed by wildfire to buildings in the WUI.

Given the high cost of protecting buildings and the likelihood of increasing wildfires in the future, homeowners and local authorities face challenging questions after a fire occurs: should buildings lost to wildfire be rebuilt? If so, should they be rebuilt in the same location? Which materials and vegetation treatments should homeowners use? A heightened perception of fire risk after a fire has occurred may discourage rebuilding, but WUI homeowners have in general widely varying attitudes, behaviours and perceptions regarding fire, making it difficult to predict how fire occurrence may affect them. Instead, the combination of a person's previous experience with fire, aesthetic preferences, and knowledge and beliefs about fire behaviour will influence the decision to rebuild (Cohn *et al.* 2008; McCaffrey *et al.* 2011). Social and economic characteristics of a WUI community also shape the homeowner's receptiveness to changing the characteristics of their buildings and surrounding landscape, their ability to carry out mitigation work, and their perceptions of risk (Collins and Bolin 2009). Hence, many factors encourage homeowners to rebuild, though rebuilding rates depend on the social and economic characteristics of the region affected (Lyons *et al.* 2010; Daly and Brassard 2011; Fillmore *et al.* 2011; Fujimi and Tatano 2012).

Rebuilding homes after wildfires is problematic, because the fact that a building has burned indicates that the site is prone to future fire risk once vegetation has regenerated (Syphard *et al.* 2012). Firewise and similar programs have worked with residents and community leaders to mitigate fire risk by managing vegetation and structural characteristics. However, the placement of a building on the landscape also affects risk, and factors such as slope and terrain are important contributors to property loss (Bar Massada *et al.* 2009; Syphard *et al.* 2012). For example, in the Witch and Guejito Fires in southern California, homes near the edges of subdivisions were more likely to be destroyed by fire than those in the centre, even when Firewise practices were used, and more than half of the buildings on properties with slopes greater than 20% were destroyed or damaged (Maranghides *et al.* 2013). Unfortunately, although building materials and landscaping can make the rebuilt home more defensible and less likely to burn, its position on the landscape is not easily altered once a building is in place, and even when rebuilding, the option to build in a less fire-prone location within the lot is available only to those homeowners who have large lots. This is why it is important to understand how building location affects risk, because the fire risk related to location (e.g. slope and elevation) cannot be changed after a building is sited.

Wildfire is not the only disaster that destroys homes, and rebuilding patterns after other natural disasters suggests that homeowners commonly rebuild (Ingram *et al.* 2006; Fillmore *et al.* 2011). Prior research on post-disaster rebuilding has focussed on hurricanes and earthquakes that destroy extensive areas and multiple communities. Studies show recovery follows a process, where typically: (1) rebuilding occurs on the same site; (2) the availability of large external sources, innovative leadership, existence of prior plans, community consensus and wide dissemination of information speed rebuilding; (3) ongoing urban trends (e.g. housing growth) accelerate after the disaster; (4) the recovery process is not egalitarian; and (5) comprehensive replanning is rare (Haas *et al.* 1977; Olshansky 2005).

Rebuilding after fire may share some of these characteristics. Homeowners who are attached to their lot, lifestyle and community are motivated to rebuild in the same location (Cutter *et al.* 2008; Norris *et al.* 2008; Mockrin *et al.* 2014). Various federal loans and grants are available to help communities rebuild or repair essential services and facilities (e.g. water, sewage treatment, communications), and although homeowners bear the burden for rebuilding private residences, they may receive insurance payments to cover much of the cost. In addition, local governments may facilitate the process of issuing permits (Mockrin *et al.* 2014) and ease regulations both to assist homeowners and to re-establish their property tax base (Becker 2009). Local governments lose tax revenues if homeowners move and their lot is not rebuilt on (Becker 2009), which is why local governments are inclined to assist homeowners to rebuild (Mockrin *et al.* 2014).

The broader post-disaster recovery literature provides a basis for our research, but fires are somewhat different, in that they tend to destroy only a small fraction of all the homes within a fire perimeter. However, in a given neighbourhood, a large portion of homes can burn, as was the case in Majestic Drive and Courtney Court communities within the Waldo Canyon fire in Colorado, 2012. More information about post-fire rebuilding is needed, as Federal and local fire managers shift emphasis away from expectations of fire suppression towards communities becoming more fire-adapted (see www.fireadapted.org, verified 10 July 2014). Understanding the rebuilding process can help clarify what role local and state governments play in wildfire regulation and policy, specifically regarding residential construction and reconstruction. Information on rebuilding patterns needs to be region-specific to accommodate ecological and economic differences (Agee 1993; Busenberg 2004), but also because states, counties and municipalities have different building codes, some of which were changed after major fire events. For example, in Boulder, Colorado, new building codes were adopted after the Black Tiger fire (1989, 850 ha) to reduce wildfire damage (DORA 2010).

In terms of the ecological differences in fire regimes, these are strongly related to landscape characteristics (vegetation, fuel load, topography), climate and weather conditions (Flatley *et al.* 2011). Ecoregions encompass areas with similar characteristics with regard to geology, physiography, vegetation, climate, soils, land use, wildfire and hydrology, and are critical for structuring and implementing ecosystem management strategies (Omernik 1987; McMahon *et al.* 2001). Ecoregions also represent the ecological environment to which homeowners or their communities must adapt. Examining patterns of loss and rebuilding across ecoregions can reveal variations in post-fire adaptive response; regions with fire intervals of 100 years or more, such as Northern Hardwoods in Maine (Lorimer 1977) or the Great Lakes Region (Cardille and Ventura 2001; Sturtevant and Cleland 2007), may exhibit very different patterns than regions with short fire-return intervals where future risk is higher. Similarly, social institutions vary markedly by state and county, including regulations regarding development before and after wildfires. Such social factors can eclipse the effects of ecological patterns, and if that is the case, then rebuilding patterns will be strongly related to political boundaries. For this reason, we examined rebuilding rates also at the state and county levels. Because information on buildings' presence, absence, loss and reconstruction is not part of fire (or any other public) records, it has not been possible to analyse post-fire recovery. We turned to a new resource, satellite images compiled by Google, to fill this information gap, developing protocols to extract and analyse these data.

