CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2007, **16**, 255–265

Wildland–urban interface housing growth during the 1990s in California, Oregon, and Washington

Roger B. Hammer[A,E], *Volker C. Radeloff*[B], *Jeremy S. Fried*[C] *and Susan I. Stewart*[D]

[A]Department of Sociology, Oregon State University, Corvallis, OR 97331, USA.
[B]Department of Forest Ecology and Management, University of Wisconsin, Madison, WI 53706, USA.
[C]Pacific Northwest Research Station, USDA Forest Service, Portland, OR 97208, USA.
[D]North Central Research Station, USDA Forest Service, Evanston, IL 60201, USA.
[E]Corresponding author. Email: rhammer@oregonstate.edu

Abstract. In the present study, we examine housing growth in California, Oregon, and Washington in the wildland–urban interface (WUI), the area where homes and other structures abut or intermingle with wildland vegetation. We combine housing density information from the 1990 and 2000 USA censuses with land cover information from the 1992/93 National Land Cover Dataset to demarcate the location and extent of the WUI and its growth, both in terms of area and number of housing units during the 1990s. We overlay the WUI with coarse-scale fire regime condition class information to evaluate implications for wildland fire management. During the 1990s, WUI area in the three-state region increased by 5218 km^2 (10.9%) to nearly 53 000 km^2 and the number of housing units in the WUI increased over 1 million units (17.6%) and in 2000 encompassed 6.9 million units, 43% of all housing in the region. Over a million new homes were constructed in the WUI, comprising 61% of the new homes constructed in the region. By 2000, there was far more intermix WUI (75% of the WUI area and 64% of the WUI housing units) than interface WUI. Expansion of the WUI accounted for only 13% of WUI housing unit growth and WUI that existed in 1990 encompassed 98% of WUI housing units in 2000. In 2000, there were nearly 1.5 million WUI housing units in areas with 0–35-year fire return intervals and 3.4 million in areas with 35–100+ year fire return intervals. In both these fire regimes, the majority of WUI housing units (66% and 90% respectively) are in areas with a current condition outside the historic range of variability. Housing growth patterns in this three-state region are exacerbating wildland fire problems in the WUI. Any long-term solution to wildland fire issues in the western United States will have to address housing growth patterns. Using a consistent, nationally applicable assessment protocol, the present study reveals the vast extent of WUI in the west coast states and its growth in the 1990s, and provides a foundation for consistent monitoring efforts.

Introduction

Wildland fires in the USA have declined in recent decades from a peak of 250 000 in 1981 to 67 000 in 2005 (NIFC 2006). However, the area within fire perimeters has increased substantially, with a modern record of 34 000 km^2 set in 2000 and again in 2005 with 35 000 km^2. Federal fire suppression costs soared to US$1.66 billion in 2002 (NIFC 2006). The increases in the area burned and structures destroyed have been attributed to a number of factors, including increasing density of small trees and understorey shrubs that became established over decades of vigorous fire suppression and an increasing number of homes located in close proximity to wildland areas (USDA and USDI 2001).

In the present study, we examine housing growth in or near wildlands during the 1990s in California, Oregon, and Washington. The area where homes, businesses, and other structures abut or are intermingled with wildland vegetation has been termed the Wildland–Urban Interface (WUI). WUI has been recognised as an important element of wildland fire policy at least since 1960 (USDI and USDA 1995) because WUI areas often present a challenging fire management situation, with firefighting resources inevitably pressed into defending homes at the expense of progress on fireline containment. Fire management decisions concerning the WUI have potentially substantial political and economic impacts.

Furthermore, higher housing density contributes significantly to higher rates of human-caused wildland fire ignitions (Sapsis 1999; Cardille *et al*. 2001). Spero (1997) used linear regression to demonstrate that ignition rates increased by 0.17 fires per mi^2 (44 per km^2) per year with the addition of 100 housing units. Fire prevention efforts commonly focus on the WUI (Fried *et al*. 1999; Winter and Fried 2000) and wildland fire control efforts are increasingly being directed to protect structures in the WUI (USDA and USDI 2001).

Previous research established that 9% of the land area (720 000 km^2) and 39% of all housing units (44.3 million) in the coterminous USA are located in the WUI (Radeloff *et al*. 2005*b*), according to the definition published in the *Federal Register* (USDA and USDI 2001). Although not all of these WUI areas are at high risk from wildland fire, these numbers

 10.1071/WF05077 1049-8001/07/030255

highlight the magnitude of the challenge that resource managers face. What is not known is how fast WUI is growing, and how much housing growth is occurring in existing WUI. This was the central research question of the study presented here.

Housing growth in the United States has been strong in recent decades (Hammer *et al*. 2004; Radeloff *et al*. 2005*a*). Throughout the USA, the number of housing units increased by 13.6 million during the 1990s, thereby potentially increasing WUI area and the number of houses in the WUI. Furthermore, the USA has undergone a process of population deconcentration (Long and Nucci 1998). Substantial residential and commercial development has occurred both in the outlying fringe of metropolitan areas and in more remote rural areas with attractive recreational and aesthetic amenities. This phenomenon has been especially prominent in the West, in forested areas, and in areas adjacent to federal lands. The combination of suburban development, or suburban sprawl (Benfield *et al*. 1999; Daniels 1999), and recreational and amenity development, or rural sprawl (Radeloff *et al*. 2001, 2005*a*), may have resulted in a substantial expansion of low-density housing located in close proximity to wildland fuels, but WUI growth remains largely undocumented.

WUI associated with high fire hazard is especially common in the western United States. For decades, the WUI was widely viewed as a problem limited to California, owing to the state's preponderance of wildlands covered with fire-adapted vegetation types, summer drought and episodic high wind events that lead to extreme fire behaviour, and the large numbers of homes sited in or adjacent to these wildlands (Teie and Weatherford 2000). During the 30-year period from 1955 to 1985, wildland fires in California destroyed 3533 structures and resulted in 25 deaths. Wildland fire-caused losses increased in the ensuing 15-year period between 1985 and 2000, with 32 deaths and 7467 structures destroyed (although 25 of those deaths and 2900 of the structures destroyed occurred as a result of a single fire, the 1991 Tunnel fire in the Oakland Hills).

However, such losses are no longer confined to California. Between 1985 and 2000, wildland fires in Oregon and Washington destroyed 570 structures. The wildland fire problems in the western United States make studying housing growth in this region's WUI particularly important. In addition, the ecosystems present in these three states vary widely, ranging from the 4.6 million acres of chaparral in southern California where frequent, intense fires are common (Fried *et al*. 2004), to the temperate rain forests of the Washington coast where fires are infrequent.

The goal of the present study was to estimate WUI housing growth during the 1990s for California, Oregon and Washington State and to relate this information to fire regimes and vegetation condition to create a comprehensive portrayal of WUI growth and its implications for wildland fire management.

