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Author(s): V. C. Radeloff, R. B. Hammer, S. I. Stewart, J. S. Fried, S. S. Holcomb and J. F. McKeefry

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## THE WILDLAND–URBAN INTERFACE IN THE UNITED STATES

V. C. RADELOFF,<sup>1,5</sup> R. B. HAMMER,<sup>2</sup> S. I. STEWART,<sup>3</sup> J. S. FRIED,<sup>4</sup> S. S. HOLCOMB,<sup>1</sup> AND J. F. MCKEEFRY<sup>1</sup>

<sup>1</sup>*Department of Forest Ecology and Management, University of Wisconsin-Madison, 1630 Linden Drive, Madison, Wisconsin 53706 USA*

<sup>2</sup>*Department of Rural Sociology, University of Wisconsin-Madison, Madison, Wisconsin 53706 USA*

<sup>3</sup>*USDA Forest Service, North Central Research Station, Evanston, Illinois 60201 USA*

<sup>4</sup>*USDA Forest Service, Pacific Northwest Research Station/FIA, Portland, Oregon 97205 USA*

**Abstract.** The wildland–urban interface (WUI) is the area where houses meet or intermingle with undeveloped wildland vegetation. The WUI is thus a focal area for human–environment conflicts, such as the destruction of homes by wildfires, habitat fragmentation, introduction of exotic species, and biodiversity decline. Our goal was to conduct a spatially detailed assessment of the WUI across the United States to provide a framework for scientific inquiries into housing growth effects on the environment and to inform both national policy-makers and local land managers about the WUI and associated issues. The WUI in the conterminous United States covers 719 156 km<sup>2</sup> (9% of land area) and contains 44.8 million housing units (39% of all houses). WUI areas are particularly widespread in the eastern United States, reaching a maximum of 72% of land area in Connecticut. California has the highest number of WUI housing units (5.1 million). The extent of the WUI highlights the need for ecological principles in land-use planning as well as sprawl-limiting policies to adequately address both wildfire threats and conservation problems.

**Key words:** fragmentation; housing growth; urban sprawl; urbanization; wildfire; wildland fire; wildland–urban interface.

### INTRODUCTION

Urban and suburban development in or near wildland vegetation poses a major threat to the environment (Johnson 2001). Housing development causes habitat loss and fragmentation (Theobald et al. 1997), threatens wildlife populations (Soulé 1991), and results in biodiversity declines (McKinney 2002). It has been estimated that >50% of all federally listed threatened and endangered species in the United States are in peril due to urbanization (Czech et al. 2000). These problems are of particular concern in the wildland–urban interface (WUI), where homes and associated structures are built among forests, shrubs, or grasslands.

The WUI has received considerable attention because of recent increases in both the number of structures destroyed and the area burned annually by wildland fire (NIFC 2004). It is in the WUI where protection of structures from wildland fires is most challenging (Cohen 2000, Winter and Fried 2001) and where human-caused fire ignitions are most common (Cardille et al. 2001). Human-caused fires burned 43% of the record-setting 34 083 km<sup>2</sup> that were burned in the United States during the 2000 fire season (NIFC 2004). In 2003, over 4200 homes in the United States were destroyed by wildland fires, nearly all of them during the October fires in southern California, resulting in more

than two billion U.S. dollars in damages (NIFC 2004). The wildland fire threat to houses was one major impetus for new, and highly controversial, U.S. legislation purportedly aimed at restoring forest health, which focuses on reducing fuel loads (Service 2003). Housing development in the WUI is thus of concern both for wildland fire issues (Covington 2000) and for conservation in general (McKinney 2002).

Housing growth in the United States has been strong in recent decades. During the 1990s, 13.6 million new housing units were built in the United States (13% growth). Americans' affinity for rural settings (Sullivan 1994, Brown et al. 1997) has increased development in exurban and rural areas (Theobald 2001, Hansen et al. 2002, Radeloff et al. 2005). A significant portion of new development occurs at low and medium density and tends to be more dispersed, thus affecting a larger area per housing unit when assuming a disturbance zone with a fixed radius around each house (Theobald et al. 1997, Hammer et al. 2004). Furthermore, housing growth is particularly high in areas that are rich in natural amenities (Johnson and Beale 1994), such as forests (Radeloff et al. 2005), lakes (Radeloff et al. 2001, Schnaiberg et al. 2002), and seashores (Bartlett et al. 2000), or are adjacent to protected areas (Rasker and Hansen 2000). As development pressure mounts in the WUI, environmental problems associated with it may increase.

Despite the significance of the WUI both in the current debate on fire policy and fuel treatment, and for environmental quality in general, empirical data on its

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<sup>5</sup> E-mail: radeloff@wisc.edu

extent and location are lacking. Our goal was to conduct a spatially detailed national assessment of the WUI across the conterminous United States. By doing so, we wanted to provide a framework for scientific inquiries into the effects of housing growth on the environment and to inform both national policymakers and local land managers about the WUI and associated issues.