Our goal was to characterise the pattern of buildings destroyed by wildfire, and the rebuilding and new development patterns across the conterminous United States for all fires that occurred from 2000 to 2005. Our specific objectives were to:

- Assess rebuilding rates across the conterminous USA, at the fire and county, state and ecoregion levels
- Compare rebuilding rates with rates of new development at each of the three levels of analysis
- Compare the rate of new housing development within fire perimeters with the rate of new housing development in the surrounding county.

Fig. 1. Example of a building rebuilt after a fire in 2003 in Colorado. From left to right: 2000, 2003, 2005.

By answering these questions, we identify when and where homeowners decide to rebuild or build new houses in areas that suffered a wildfire. We provide the information on rebuilding and new construction after wildfires for the years 2000 to 2005, and this information can assist national fire policy development and local land-use planning, because future rates of rebuilding and new development within fire perimeters are likely to be similar to those in the first decade of the 2000s.

Material and methods

Data collection

We identified all burned and rebuilt buildings within 2000–05 fire perimeters from the Monitoring Trends in Burn Severity (MTBS, www.mtbs.gov, verified 10 July 2014) dataset, across the conterminous USA, using Google Earth (www.google.com/earth, verified 10 July 2014) imagery. We chose the 2000–05 time frame because it contains the housing boom peak (Weller 2006; Haughwout *et al.* 2012), and because satellite imagery from this period that was available from Google Earth was of high enough resolution to assess whether or not a building was burned by fire. The MTBS project provides consistent, 30-m-resolution burn-severity data and fire perimeters (USDA Forest Service 2011*b*). We used the National MTBS Burned Area Boundaries, downloaded in September 2011 using the ESRI Shapefile/Metadata option. We analysed the fire perimeters in a geographic information system (ArcGIS 10, ESRI 2011) and intersected them with 2010 US decennial census block-level housing density data (www.silvis.forest.wisc.edu, verified 10 July 2014), adjusted for public land boundaries (Radeloff *et al.* 2010), to exclude fires that did not contain any buildings within their perimeters. Out of a total of 4078 fire perimeters from 2000 to 2005, 2318 had a housing density greater than zero.

We use the term 'building' (instead of 'home' or 'house') because we could not distinguish between houses, barns and sheds in the Google Earth images. However, we were able to distinguish buildings from other structures such as roads, antennas and bridges, and that is why we did not use the more generic term 'structures'.

For each fire perimeter, we digitised: (1) each building within the fire perimeter that was present before the fire and that was not burned to the ground, i.e. a surviving building; (2) each building burned to the ground; (3) each building rebuilt within 5 years after the fire; (4) new buildings built within 5 years after the fire; and (5) buildings present in the images, but for which either the time between images in Google Earth was too long, or the resolution of the images too coarse to determine the origin or fate of the building (called 'unknown'). We could not distinguish damaged from undamaged buildings using satellite images, except when the building burnt to the ground, (see Fig. 1). Hereafter, 'burned building' refers to those that burned to the ground, and we acknowledge that some surviving buildings may have sustained damage in the fire.

Data were collected between September 2011 and December 2012 by four people. The lead author conducted training and frequently checked for errors, both visually and by comparison with ancillary data. Google Earth imagery came from different sources (e.g. LANDSAT, SPOT Image, GeoEye-1, IKONOS) and presented several challenges. When using the historical imagery tool and going backward and forward in time, there were spatial shifts in the images of up to several metres. To overcome this problem, we analysed images in a chronosequence with the fire-year period as the central point of reference. Depending on the best image available after the fire, we always digitised on the same image to avoid spatial shifts. To determine if a building was rebuilt, we analysed all the available images up to 5 years after the fire event and we assumed that the building was rebuilt in the earliest year for which it was present in imagery. For example: a fire destroyed a home in 2002, and then there was a new home in the same location depicted in an image from 2004. In this case, we labelled the building as 'rebuilt', because it was rebuilt within 5 years. However, if the first images in which a new building was present dated from 2008, then we did not digitise the new building, because more than 5 years had passed.

Another issue that we encountered was that there was sometimes a gap of several years between images. For example, for some of the earlier fires (in 2000 and 2001), the pre-fire image was recorded as early as 1992 or 1994, and the post-fire image was from 2003 or later. If a building occurred only in the 2003 images, we digitised the building and labelled it as 'unknown' because the image dates made it impossible to discern whether the building had been built before the fire (and survived it) or whether it represented new development. In total, these 'unknown' buildings (3185) represented only 7% of all the buildings we digitised. Further, this problem disappeared from 2002 onwards because the image records in Google Earth were much more complete thereafter.