Methods

Our WUI change analysis was based on the WUI definition published in the *Federal Register* (USDA and USDI 2001; Radeloff *et al*. 2005*b*). We used housing density information from the 1990 and 2000 censuses (US Census Bureau 1992, 2002), the National Land Cover Dataset (NLCD), a land-cover classification conducted over the entire United States (Vogelmann *et al*. 1998), and coarse-scale maps of fire regime current condition classes (Schmidt *et al*. 2002). These data were analysed and summarised for three states: Washington, Oregon and California. We also summarised WUI growth separately for the Sierra Nevada foothills and for southern California, areas where wildfire hazard to houses and other structures is particularly high.

WUI definition

In order to identify WUI communities near Federal lands that are at high risk from wildland fire, a notice published in the *Federal Register* on 4 January 2001 included a definition of WUI (USDA and USDI 2001). In this definition, the WUI is composed of interface, intermix, and occluded areas. Interface communities directly abut wildland areas and there is a clear demarcation between developed areas and adjacent wildland areas. In intermix areas, structures are often surrounded and even overtopped by wildland vegetation, and the structures can be thought of as islands scattered in a sea of wildland fuel. Housing densities in intermix areas range from one house per 40 acres (0.16 km^2) at the low end to 'structures very close together.' Occluded communities were not identified in the current study and there are not other estimates of their extent available.

Mapping this particular definition of the WUI using the data and operational definitions we developed, we arrived at one possible representation of the WUI. The map is necessarily shaped by the data used and the way in which we transformed a relatively imprecise descriptive definition into an operational one. The sensitivity of outcomes to definitional parameters and alternative definitions are discussed elsewhere (Radeloff *et al*. 2005*b*; S. I. Stewart *et al.* in press). In particular, it should be noted that consideration of fire risk would limit the amount of WUI and its distribution; but we mapped this intersection of housing and vegetation as a foundation, one from which we examined WUI in relation to fire regime condition class (FRCC), analysis that can be extended as other fire hazard information becomes available.

Because interface and intermix areas pose different challenges for wildland fire protection, growth in these types of WUI is worth monitoring separately. Fires in the intermix WUI often spread through residential areas in much the same way as they do in wildlands – over continuous expanses of wildland fuels. In this case, however, dispersed homes and other structures integral to the fuel complex are extremely likely to become involved in fire and unlikely to have much impact on the overall spread and intensity of the fire (Cohen 1999). Moreover, growth in the intermix frequently results from splitting existing lots – a process that, compared with establishment of whole new subdivisions at the edge of the interface, involves little scrutiny by local planners and few restrictions or conditions on approval designed to enhance fire protection. Whereas fires in the interface sometimes spread directly between structures, it is often embers carried aloft that land on the roofs of homes, sometimes even kilometres from the main fire front, ultimately leading to the destruction of those homes and further propagation of wind-carried embers and expansion of the fire's destructive extent (Rehm *et al*. 2001).

Housing density

We used 1990 and 2000 block-level housing unit counts from the decennial censuses to determine housing density (Fig. 1*a*).

We constructed block boundary Geographic Information System (GIS) coverages for both 1990 and 2000 (US Census Bureau 2000). Owing to boundary changes, 62% of the blocks in the three states had different boundaries in 1990 and 2000. Block boundary changes occurred at higher rates in suburbanising and rural areas than in long-developed urban and suburban areas. The magnitude of block boundary changes during the decade has important implications for any type of fine-scale analysis of demographic, economic, or social change using 1990 and 2000 census data, especially in rural areas. Scaling up to the block group- or tract-level could reduce the problem but would not eliminate it; scaling up would also result in much coarser resolution, and ultimately, misclassification of WUI at the scale relevant to fire hazard. These boundary shifts preclude a simple calculation of housing density change between 1990 and 2000 and necessitate a spatial interpolation, assigning housing units from one decade to the blocks delineated for the other decade.

To preserve the spatial detail provided by block-level data, rather than aggregating blocks to create block-equivalents common to both 1990 and 2000, we assigned 1990 housing units to 2000 blocks (Radeloff *et al*. 2005*b*; S. I. Stewart *et al*. in press). Based on the parsimonious assumption that the location of housing units in one decade is highly correlated with the location of housing units in both the previous and subsequent decades, we allocated 1990 housing units to 2000 blocks based on the proportional allocation of 2000 housing units. For example, for a 1990 block divided into multiple 2000 blocks, the 1990 housing units were assigned to the 2000 block polygons based on the 2000 distribution of housing units among those blocks.

In our assignment of housing units to intersected blocks, we made several assumptions concerning blocks with shifting boundaries that did not contain housing units. First, we assumed that if a block's boundaries shifted and it did not contain housing units in 2000, it did not contain housing units in 1990. This assumption would hold true except in cases in which boundaries shifted and all the housing units in the block were demolished during the decade. Second, to avoid overestimating change in housing density, we also assumed that if a block's boundaries shifted and it did not contain housing units in 2000, it did not contain housing units in 1990. Both of these assumptions are conservative with regard to housing growth, meaning that our change assessment may have missed some areas of actual housing growth on the ground, but we did not generate any spurious housing growth. For a more detailed description and analysis of the housing location spatial interpolation method that we developed, see Hammer and Radeloff (2006).

Land cover

Identifying the WUI requires, in addition to the housing density, some representation of vegetation. We used the United States Geological Survey's National Land Cover Dataset (NLCD), the result of a classification of Landsat Thematic Mapper imagery dating to 1991–93, as a basis for representing potential fuels in the context of intermix and interface designation. Census blocks meeting the WUI in which forests, shrubs, and grasslands collectively comprise 50% or more of the land cover were labeled as intermix WUI; census blocks containing less than 50% of land cover in these vegetation classes that were within 1.5 miles (2.4 km) of areas containing at least 75% of the land cover in these classes were labeled interface WUI. This approach to map the WUI follows closely the WUI definition in the *Federal Register* (USDA and USDI 2001), and examines all wildland vegetation, irrespective of fuel loads, and ignition likelihoods. Wildland fire hazard thus varies among areas identified as WUI according to this definition.

Forests are the most prominent land cover in the region (Fig. 1*b*), encompassing most of western Washington and Oregon, northern California, the Sierra Nevada, north-east Washington, and north-east Oregon. Forests are also scattered throughout the coastal portions of central and southern California. Southern California is dominated by shrubs and desert vegetation as is south-east and north central Oregon. California's Central Valley and Oregon's Willamette Valley are primarily agricultural. Grasslands are prominent on the fringe of California's Central Valley. South-east Washington is a mosaic of agriculture, grass, shrub lands and desert. Because the NLCD vegetation classes are so broadly defined (e.g. coniferous forest, hardwood forest, shrubs), the identification of WUI provides very limited insight concerning the actual wildland fire hazard, as the wildland vegetation in these ecosystems ranges widely in its flammability and the associated fire regimes.

Fire Regime Condition Class

We used coarse-scale maps of fire regime condition classes in an attempt to capture broad, regional variation in fire hazard. The Fire Regime Condition Class (FRCC) system is both a general indication of the role fire would play across a landscape in the absence of modern human intervention (Agee 1993; Brown 1994) and an estimate of the degree of departure from that historical regime (Hann and Bunnell 2001). The coarse-scale FRCC maps that have been compiled for the conterminous United States (Schmidt *et al*. 2002) identify three classes of expected fire return (FR) intervals (0–35, 35–100+, and 200+ years) and three classes of current departure (low, moderate, and high) from the historical fire regime. Areas classified as low departure are considered to be within the natural (historical) ranges of variability for fuel composition, fire frequency, fire severity, vegetation type, and disturbance characteristics, whereas moderate and high departures are outside of these ranges. The national FRCC data are fairly coarse and should only be used at broad scales (Schmidt *et al*. 2002). This is why we only present aggregated WUI statistics for each FRCC class across the entire study area. Ultimately, it will be desirable to link our WUI data to more detailed maps of wildland fire hazard, fuels, and fire behaviour, but such data do not exist currently for the three states that we studied. In the absence of more detailed data, the FRCC data are widely used by managers and policy makers for strategic fire planning. For example, reducing the FRCC class is an explicit goal in the Healthy Forest Restoration Act. The lack of more detailed data, and the policy relevance of the FRCC data are the reasons why we analysed our WUI data in relation to FRCC despite FRCC's known limitations.

Land cover patterns are reflected in the geographic distribution of FRCC (Fig. 1*c*). The agricultural areas in the Central Valley of California, the Willamette Valley of Oregon, and much

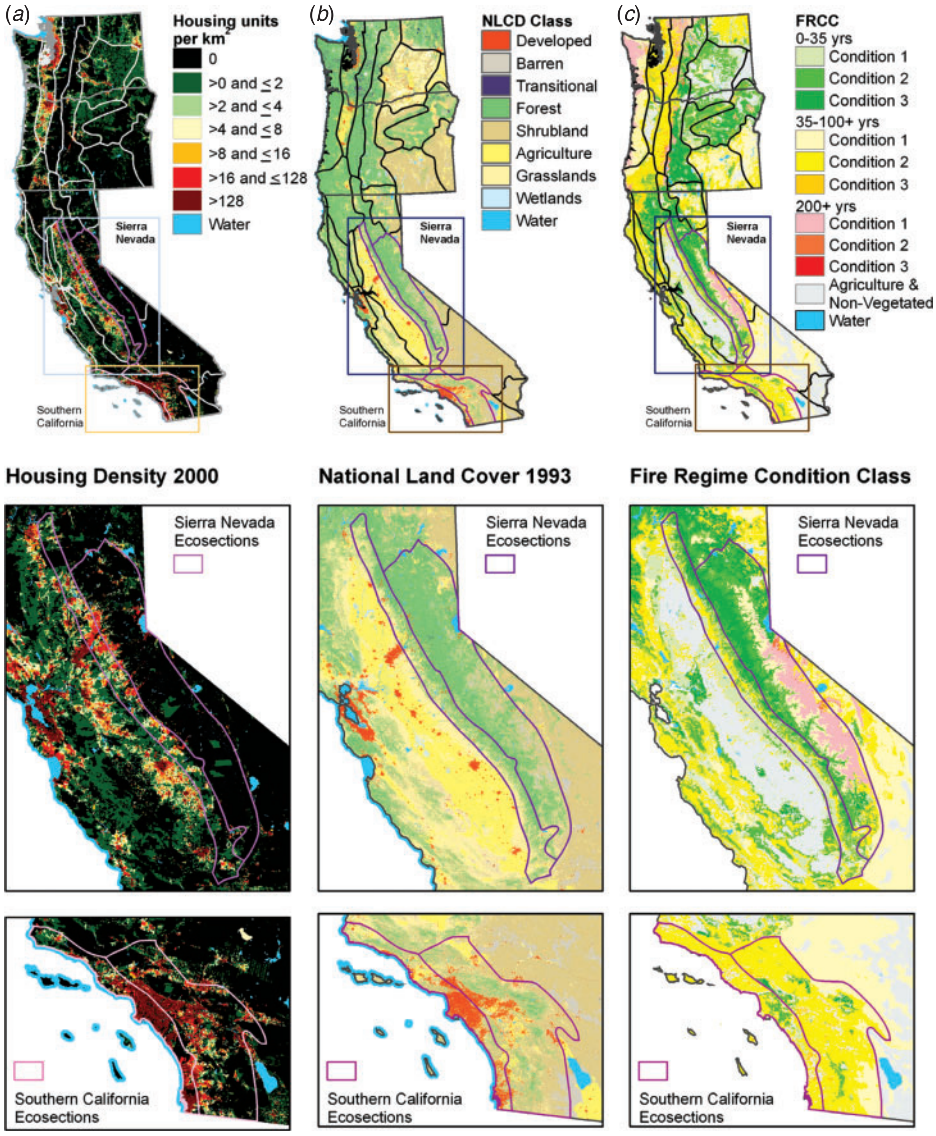

Fig. 1. Housing density, land cover, and fire regime condition class.

of south-east Washington and large areas of desert scrub in south-east California are not assigned a class under the FRCC system because wildland fire is not considered a significant factor in the management of these lands. Areas with a fire return interval of 200+ years are found mainly on Washington's Olympic Peninsula, at the Sierra Nevada crest, in the North Cascades, and in a narrow band on the western edge of the Southern Cascades in Oregon. The 35–100+ year FR is quite widespread throughout the region, but is associated primarily with areas of high departure from normal FR in south-western Oregon, with a smaller cluster in north-west California and scattered areas in western Washington. Moderate condition class in the 35–100+ FR stretches along much of the California coastline and more inland in the southern portion of the state, as well as throughout the Cascades in both Washington and Oregon, and in north-east Washington. South-east Oregon and north-east California are predominantly 35–100+ year FR areas with a mix of condition classes. The low condition class in 35–100-year FR is most prominent along the Oregon coast, and inland southern California, with some in west central Washington.

The shortest fire return interval, 0–35 years, is prominent along the Sierra Nevada and is dominated by the high condition class, except in areas closest to the Central Valley where the condition class tends to be low. Central Oregon is dominated by the 0–35-year FR and the high condition class. Areas in south-east Washington and north-east Oregon are dominated by the short fire return interval regime and a mix of moderate and high condition classes.