Table 1. Buildings digitised using Google Earth, by type and by fire
Only the 106 fires that contained at least one building were included in this analysis

Year	2000	2001	2002	2003	2004	2005	Total
Total buildings before fire	3309	5896	3560	13 240	2482	9953	38 440
Surviving buildings	3212	5870	3457	10 536	2415	9346	34 836
Burned buildings	97	26	103	2704	67	607	3604
Rebuilt buildings[A]	6	2	26	1726	22	99	1881
New buildings	46	38	69	1131	91	1028	2403
Total buildings after fire	3264	5910	3552	13 393	2528	10 473	39 120
Housing types by fire ($n = 106$)							
New buildings	4	0	32	1112	19	618	1785
Surviving buildings	747	346	1365	9035	976	6194	18 663
Burned buildings (%)	46.5	32.0	16.1	33.2	23.6	13.5	23.6
Rebuilt buildings (%)	2.9	5.0	25.0	34.8	19.9	10.2	14.7
New buildings (%)	3.9	0.0	0.9	6.3	5.5	10.8	6.9
Total area (ha)	127 519	6343	179 396	315 079	36 740	438 853	1 103 930

[A]Buildings rebuilt within 5 years after the fire occurred, i.e. for a 2001 fire, by 2006; for a 2004 fire, by 2009.

Table 2. Number of fires that contained buildings by year and type of building

Year	2000	2001	2002	2003	2004	2005	Total
Number of fire perimeters	573	375	306	345	245	474	2318
Building type							
Any	228	168	119	114	93	209	931
Surviving	195	160	114	109	87	205	870
Burned	17	5	12	13	13	46	106
Rebuilt	2	1	4	9	6	17	39
New	6	4	3	8	16	93	130
Mean fire area (ha)	6858	2136	7898	6906	2148	6201	5527
Max. fire area (ha)	132 357	31 099	198 297	116 845	17 320	128 586	198 297

Data analysis

We used the total number of surviving plus burned buildings as the denominator when calculating the percentage of both burned and new buildings, because this is the total number of buildings that were within the fire perimeter at the time of the fire (Eqns 1 and 2). To calculate percentage rebuilt, we divided the number of rebuilt buildings by the number of burned buildings within the fire (Eqn 3).

$$\%\ Burned = \frac{Burned\ buildings}{Surviving + Burned} \tag{1}$$

$$\%\ New = \frac{New\ buildings}{Surviving + Burned} \tag{2}$$

$$\%\ Rebuilt = \frac{Rebuilt\ buildings}{Burned\ structures} \tag{3}$$

In order to compare the new development rates inside and outside fire perimeters, we compared post-fire development rates with county-level data on housing growth from the 2000 and 2010 US decennial census (United States Census Bureau 2001, 2011). For each fire where we recorded new development, we calculated an annual development rate based on the total number of new buildings inside the fire perimeter, divided first by the fire area, and second by the number of years that had elapsed since the fire, resulting in the number of buildings built per year per km^2. When a fire spanned multiple counties, then we compared the within-fire-perimeter development rate with the development rate for the county that contained the majority of the fire's area. The county's development rate was based on the difference between the total number of housing units in 2000 and 2010, minus the number of buildings inside the fire perimeter, divided by the county area and by 10 years. We then compared annual development rates inside and outside the fire perimeters, to determine the difference. Differences $\geq |0.1|$ (new buildings per km^2) were considered different rates of development. Because we analysed all the fires that occurred during our time frame (a complete enumeration and not a sample), we did not test for statistical significance in differences.

Results

Of the selected 2318 fires that occurred between 2000 and 2005 across the 48 contiguous states, 931 contained buildings, and 106 contained buildings that burned to the ground. We analysed a total of 42 724 buildings, of which 3604 were burned, 1881 were rebuilt within 5 years of the fire, and 34 836 survived (Table 1). Concomitantly, 2403 new buildings were built inside the fire perimeters within 5 years of the fire. This means that there were more buildings within fire perimeters 5 years after the

Table 3. Summary of buildings within fire perimeters by fire year

Percentages were calculated using the totals for each year; example: number of fire perimeters in 2000 = 573, fire perimeters that had any kind of buildings in 2000 = 228, percentage = 39.8%. Percentage rebuilt was calculated using the number of rebuilt buildings in a year divided by the number of burned buildings in that year. Percentage new was calculated using the number of new buildings in a year divided by the sum of surviving and burned buildings. Percentage unknown was calculated using the number of new buildings in a year divided by the sum of surviving and burned buildings

	2000	2001	2002	2003	2004	2005	Total
Fires with buildings within their perimeter (%)	39.8	44.8	38.9	33.0	38.0	44.1	40.2
Burned buildings (%)	2.9	0.4	2.9	20.4	2.7	6.1	5.9
Rebuilt buildings (%)	6.2	7.7	25.2	63.8	32.8	16.3	25.3
Buildings newly built (%)	1.4	0.6	1.9	8.5	3.7	10.3	4.4

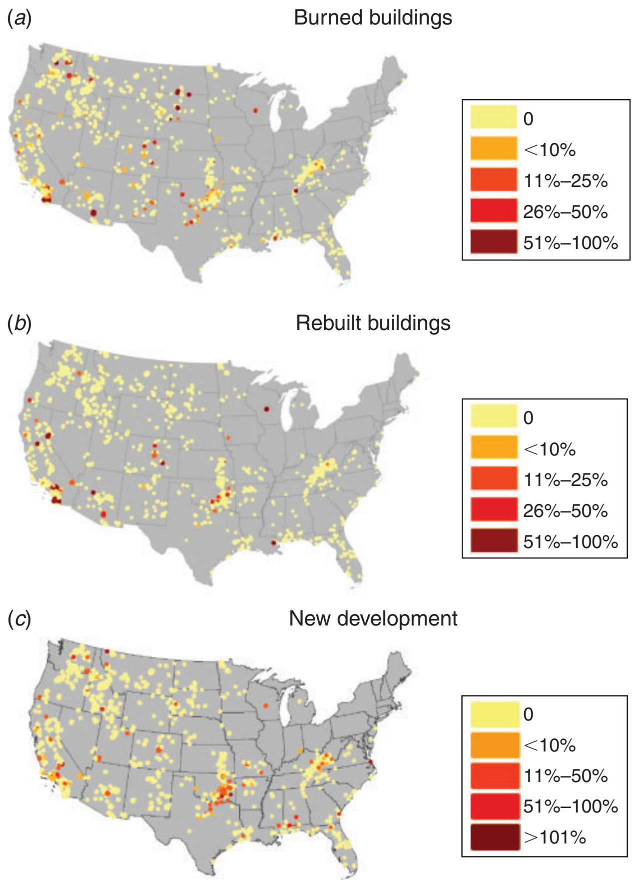

Fig. 2. Fires that occurred between 2000 and 2005 and the respective percentages of (*a*) burned buildings; (*b*) rebuilt buildings; and (*c*) new development within the fire perimeters.

fire than before, and that by the 5-year post-fire anniversary, the number of new buildings within the fire perimeters was greater than the number of rebuilt buildings (Table 1).

Among the fires for which census data indicated a potential presence of buildings (2318), 40% contained buildings within their perimeters (931 of 2318). Among the fires with buildings, 11% (106 of 931) contained buildings that burned to the ground, and 4% (39) contained buildings that were rebuilt (Table 2). However, post-fire new development was more common, occurring in 14% (130) of fires (Table 2). We found a moderate correlation (Spearman's correlation $r = 0.514$) between fire size and the number of buildings lost.

Overall, the percentage of burned buildings relative to all buildings within fire perimeters was low, and so were rebuilding percentages. Over the 6-year study period, the percentage of burned buildings within fire perimeters ranged from 0.4 to 20.4% per year (average of 5.9%, Table 3). For each fire year, the percentage of buildings rebuilt within 5 years varied from 6.2 to 63.8% (average of 25.3%, Table 3). The percentage of new buildings within fire perimeters also varied among years from 1.4 to 10.3% (average of 4.4%, Table 3). Interannual variation was very high partly because 2003 was a severe fire year with an exceptionally large number of fires. The number of burned buildings in 2003 was an order of magnitude larger than for all other years combined (20.4% of burned buildings), and 2003 had the highest rebuilding rate (63.8%) (Table 3).

Analysing our data at the level of individual fires, there were only 10 fires that burned all of the buildings within their perimeter during the 6-year period that we studied, and those fires contained only two to five buildings each. For each fire year, the rate of rebuilding varied considerably, with 2003 being a unique year, especially in California, in that rebuilding rates were very high. However, even in 2003, there was not one fire perimeter in California within which all buildings were rebuilt. Colorado, Kansas, Louisiana and Arizona each had one fire perimeter within which all buildings were rebuilt, but in those four fires, the total number of burned buildings ranged from one to four. Indeed, only 11.3% of all fires that burned buildings had a rebuilding rate >50% (12 out of 106 fires).

Buildings lost to wildfires were concentrated in the western and central states (Fig. 2*a*). However, fires that burned more than 25% of the buildings within their perimeters occurred mainly in the Central Great Plains, Pacific north-west and south-western states (Fig. 2*a*). High rebuilding rates often coincided with high percentages of burned buildings, and such fires were concentrated in California, Texas and Oklahoma (Fig. 2*b*). Rates of new development inside the fire perimeters had no particular geographic patterns (Fig. 2*c*).

Summarising data by state, California was the top-ranked state in terms of the number of buildings within fire perimeters, and of burned, rebuilt and new buildings (Fig. 3*a*, *c*, *e*, *g*). After California, Texas, Arizona and Washington had the highest number of burned buildings (Fig. 3*a*). However, California, Arizona and Wisconsin had the highest percentages of burned buildings (Fig. 3*b*). Rebuilding rates were low in general (less than