The coarse scale of the current FRCC information (Schmidt *et al*. 2002) provides only a gross assessment of the fire hazard associated with the WUI and its growth and obscures fine-scale spatial variation in fire regimes and departures (and by extension, the vegetation conditions on which these are based). Thus, some areas that meet housing density and land cover criteria for WUI have not been assigned an FRCC class. The result is that 20% of WUI in California and Oregon and nearly 25% in Washington are unclassified under FRCC. Because of this limitation, we only summarised the WUI data for the different areas where FRCC classes had been assigned. This allowed us to compare WUI growth in different FRCC classes, but we could not map all WUI areas according to their FRCC designation. Because of these limitations, we also analysed WUI specifically for areas where wildfires pose particular challenges for managers.

Fire-prone ecoregions

We selected four fire-prone ecoregions (ecological sections; Bailey 1995) in California and in the Sierra Nevada Foothills to examine WUI growth in areas renowned for their challenges in wildfire management: Southern California Coast (261B), Southern California Mountains and Valleys (M262B), Sierra Nevada (M261E), and Sierra Nevada Foothills (M261F). In the Sierra Nevada sections, the fire regime has largely shifted from frequent, low intensity surface fires to infrequent, low, moderate and high intensity surface fires, and high intensity stand-replacing fires (Miller and Urban 1999*a*, 1999*b*; Nagel and Taylor 2005; Taylor and Beaty 2005). Fire managed landscapes such as parts of Yosemite and Sequoia National Parks are exceptions to this change (Stephenson 1999). The southern California sections are dominated by shrublands that have relatively frequent and high intensity fires (Wells *et al.* 2004; Franklin *et al.* 2005).

Results

In the following section, we first examine WUI growth patterns; both in terms of WUI area and WUI housing unit growth, then relate these trends to the FRCC. Finally, WUI growth trends in relation to FRCC are examined in four selected fire-prone ecosections.

WUI area growth

The 1990s was a decade of WUI growth for the region, both in the number of housing units and land area. WUI area in this three-state region increased by 11% to nearly 53 000 km^2 (Table 1). But growth was not uniform across states: WUI area expanded by less than 10% in California and Oregon but by over 16% in Washington.

The major metropolitan areas in the region have extensive WUI at their fringes, especially Los Angeles, San Diego, San Francisco, Seattle, and Portland (Fig. 2*a*). Intermix is more prominent in southern California than in the other metropolitan fringe WUI areas. WUI is also prominent in smaller metropolitan areas, including Spokane, Washington, Medford and Bend, Oregon, and in the northern California micropolitan areas of Eureka and Redding. A very prominent chain of non-metropolitan WUI areas can be seen in the foothills of the Sierra Nevada, dominated by intermix with the exception of interface areas near Sacramento.

In all three states, over 70% of the WUI area is composed of intermix, and intermix grew faster than interface. Region-wide during the 1990s, intermix area expanded at a rate more than five times that of the interface, 14% and 2.5% respectively. Most growth occurred adjacent to existing WUI areas, with the area north of Spokane, Washington, being perhaps most prominent (Fig. 2*b*).

Table 1. Wildland–urban interface (WUI) area (km^2), 1990 and 2000

Location	1990	2000	Growth	
			n	%
California				
Interface	7266	7328	63	0.9
Intermix	18 998	21 219	2221	11.7
Total WUI	26 263	28 547	2284	8.7
Oregon				
Interface	2523	2617	94	3.7
Intermix	5775	6464	688	11.9
Total WUI	8299	9081	782	9.4
Washington				
Interface	3197	3371	174	5.4
Intermix	9951	11 929	1978	19.9
Total WUI	13 148	15 300	2152	16.4
Pacific West Region				
Interface	12 986	13 317	331	2.5
Intermix	34 724	39 611	4887	14.1
Total WUI	47 710	52 928	5218	10.9

WUI housing unit growth

The WUI in 2000 contained almost 7 million housing units (Table 2), ~75% of them in California. In 2000, nearly one-half of Washington's 2.4 million housing units were located in the WUI, whereas in California and Oregon, 42% of housing units were in the WUI (5.1 million and 0.6 million units respectively). Although only one quarter of the region's WUI area is interface, 64% of the WUI housing units are located in interface areas. Nearly 70% (3.4 million) of California WUI units were in the interface, nearly 60% (0.4 million) of Oregon units, but just less than half (0.6 million) of Washington units.

The 18% growth in WUI housing units surpassed the 11% growth of the WUI area in the region, with over 1 million housing units added during the decade. Just over 60% of the net housing unit growth during the 1990s occurred in the WUI; though in Oregon, the proportion was low (46%) compared with California (62%) and Washington (66%). Washington experienced both the greatest proportional expansion of WUI areas and the largest proportional growth of WUI housing units – nearly 30%. Intermix housing units in this region grew at nearly three times the rate of interface units. The WUI areas that already existed in 1990 accounted for nearly all (98%) of the 2000 WUI housing units (Table 3). Moreover these pre-existing WUI areas contributed 87% (882 203) of the WUI housing growth during the 1990s.

WUI growth and Fire Regime Condition Class

In 2000, 7% of the area in this region for which FRCC has been determined (41 817 km^2) was also part of the WUI. Of the area with a 0–35-year FR, 5% was in the WUI, whereas 10% of the