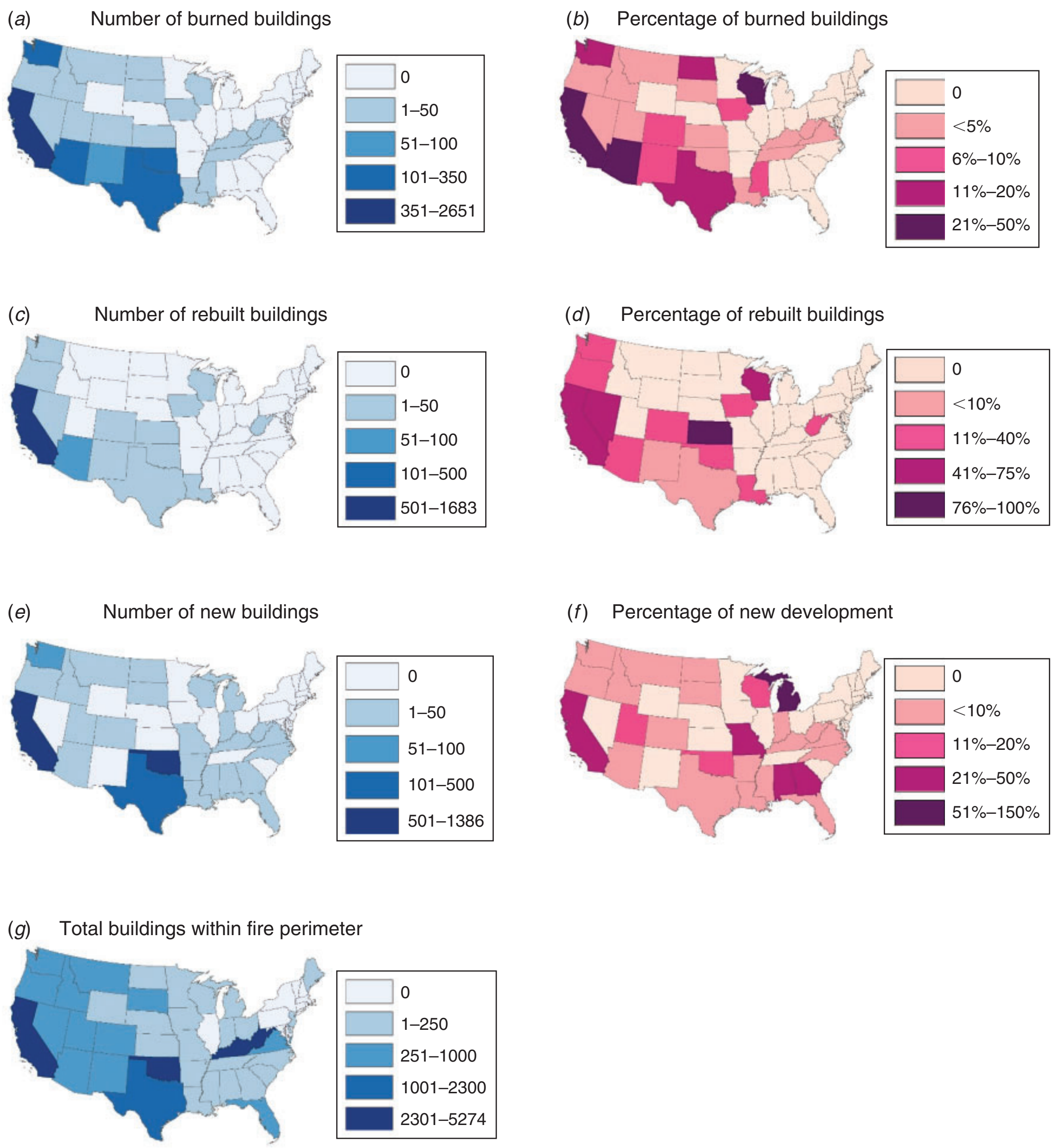

Fig. 3. Summary data for fires that occurred between 2000 and 2005 of (*a*) burned buildings; (*b*) percentage of burned buildings; (*c*) rebuilt buildings; (*d*) percentage of rebuilt buildings; (*e*) new buildings; (*f*) percentage of new buildings; and (*g*) total number of buildings within states.

40% in 10 states) but highest in Kansas, followed by California, Nevada and Wisconsin (Fig. 3*d*). The greatest numbers of rebuilt buildings were in California and Arizona (Fig. 3*c*). Finally, the greatest number of new buildings were built in California, Oklahoma and Texas (Fig. 3*e*), but rates of new housing development were highest in Michigan, followed by California, Missouri, Georgia and Alabama (Fig. 3*f*). Oklahoma, Kentucky and West Virginia also had a high total number of buildings (surviving plus burned buildings) within fire perimeters (Fig. 3*g*).

Variability among ecoregions was also high (Fig. 4*a*). The ecoregions with the most buildings within fire perimeters (surviving plus burned) were the Ozark, Ouachita–Appalachian Forests and Mediterranean California (Fig. 4*h*). Mediterranean California had the most burned buildings, followed by the South Central Semiarid Prairies, and the Western Cordillera (Fig. 4*b*). In terms of percentage of burned buildings, Mediterranean California was highest, followed by Western Sierra Madre Piedmont and the Mixed Wood Plains (Fig. 4*c*). Although rebuilding numbers were low, Mediterranean California had the most rebuilt buildings (Fig. 4*d*), and together with the Mixed Wood Plains the highest rebuilding rates (Fig. 4*e*). The most new buildings were in Mediterranean California and the Ozark,