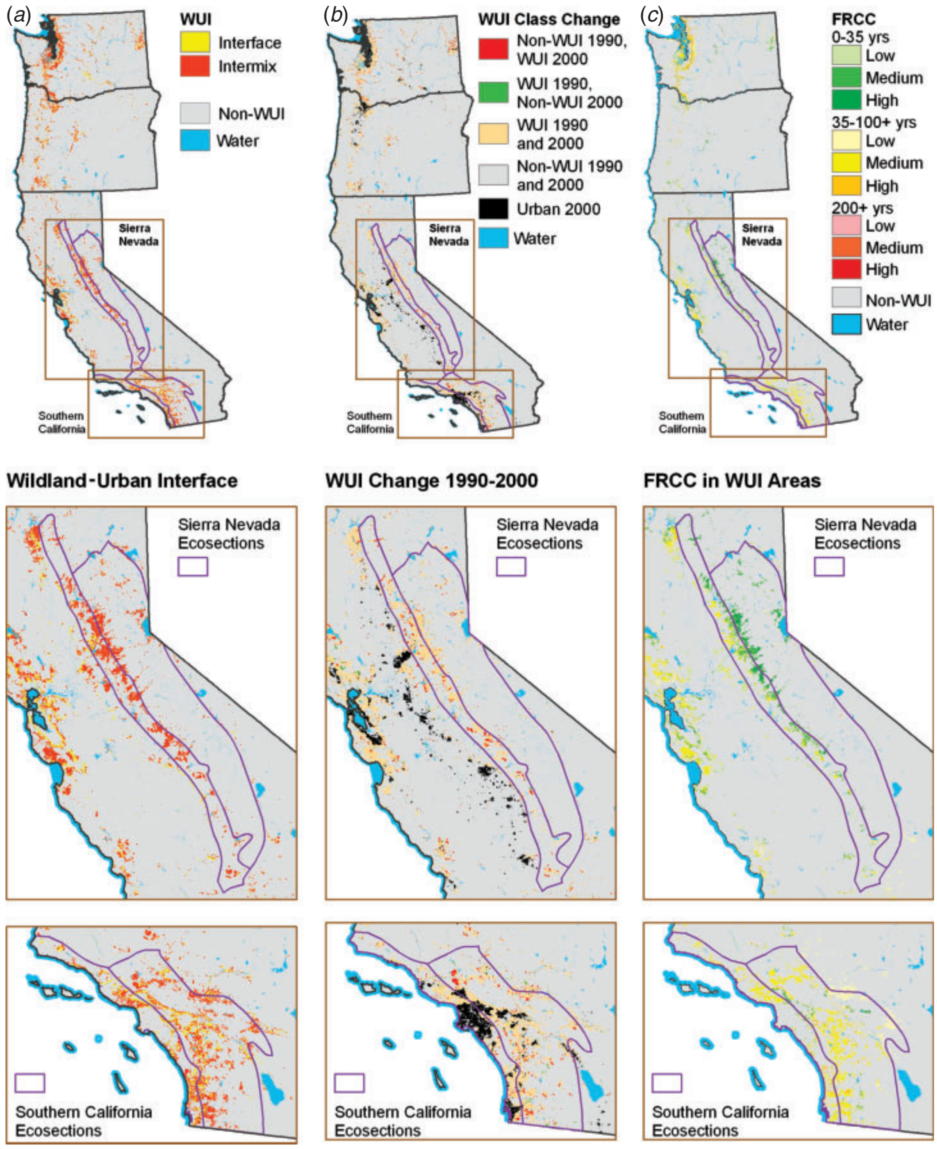

Fig. 2. Wildland–urban interface 2000, wildland–urban interface change 1990–2000, and wildland–urban interface fire regime condition class 2000.

area with a 35–100+ year FR, and just 3% of the 200+ year FR area were WUI (Table 4). Owing to the limited area of 200+ year FR WUI in the region and its long return interval, we did not distinguish among condition classes for this fire regime.

With regard to condition class, three-quarters of the WUI area in the 0–35-year FR was outside the historic range of variability; however, WUI represents less than 2% of this area compared with just under 9% of both the low and medium departure condition classes. Approximately 2/3rds of the WUI was in the 35–100+ year FR. The chain of WUI in the Sierra Nevada foothills contains considerable 0–35-year FR (Fig. 2*c*). There is also considerable 0–35-year FR WUI in the San Francisco area, although generally in the low departure condition class.

In the 35–100+ year FR, 12% of WUI was within the historic range of variability. WUI comprised 15% of the high departure condition class and proportionately less of the moderate departure class, just 4%. The WUI surrounding the Los Angeles and San Francisco areas was dominated by 35–100+ year FR with moderate departure condition class. Surprisingly, this was also the case in the WUI areas of Portland and Seattle–Tacoma.

In 2000, there were nearly 1.5 million WUI housing units in areas with a FR of 0–35 years and 3.4 million in areas where the FR is 35–100+ years (Table 5). Fewer than 90 000 WUI housing units were located in areas where FR is 200+ years. In both the 0–35-year and 35–100+ year FRs, the majority of WUI housing units were in areas of moderate departure.

During the 1990s, the number of housing units in the 0–35-year FR grew 20% and by slightly less (18%) in the 35–100+ year FR and the 200+ year FR (15%). In the 0–35-year FR, the

Table 2. Wildland–urban interface (WUI) housing units, 1990 and 2000

Location	1990 (*n*)	2000 (*n*)	Growth	
			n	%
California	11 182 851	12 214 549	1 031 698	9.2
Interface	3 163 846	3 480 126	316 280	10.0
Intermix	1 305 616	1 633 685	328 069	25.1
Total WUI	4 469 462	5 113 811	644 349	14.4
Oregon	1 193 567	1 452 709	259 142	21.7
Interface	315 024	370 745	55 720	17.7
Intermix	190 165	254 063	63 898	33.6
Total WUI	505 190	624 808	119 618	23.7
Washington	2 032 374	2 451 075	418 701	20.6
Interface	504 190	587 484	83 293	16.5
Intermix	425 356	617 439	192 083	45.2
Total WUI	929 547	1 204 923	275 376	29.6
Pacific West Region	14 408 792	16 118 333	1 709 541	11.9
Interface	3 983 061	4 438 354	455 294	11.4
Intermix	1 921 138	2 505 188	584 050	30.4
Total WUI	5 904 198	6 943 542	1 039 344	17.6

Table 3. Housing units in existing and emergent wildland–urban interface (WUI), 1990 and 2000

Variable	California	Oregon	Washington	Total
Existing WUI				
1990	4 469 462	505 190	929 547	5 904 198
2000	5 011 398	605 119	1 169 884	6 786 402
Growth (*n*)	541 936	99 930	240 338	882 203
Growth (%)	12	20	26	15
New WUI				
1990	13 581	5260	11 564	30 405
2000	106 704	21 277	36 736	164 718
Growth (*n*)	93 123	16 017	25 172	134 313
Growth (%)	686	305	218	442
Percentage of growth	15	14	9	13

Table 4. Wildland–urban interface (WUI) area (km^2) and fire regime condition class (FRCC), 2000

FRCC	Total (km^2)	WUI (km^2)	WUI (%)	Percentage of WUI
0–35 years				
Low	38 836	3362	8.7	8.0
Moderate	77 583	6472	8.3	15.5
High	156 981	2971	1.9	7.1
Subtotal	273 400	12 806	4.7	30.6
35–100+ years				
Low	145 248	17 741	12.2	42.4
Moderate	95 719	3834	4.0	9.2
High	38 842	5966	15.4	14.3
Subtotal	279 809	27 542	9.8	65.9
200+ years	50 306	1469	2.9	3.5
Total	603 515	41 817	6.9	

Table 5. Wildland–urban interface housing units and fire regime condition class (FRCC), 1990 and 2000

FRCC	1990	2000	Growth	
			n	%
0–35 years				
Low	366 329	487 292	120 962	33.0
Moderate	519 690	604 758	85 069	16.4
High	319 654	356 832	37 178	11.6
Subtotal	1 205 673	1 448 881	243 209	20.2
35–100+ years				
Low	285 037	337 571	52 534	18.4
Moderate	2 239 223	2 596 071	356 849	15.9
High	361 633	462 592	100 959	27.9
Subtotal	2 885,893	3 396 234	510 341	17.7
200+ years	76 824	88 391	11 567	15.1
Undetermined	1 735 809	2 010 035	274 227	15.8

majority of housing units added to the WUI were in areas with low departures. Where FR was 35–100+ years, proportionately more housing units were added to areas with high departures.