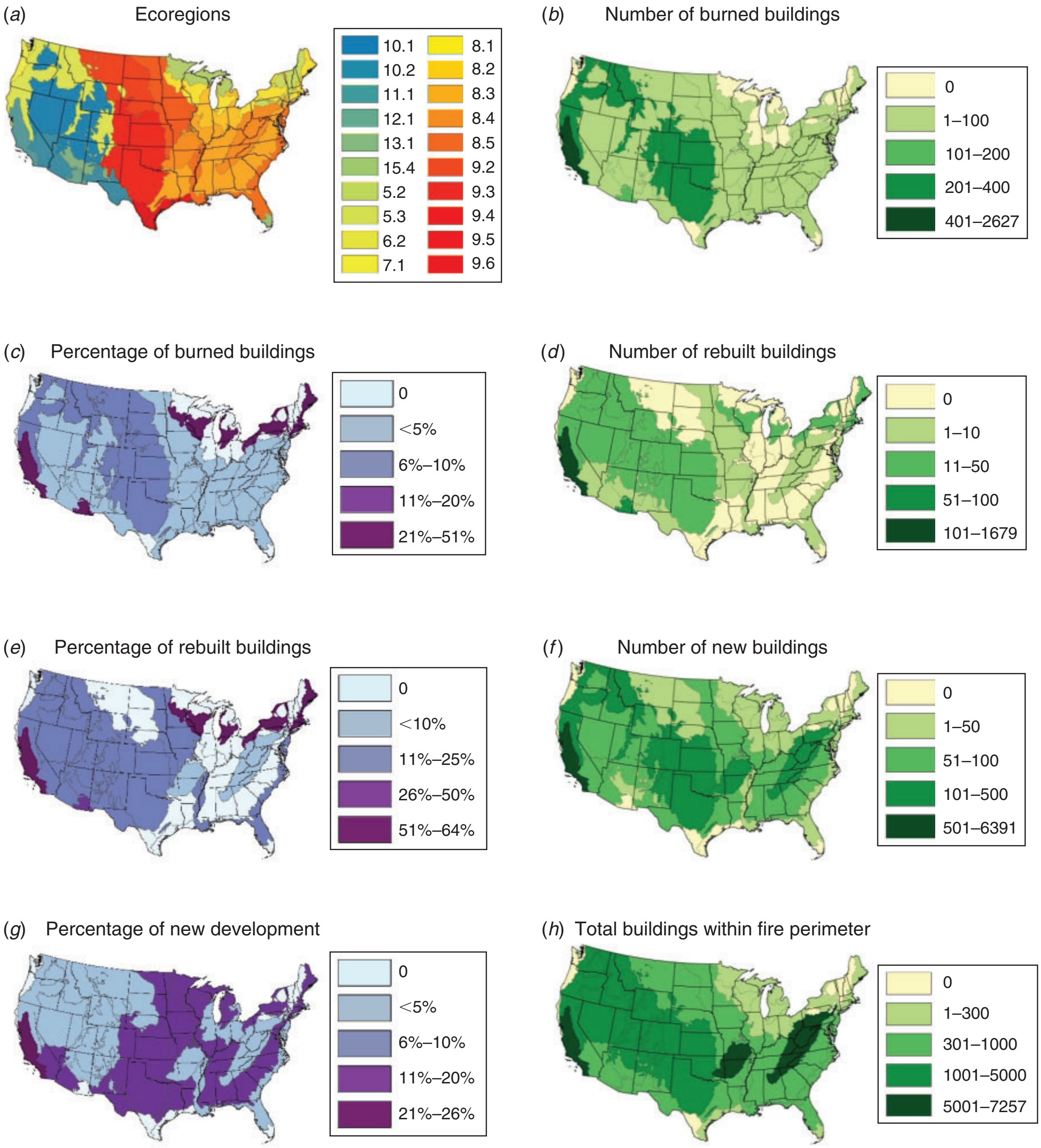

Fig. 4. (*a*) Map of Bailey's ecoregions for the USA (legend:10.1 Cold Deserts; 10.2 Warm Deserts; 11.1 Mediterranean California; 12.1 Western Sierra Madre Piedmont; 13.1 Upper Gila Mountains; 15.4 Everglades; 5.2 Mixed Wood Shield; 5.3 Atlantic Highlands; 6.2 Western Cordillera; 7.1 Marine West Coast Forest; 8.1 Mixed Wood Plains; 8.2 Central US Plains; 8.3 South-eastern US Plains; 8.4 Ozark, Ouachita–Appalachian Forests; 8.5 Mississippi Alluvial and South-east US Coastal Plains; 9.2 Temperate Prairies; 9.3 West Central Semiarid Prairies; 9.4 South Central Semiarid Prairies; 9.5 Texas–Louisiana Coastal Plain; 9.6 Tamaulipas–Texas Semiarid Plain), and summary data for fires that occurred between 2000 and 2005 of (*b*) burned buildings; (*c*) percentage of burned buildings; (*d*) rebuilt buildings; (*e*) percentage of rebuilt buildings; (*f*) new buildings; (*g*) percentage of new buildings; and (*h*) total number of buildings within ecoregions.

Ouachita–Appalachian Forests (Fig. 4*f*). Mediterranean California had the highest rate of new development within fire perimeters (25% new buildings on average within 5 years after a fire; Fig. 4*g*).

We compared annualised rates of housing growth for our study period (2000–05) within the fire perimeters with the housing growth rates within the counties where fires occurred from 2000 to 2010 (census count of housing units in 2010 – housing units in 2000, divided by 10). We found that fire and county growth rates were similar (Fig. 5), and only very few counties experienced a decrease in total housing units. Of all the fire perimeters, 29% had higher development rates and 25% had