WUI growth in fire prone ecoregions

WUI in the four selected fire-prone ecosections varied considerably (Table 6). In the Southern California Coast (261B), less than 30% of the housing units in 2000 were located in the WUI but over 60% of the housing growth during the 1990s occurred there. The proportion of housing units in the WUI in the Southern California Mountains and Valleys (M262B) was twice as high (61%), but the number of WUI housing units was similar: 1.42 million and 1.26 million, respectively. In both Southern California ecosections, the majority of WUI housing units were in the interface, but intermix housing grew faster. In the two ecoregions combined, nearly 300 000 housing units were added to the WUI during the 1990s. In contrast, in the Sierra Nevada (M261E) and Sierra Nevada Foothills (M261F), WUI housing units were predominately intermix. Over 90% of the housing units in these two ecosections were located in the WUI in 2000 and the WUI captured virtually all the net growth in housing units during the decade.

Discussion and conclusions

The results from our study show that California, Oregon and Washington experienced extensive housing growth during the 1990s, particularly in the WUI. Of all new housing units built in these three states in the 1990s, 61% (1 039 344 units) were located in the WUI. Given that past housing growth rates and patterns are good predictors of future development (Hammer *et al*. 2004), these findings portend challenges for fire hazard mitigation, fire protection, and resource management. However, there are important details embedded in our results that warrant a closer look in order to understand the full implications of recent growth trends on wildland fire issues in the three west coast states.

Table 6. Wildland–urban interface (WUI) housing units
California Ecosystem Section (1990, 2000) coordinates refer to Bailey (1995)

California Ecosystem Sections, 1990 and 2000	1990 *n*	2000 *n*	Growth *n*	Growth %
Southern California Coast (261B)				
Total	4 092 375	4 337 694	245 319	6.0
Interface	811 906	890 703	78 797	9.7
Intermix	297 582	368 915	71 333	24.0
Total WUI	1 109 488	1 259 618	150 130	13.5
% WUI	27	29	61	
Southern California Mountains and Valleys (M262B)				
Total	2 107 191	2 318 988	211 797	10.1
Interface	896 810	990 920	94 110	10.5
Intermix	349 536	433 482	83 946	24.0
Total WUI	1 246 346	1 424 402	178 056	14.3
% WUI	59	61	84	
Sierra Nevada (M261E)				
Total	136 537	151 513	14 975	11.0
Interface	22 781	23 755	974	4.3
Intermix	102 405	115 951	13 546	13.2
Total WUI	125 186	139 706	14 520	11.6
% WUI	92	92	97	
Sierra Nevada Foothills (M261F)				
Total	197 742	237 694	39 953	20.2
Interface	56 295	64 249	7954	14.1
Intermix	119 437	151 570	32 133	26.9
Total WUI	175 732	215 819	40 088	22.8
% WUI	89	91	100	

The WUI grew substantially – by 11% or 5218 km^2. However, even higher growth was observed in the number of houses in areas that were WUI in both 1990 and 2000 (15%). The dominant WUI growth trend is the increasing number of housing units located in census blocks that were already WUI in 1990. Although greater numbers of houses in existing WUI areas may further complicate initial attack and raise the stakes in terms of potential losses when fire occurs, it can also be viewed as good news for land managers because it may translate to less expansion of the area requiring fuel treatments and fire prevention efforts, and possibly less hazard as pavement and landscaping replace wildland vegetation.

The comparison of WUI growth in intermix and interface areas highlights a different trend, which could be potentially problematic with respect to wildland fire management. Most new housing construction occurs in intermix areas. The juxtaposition of houses and vegetation creates challenges for both wildland fire fighters and their structural firefighting counterparts. From a fire fighting perspective, in most cases it is easier to protect a given number of houses when they are clustered, rather than scattered across a comparatively large area dominated by wildland fuels. The second problem related to housing growth in intermix WUI is the rural character of many of these areas. Some rural areas lack any kind of local fire protection, whereas others have local fire departments that are completely dependent on volunteer firefighters, community donations and grants because they receive no tax revenue. Although they are often the first to attack wildland fires, such departments are typically not as well equipped, especially in terms of the specialised equipment needed for wildland fires, or as well trained as their professionally staffed urban and suburban counterparts (Teie and Weatherford 2000). The higher rate of growth in the intermix WUI highlights a difficult land use and fire management problem.

Given both the number of and the increase in WUI housing units, it is surprising that there has not been a larger increase in the number of structures lost to wildland fires in recent years. The number of structures lost in 2004 to wildland fires is substantial (1084 in the USA), but not when compared with 6.9 million WUI housing units in the three-state study area, or even to the million new WUI homes in this region. One reason is that fire-fighting efforts are in most cases successful in protecting structures threatened by wildland fires, though often at the expense of fires becoming larger owing to less focused attention on fire containment. The other important reason is that fire hazard varies considerably and substantial portions of the WUI are located in areas that are not of primary concern to wildland fire managers because fires are infrequent there.

When examining the amount of WUI in different FRCCs, a mixed picture emerges. One FRCC that is of major concern to resource managers are forests that were historically dominated by frequent surface fires but are no longer within the historic range of variability (i.e. FR 0–35 years, high departure). In these forests, aggressive fire prevention and suppression has resulted in considerable lengthening in FR intervals, both tree and shrub vegetation density has increased, and fuel loads are high. This is the most widespread FRCC, covering 158 257 km^2. However, WUI is relatively uncommon in this FRCC and occupies only 1.7% compared with an average of 7.1% across all FRCCs. We suggest that the most likely reason for this pattern is that areas in this FRCC are largely in public ownership, where there are limited opportunities for housing development.

The analysis of different FRCCs in terms of their WUI percentages provides only a partial picture of fire hazard in the WUI. One reason for this is that FRCC is determined at a coarse scale for entire ecoregions, obscuring spatial variation in fire regimes and vegetation conditions within a given FRCC area. The WUI data are of much higher spatial resolution than the available FRCC data, and owing to this scale mismatch, they are only valid to analyse how much WUI there is in each FRCC. Inverting this analysis to compute the percentage of each FRCC in, for example, all intermix WUI might yield interesting results, but will only be possible when fine-scale FRCC data, currently in development by the LANDFIRE project, becomes available. Moreover, even when fine-scale FRCC data becomes available, it remains unclear as to whether departure attributes will capture past land use, timber harvest, landscape-scale fuel treatments, or even buffer-style fuel reduction zones surrounding communities, potentially leading to significant misrepresentation of fire hazard.

In addition to the scale issues, and incomplete coverage, our experience with this analysis led us to question the value of FRCC as a proxy for fire hazard. There is potential for houses burning in virtually every fire regime, and at all levels of departure, and in short FR interval regimes such as grasslands, the degree of departure is probably unrelated to the probability of a house ignition. We know of no meaningful way to translate either fire frequency or departure into fire hazard, so at best, FRCC yields not much more than a possibility of damage. Spatially comprehensive data layers for surface and crown fuels such as those being produced by the LANDFIRE project in the USA appear to be far more promising as a basis for estimating hazard in conjunction with WUI and WUI growth because they can be easily transformed into spatially explicit estimates of, for example, flame height, fireline intensity, and fire rate of spread for locally representative weather observations using models such as FLAMMAP (Stratton 2004). Conceivably, such modelled attributes could serve as a strong foundation for a model of hazard to the built environment.

WUI dynamics differed substantially among the four fire-prone ecoregions examined in California. In the Southern California Coast, less than one third of the housing units were located in the WUI, partly owing to the geographic reality of long-existent urban sprawl in the Los Angeles basin and conversions of agricultural land, not wildlands, in Orange County. However, almost two thirds of new housing units were built in the WUI, and the vast majority of these were added to interface, not intermix. This is consistent with the fact that the few areas on the southern coast that remain sufficiently vegetated to potentially qualify as WUI are typically in public ownership, not zoned for housing, or protected *de facto* by the presence of endangered species, especially in areas dominated by chaparral. Furthermore, local governments in this area tend, in general, towards greater protection of natural areas and stronger zoning laws. Given that it is not unusual for buildable land in this ecoregion to command prices of over a million dollars per acre (4046 m^2), it is not a complete surprise that the addition of houses to existing high-density interface areas is a more frequent occurrence than the expansion of low density (e.g. 5–20 acre (20 234–80 937 m^2) parcels) intermix. In contrast, nearly all the housing units in the Sierra Nevada and the Sierra Nevada Foothills were located in the WUI, as was nearly all the net housing growth, although the number of housing units was quite modest, compared with the Southern California sections. In part, this reflects the near-absence from this ecoregion of urban zones far enough from wildland vegetation to not be WUI, more favourable attitudes towards growth (and less strict zoning laws) in these communities transitioning from natural resource dependence to other economic bases, and prices for buildable land in the realm of 10 thousand dollars per acre low enough to encourage the construction of ranchettes and an intermix pattern of housing development. In total, 380 000 new housing units were added to WUI in southern California and in the Sierra Nevada during the 1990s, highlighting how rapid development has been, even in extremely fire prone areas.

Our analysis of WUI growth has several management implications. The most important is that current housing growth patterns are exacerbating wildland fire problems in the WUI. Any long-term solution to wildland fire issues in the western United States will have to address housing growth patterns. Although resource managers are generally aware of this issue, we provide specific documentation regarding how much the WUI has grown. Resource managers concerned with wildland fire issues and charged with limiting damage to structures will need to participate in local and regional land-use planning efforts. Incentives for community planning provided by the Healthy Forest Restoration Act may provide the impetus for engaging communities, land-use planners, and fire managers in discussions about their shared problems.

A second important lesson is that the WUI is widespread and encompasses millions of houses. Acting alone, governmental agencies cannot possibly protect all these structures when the weather and fuel conditions inevitably develop that will place tens of thousands of homes and lives at immediate risk. It will require citizen and community involvement and considerable investment by homeowners, in both time and money. Government initiatives, such as the FIREWISE program, that encourage homeowners to engage in basic fire preparedness are also crucial in this context. As insurance companies in some fire-prone areas begin to add private market incentives, more homeowners may become effectively involved in hazard mitigation on their property. However, our results highlight the magnitude of the task at hand, given that 1.7 million new homes across three states were built in the WUI during the 1990s alone. This growth, paired with the traditional high turnover in ownership of existing homes in the United States, particularly in fast-growing western states (Cromartie 1999), suggests an enormous number of homeowners with whom fire managers need to engage.

Finally, our results have important implications for fire science. First, socioeconomic aspects of wildland fire have only recently begun to receive concerted attention. Given the abundance of the WUI, there is a clear need for more research on the interactions between people and fire. Second, the WUI presents a very complex mosaic of built environment and vegetation fuels. Fire spread and fire behaviour under these conditions are not well understood and the present study suggests that further research on this topic is important given that housing growth in the WUI shows no sign of abatement.

Wildland fires present a major, ongoing challenge to natural resource management agencies. With protection of homes in the WUI a key focus of current wildland fire policy, the need for an objective, consistent, easily updated and universally accepted delineation of this zone has taken on fresh urgency. Furthermore, proactive fire preparedness planning relies on an understanding of the trends in wildland fire risk factors, including the growth of the WUI. The present study analyses WUI extent at two different points in time, thereby allowing an examination of changes in the location and extent of the WUI and providing a foundation for predicting its future extent. The spatial assessment of the WUI for California, Oregon, and Washington for 1990 and 2000 can contribute to fire management, protection, and prevention efforts and provides a unique source of information for wildland fire planning.

However, there remains opportunity to substantially refine and expand the analysis presented here. The allocation of both 1990 and 2000 housing units to block polygons must be improved in order to evaluate fine-scale transitions among non-WUI areas and to assess the various types of WUI. WUI housing density categories may not adequately encompass the wildland fire threat to residential areas and need to be evaluated using fire incidence data. Likewise, the vegetation cover thresholds of the WUI may need to be modified in order to capture the full extent of areas in which wildland fires threaten residential areas, and fine-scale fuels data will ultimately be better suited to identify WUI than currently available land cover classifications. These modifications could incorporate the flammability of various wildland fuels by adjusting land cover thresholds and interface buffer distances. These changes would more smoothly integrate assessment of wildland fire hazard into the delineation of WUI areas. Such new methods are urgently needed to meet the challenge of wildland fire management.

Acknowledgements

We are grateful for the comments provided by two anonymous reviewers, which significantly improved this manuscript and for financial support provided by the USDA Forest Service through two sources: the Pacific Northwest Research Station's Forest Inventory and Analysis Programme and the North Central Research Station via the National Fire Plan and the Northern Global Change Programme.

References

Agee K (1993) 'Fire ecology of Pacific Northwest Forests.' (Island Press: Washington, DC)

Bailey RG (1995) 'Ecosystem geography.' (Springer: New York)

Benfield FK, Raimi M, Chen D (1999) 'Once there were greenfields: how urban sprawl is undermining America's environment, economy, and social fabric.' (Natural Resources Defense Council: Washington, DC)

Brown JK (1994) Fire regimes and their relevance to ecosystem management. In 'Proceedings of the 1994 Society of American Foresters/Canadian Institute of Forestry Convention; 18–22 September 1994, Anchorage, AK'. pp. 171–178. (Society of American Foresters: Bethesda, MD)

Cardille JA, Ventura SJ, Turner MG (2001) Environmental and social factors influencing wildland fires in the Upper Midwest, United States. *Ecological Applications* **11**, 111–127. doi:10.2307/3061060

Cohen J (1999) 'Reducing the wildland fire threat to homes: where and how much?' USDA Forest Service, Pacific Southwest Research Station General Technical Report PSW-GTR-173. (Albany, CA)

Cromartie J (1999) Higher inmigration, lower outmigration contribute to non-metro population growth. *Rural Conditions and Trends* **7**, 13–17.