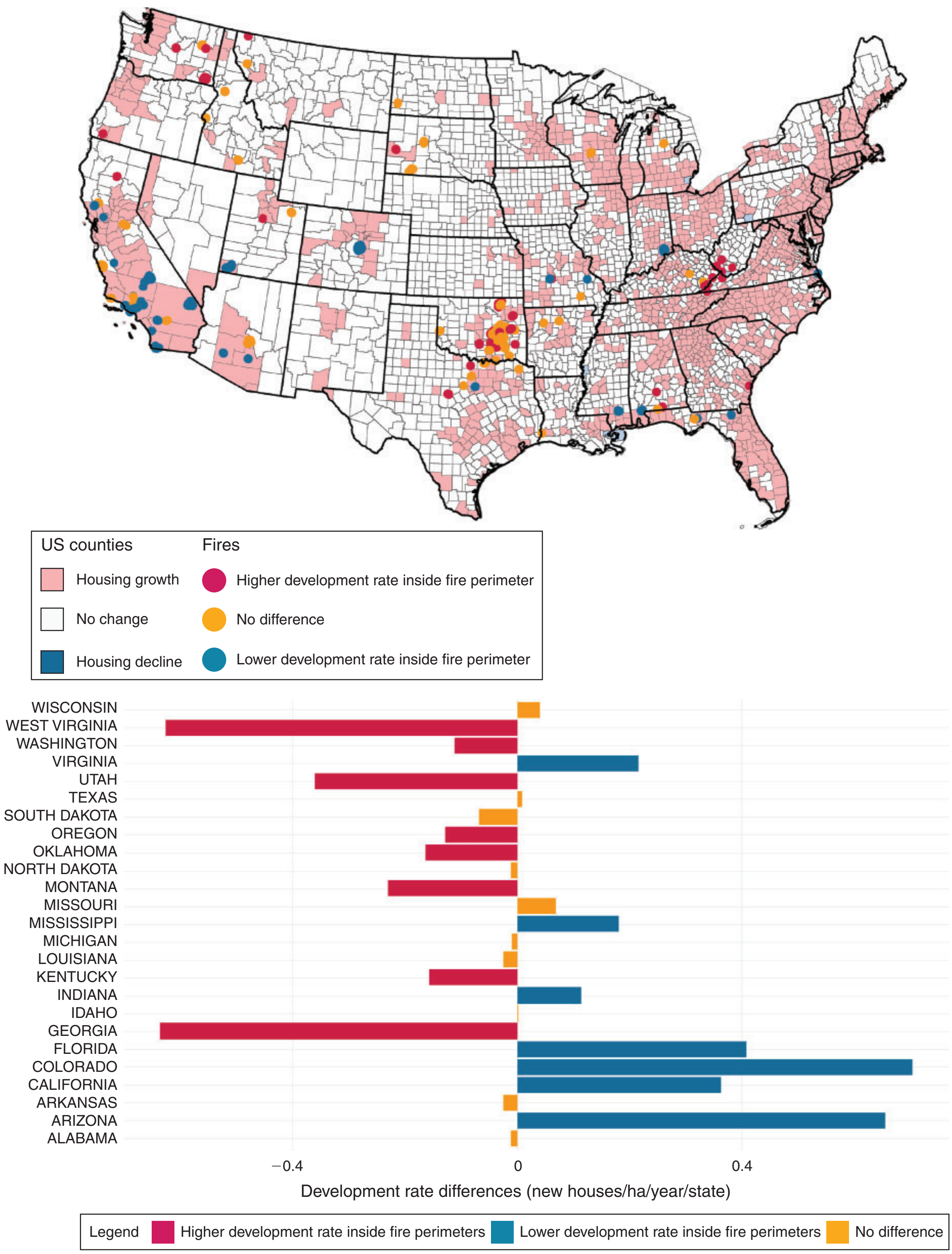

Fig. 5. Development rates within and outside fire perimeters 2000–05, and housing growth by county for the whole USA, 2000–10. Bar plot shows states where fires occurred and if the average development rate was higher or lower inside the fire perimeters for that state.

lower development rates than the surrounding county. The majority of fires (46%) had similar housing development rates to their surrounding county (difference between inside and outside rates between -0.1 and 0.1 new buildings/km^2/year). In Kentucky and West Virginia, even though the surrounding counties experienced housing declines, the number of buildings within those fire perimeters increased. By contrast, California, Arizona, Colorado, Wisconsin and most of Utah experienced lower development rates within fire perimeters than their surrounding counties (Fig. 5).

Discussion

The main goal of our study was to characterise rebuilding and new development patterns after wildfire across the conterminous United States. The fact that buildings are frequently located in fire-prone areas is a key aspect of the US wildfire problem (Syphard *et al.* 2009), partly because there is a positive feedback loop in that home ignitions increase as more people build near wildland vegetation (Syphard *et al.* 2012). The homeowners' response to losing their home, and whether they decide to move, rebuild, or even preferentially build new homes in burned areas, is thus an important question for fire policy and management.

One current national-level policy emphasis is on creating fire-adapted communities, where fire is expected to occur and communities are configured to survive fire (Winter *et al.* 2009; McCaffrey *et al.* 2013). If communities are to become 'adapted' to fire, they must respond to the occurrence of fire, and choosing not to rebuild a burned home is one possible adaptive response. Our results showed that rebuilding was limited, and we found more new development than rebuilding. Concomitant with these national-level efforts are local-level changes in building codes that have often been adopted in response to major wildfires. Examples of fires that prompted communities to adopt fire-related building codes include the Black Tiger Fire in Colorado in 1989 (DORA 2010) and the Cedar Fire in San Diego, California, in 2003, after which existing codes were refined (http://www.amlegal.com/sandiego_county_ca/, verified 10 July 2014). Changes in the codes included both building construction requirements, such as the use of non-combustible, ignition-resistant materials in exterior walls, and fuel modification requirements, such as keeping the area within 15 m (50 feet) of any structure cleared or planted with fire-resistant plants, and reducing fuels within at least 30 m (100 feet) from buildings (http://www.sdcounty.ca.gov/pds/docs/pds664.pdf, verified 10 July 2014). However, none of the building codes changes are retroactive, meaning that the buildings already in place would remain at risk of being lost in a wildfire.