Daniels T (1999) 'When city and country collide: managing growth in the metropolitan fringe.' (Island Press: Washington, DC)

Franklin J, Syphard AD, He HS, Mladenoff DJ (2005) Altered fire regimes affect landscape patterns of plant succession in the foothills and mountains of southern California. *Ecosystems* **8**, 885–898. doi:10.1007/S10021-005-0017-6

Fried JS, Winter GJ, Gilless JK (1999) Assessing the benefits of reducing fire risk in the wildland–urban interface: a contingent valuation approach. *International Journal of Wildland Fire* **9**, 9–20. doi:10.1071/WF99002

Fried JS, Bolsinger CL, Beardsley D (2004) 'Chaparral in southern and central coastal California in the mid-1990s: area, ownership, condition, and change.' USDA Forest Service, Pacific Northwest Research Station PNW-RB-240. (Portland, OR)

Hammer RB, Radeloff VC (2006) 'Reconciliation of 1990 and 2000 Census block boundaries: housing unit location-based spatial interpolation.' Center for Demography and Ecology working paper 2006–02. Available at http://www.ssc.wisc.edu/cde/cdewp/ [Verified 11 June 2007]

Hammer RB, Stewart SI, Radeloff VC, Winkler R (2004) Characterizing spatial and temporal residential density patterns across the US Midwest, 1940–1990. *Landscape and Urban Planning* **69**, 183–199. doi:10.1016/J.LANDURBPLAN.2003.08.011

Hann WJ, Bunnell DL (2001) Fire and land management planning and implementation across multiple scales. *International Journal of Wildland Fire* **10**, 389–403. doi:10.1071/WF01037

Long L, Nucci A (1998) Accounting for two population turnarounds in nonmetropolitan America. *Research in Rural Sociology and Development* **7**, 47–70.

Miller C, Urban DL (1999*a*) Interactions between forest heterogeneity and surface fire regimes in the southern Sierra Nevada. *Canadian Journal of Forest Research* **29**, 202–212. doi:10.1139/CJFR-29-2-202

Miller C, Urban DL (1999*b*) A model of surface fire, climate and forest pattern in the Sierra Nevada, California. *Ecological Modelling* **114**, 113–135. doi:10.1016/S0304-3800(98)00119-7

Nagel TA, Taylor AH (2005) Fire and persistence of montane chaparral in mixed conifer forest landscapes in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. *The Journal of the Torrey Botanical Society* **132**, 442–457.

NIFC (2006) 'Wildland fire statistics: total wildland fires and acres (1960–2005).' (NIFC: Boise, ID)

Radeloff VC, Hammer RB, Voss PR, Hagen AE, Field DR, Mladenoff DJ (2001) Human demographic trends and landscape level forest management in the north-west Wisconsin Pine Barrens. *Forest Science* **47**, 229–241.

Radeloff VC, Hammer RB, Stewart SI (2005*a*) Sprawl and forest fragmentation in the US Midwest from 1940 to 2000. *Conservation Biology* **19**, 793–805. doi:10.1111/J.1523-1739.2005.00387.X

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005*b*) The Wildland–Urban Interface in the United States. *Ecological Applications* **15**, 799–805.

Rehm RG, Hamins A, Baum HR, Megrattan KB, Evans DD (2001) Community-scale fire spread. In 'Proceedings of California's 2001 Wildland Fire Conference: 10 years after the 1991 East Bay Hills Fire'. Oakland California Technical Report 35.01.462. (University of California Forest Products Laboratory: Richmond, CA)

Sapsis D (1999) 'Development patterns and fire suppression.' California Department of Forestry and Fire Protection Fire and Resource Assessment Program. (Sacramento, CA)

Schmidt KM, Menakis JP, Hardy CC, Hann WJ, Bunnell DL (2002) 'Development of coarse-scale spatial data for wildland fire and fuel management.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-87. (Fort Collins, CO)

Spero J (1997) 'How will increased population affect wildland fire incidence: is ignition frequency in the Sierra Nevada related to population density?' California Department of Forestry and Fire Protection Fire and Resource Assessment Program. (Sacramento, CA)

Stephenson NL (1999) Reference conditions for giant sequoia forest restoration: structure, process, and precision. *Ecological Applications* **9**, 1253–1265. doi:10.2307/2641394

Stewart SI, Radeloff VC, Hammer RB (2007) Defining the wildland–urban interface, *Journal of Forestry*, in press.

Stratton RD (2004) Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. *Journal of Forestry* **102**, 32–40.

Taylor AH, Beaty RM (2005) Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. *Journal of Biogeography* **32**, 425–438. doi:10.1111/J.1365-2699.2004.01208.X

Teie WC, Weatherford BF (2000) 'Fire in the West: the wildland/urban interface fire problem.' (Dear Valley Press: Rescue, CA)

US Census Bureau (1992) Census of Population and Housing, 1990: summary tape File 3 (Wisconsin) [machine-readable data files]. (US Bureau of the Census: Washington, DC)

US Census Bureau (2000) TIGER/Line Files [machine-readable data files]. (US Bureau of the Census: Washington, DC)

US Census Bureau (2002) Summary File 3A technical documentation. (US Bureau of the Census: Washington, DC)

USDA and USDI (2001) Urban–wildland interface communities within vicinity of federal lands that are at high risk from wildland fire. *Federal Register* **66**, 751–777.

USDI and USDA (1995) 'Federal wildland fire management policy and program review.' (USDI and USDA: Washington, DC)

Vogelmann JE, Sohl TL, Campbell PV, Shaw DM (1998) Regional land cover chacterization using Landsat thematic mapper data and ancillary data sources. *Environmental Monitoring and Assessment* **51**, 415–428. doi:10.1023/A:1005996900217

Wells ML, O'Leary JF, Franklin J, Michaelsen J, Mckinsey DE (2004) Variations in a regional fire regime related to vegetation type in San Diego County, California (USA). *Landscape Ecology* **19**, 139–152. doi:10.1023/B:LAND.0000021713.81489.A7

Winter G, Fried JS (2000) Homeowner perspectives on fire hazard, responsibility, and management strategies at the wildland–urban interface. *Society & Natural Resources* **13**, 33–49. doi:10.1080/089419200279225

Manuscript received 17 August 2005, accepted 22 August 2006