Ecoregions provide a proxy for vegetation, soils and climate (Bailey 2004), which in turn influence fire regimes (Bond and Keeley 2005). In our analysis, the Mediterranean ecoregion stood out as the area where a particularly large number of homes were lost, and fires were frequent. The Mediterranean ecoregion contains unique ecosystems because of the combination of dry summers (typical of this climate), strong winds and heat waves, together with a high human development pressure that contributes to a higher ignition probability (Vannière *et al.* 2010). Vegetation in the Mediterranean ecoregion evolved together with fire to a point where it is now fire-dependent (Keeley and Fotheringham 2003; Montenegro *et al.* 2004; Goforth and Minnich 2007). However, the Mediterranean ecoregion is also the region where past housing and population growth have been particularly rapid, growth is projected to continue in coming decades (Hammer *et al.* 2009; United States Census Bureau 2011), and fire is projected to increase both in frequency and intensity owing to climate change (Dale *et al.* 2000, 2001; Running 2006). A high demand for residential building sites to house a growing population provides incentive for rebuilding and for new development, but the risk of another loss due to fire is a disincentive. Despite this disincentive, our results showed that the occurrence of fire did not depress housing construction, and both rebuilding and new development rates within the fire perimeters were highest in the Mediterranean ecoregion. This suggests that either homeowners were not aware of fire risk, or that a combination of non-ecological factors such as local regulations, personal experience, regional cultures and insurance policies were more important determinants for people's response to wildfires that the fire patterns themselves.

Our results highlighted the importance of understanding fire damage and rebuilding in grassland or prairie ecoregions. In the Great Plains and Prairies (e.g. Oklahoma, Texas), a high number of buildings were burned. Similarly, in California, a large percentage of structures lost to wildfires are in low fuel-volume grassland areas, which tend to burn quickly and then carry fire into shrublands or woodlands (Syphard *et al.* 2012). These shrublands and woodlands, in turn, have a higher ability to produce embers and firebrands, which are a major cause of structure ignition (Cohen 2000; Blanchi *et al.* 2011; Graham *et al.* 2012). A common perception of surface fires is that they do not pose as large a danger as crown fires. However, buildings are often lost to surface fires and, therefore, risk from surface fire should be taken into consideration when developing land-use policies or helping communities adapt to fire in the Great Plains and Prairies. Indeed, the number of new buildings built after fires within their perimeters was high (between 100 and 500) in the Plains states. This may indicate that people are underestimating the risk of wildfire, maybe perceiving low risk because the vegetation was burned and there is no fuel for a subsequent fire in the short term (Rowe and Wright 2001; Brewer *et al.* 2004; Champ *et al.* 2013).

Our use of Google Earth imagery to map rebuilding patterns was a novel approach but it was not without limitations. First, the number of available images varied from region to region and there were gaps of 1 or more years between available images in some areas. This meant that in some situations it was not possible to determine a precise date of rebuilding. Second, we were only able to identify buildings that burned to the ground. Our count of buildings lost to fire excludes the many buildings that are partially damaged by the fire itself, or by smoke. Nonetheless, the dataset that we derived from Google Earth images is unique, and our mapping approach could be useful for other studies as well.

Another caveat of our study is that new development needs to be interpreted in the context of the housing construction boom, which peaked in 2005 (Weller 2006; Haughwout *et al.* 2012), the last year of our study. Housing construction started to decline after 2005, but many buildings were still being built in subsequent years. Our image analysis covered up to 5 years after a fire (i.e. new development up to 2010). However, even during this period of rapid housing growth, we saw low to moderate rebuilding rates, and across the USA, the rate of development inside fire perimeters was similar to housing development in the county at large (Fig. 5). The base rate of development also differed substantially across the country. In California, development rates were generally very high, whereas the border area of Kentucky, Virginia and West Virginia witnessed little to no growth in housing. In summary, there were no clear patterns for new development after wildfires across the USA. Patterns differed by fire, and some mix of local, social, ecological and political characteristics appeared to have determined the outcome.

Conclusions

The combination of housing growth in the WUI (Stewart *et al.* 2007; Radeloff *et al.* 2010) and climate change is likely to increase the frequency and intensity of wildfires in many WUI areas. This means that despite fire prevention and suppression efforts, the rate at which buildings are destroyed by wildfire will rise, unless there are substantial changes in homeowner preferences resulting in changes in housing growth patterns (Nelson 2013). Information on rebuilding and new development is important in order to anticipate future needs for fire management in the WUI, and to gain a deeper understanding of homeowner attitudes towards fire and perceptions of risk.

Although community adaptation to wildfire is widely discussed, few suggestions have been put forward to evaluate such adaptations, in part because adaptation can take many forms. For example, rebuilding with fire-resistant materials and following defensible space (e.g. Firewise) directives to keep the home ignition zone clean is one form of adaptation, while not rebuilding in the same place would be another adaptation as building location greatly affects fire risk (Gibbons *et al.* 2012; Syphard *et al.* 2012). The fact that we found generally low rebuilding rates may thus indicate that people are adapting to fire by choosing not to rebuild. However, high rates of new development suggest the opposite and support the notion that homeowners are not aware of fire risk, or that amenities and other considerations outweigh the risk (Donovan *et al.* 2007).

Although overall rebuilding rates were low, regional variability was high, suggesting that it is difficult to predict rebuilding responses to any individual fire. In general, we found little evidence though that homeowners or communities adapted to fire by changing the locations of buildings, or by lowering rates of new development after the fire. Given how much a home's position on the landscape determines its fire risk (Gibbons *et al.* 2012; Syphard *et al.* 2012), rebuilding in the same location may expose the home to future fire risk once the vegetation has recovered. Rebuilding in the same location thus represents a missed opportunity to adapt to wildfire.

Clarifying where and how much rebuilding occurs provides essential information for all of those involved with planning for future fires, and suggests that people will continue living in that area despite the occurrence of fire events. The insights that our study provide regarding new development within fire perimeters is important for WUI communities considering fire-specific planning, zoning, codes and infrastructures. The prevalence of new development inside fire perimeters within 5 years of a fire suggests that a proactive approach to fire policy is essential, because while the community is recovering from fire, development pressure will continue and may exacerbate future fire problems.

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