## METHODS

### *WUI definition and assessment*

Our approach to mapping the WUI was based on an existing WUI definition published in the Federal Register (USDA and USDI 2001), which we applied across the conterminous United States using fine-resolution housing density and land cover data in a Geographic Information System (GIS). The WUI definition in the Federal Register was developed to identify communities at risk in the vicinity of public lands. According to this definition, "the Wildland–Urban Interface is the area where houses meet or intermingle with undeveloped wildland vegetation" (USDA and USDI 2001). Areas where houses and wildland vegetation intermingle are referred to as intermix WUI. Developed areas that abut wildland vegetation are characterized as interface WUI. Although this definition was developed in conjunction with wildland fire policy, it does not explicitly account for differences in fire risk.

Assessing the WUI requires detailed data on housing density. According to the Federal Register definition, WUI areas must contain at least 6.17 housing units/km<sup>2</sup> (or 1 house/40 acres). No maximum housing density is set. We analyzed housing unit counts from the U.S. 2000 decennial census at the census block level. As defined by the U.S. Census Bureau, a housing unit may be a house, an apartment, or a mobile home, and can be occupied or vacant; thus, seasonal homes are included (U.S. Census Bureau 2002). Housing unit counts represent a complete enumeration. Census blocks are generally delineated based on physical features, such as roads and rivers. Blocks vary in size; the median size is 0.01 km<sup>2</sup> and the maximum reaches 2700 km<sup>2</sup> in areas with no housing units.

In addition to housing density, the WUI assessment required fine-resolution vegetation data. We derived vegetation information from the U.S. Geological Survey (USGS) National Land Cover Data (NLCD), which represents classified 30-m resolution Landsat TM satellite data from 1992 for the 48 conterminous states of the United States (Vogelmann et al. 2001). We defined as wildland vegetation the following land cover classes: coniferous, deciduous, and mixed forest; shrubland; grasslands/herbaceous; transitional; and woody and emergent herbaceous wetlands. Excluded from wildland vegetation were low- and high-intensity residential, commercial/industrial, orchards/vineyards, pasture/hay, row crops, small grains, fallow, urban/rec-

reational grasses, bare rock/sand/clay, quarries, open water, and perennial ice/snow. Using a GIS, we calculated the housing density and percentage of wildland vegetation for each census block.

The Federal Register definition distinguishes between intermix and interface WUI. Intermix WUI is defined in the Federal Register as an area above a threshold of 6.17 housing units/km<sup>2</sup> that is dominated by wildland vegetation. We set the threshold for wildland vegetation at 50% of the terrestrial area of a given census block. Interface WUI is characterized by the Federal Register definition as developed areas in the vicinity of wildland vegetation. Thus, we mapped as interface WUI all census blocks above 6.17 housing units/km<sup>2</sup> that contained <50% wildland vegetation, but were within 2.4 km of an area that is heavily vegetated (>75% wildland vegetation) and larger than 5 km<sup>2</sup>. The 2.4-km distance follows the recommendation of the California Fire Alliance (2001) and represents an estimate of the distance a firebrand can fly ahead of a fire front. If a census block was only partially within the 2.4-km distance, then the census block was split, and only the portion within 2.4 km was included as interface. We set a minimum-size threshold at 5 km<sup>2</sup> for the areas that are heavily vegetated to avoid including residential areas that are within 2.4 km of small urban parks.

### *Sensitivity analysis*

Our WUI assessment was heavily based on thresholds, which were mostly set by the Federal Register definition. We thus conducted a sensitivity analysis to test the robustness of the estimates of WUI area and WUI houses. Thresholds for housing density, intermix vegetation, and the interface buffer distance were increased by 100% or decreased by 50%; land cover classes used to identify wildland vegetation were progressively reduced to ultimately include only forests.

The minimum housing density threshold of 6.17 housing units/km<sup>2</sup> in the Federal Register definition was both doubled (12.34 housing units/km<sup>2</sup>) and halved (3.09 housing units/km<sup>2</sup>) in the sensitivity analysis. The minimum wildland vegetation threshold required for intermix WUI was 50% for our national assessment. In the sensitivity analysis, we tested both a 25% and a 75% minimum wildland vegetation threshold. The maximum buffer distance for interface WUI in the national assessment was 2.4 km, which was both doubled (4.8 km) and halved (1.2 km) in the sensitivity analysis. The land cover class list used to define wildland vegetation in the national assessment was reduced to two levels in the sensitivity analysis. The "upland" scenario excluded woody and emergent wetlands from the full list of wildland vegetation classes. The "forest" scenario included only coniferous, deciduous, and mixed forest as wildland vegetation classes. Potential interactive effects among these variables were examined via minimum and maximum WUI estimates. The

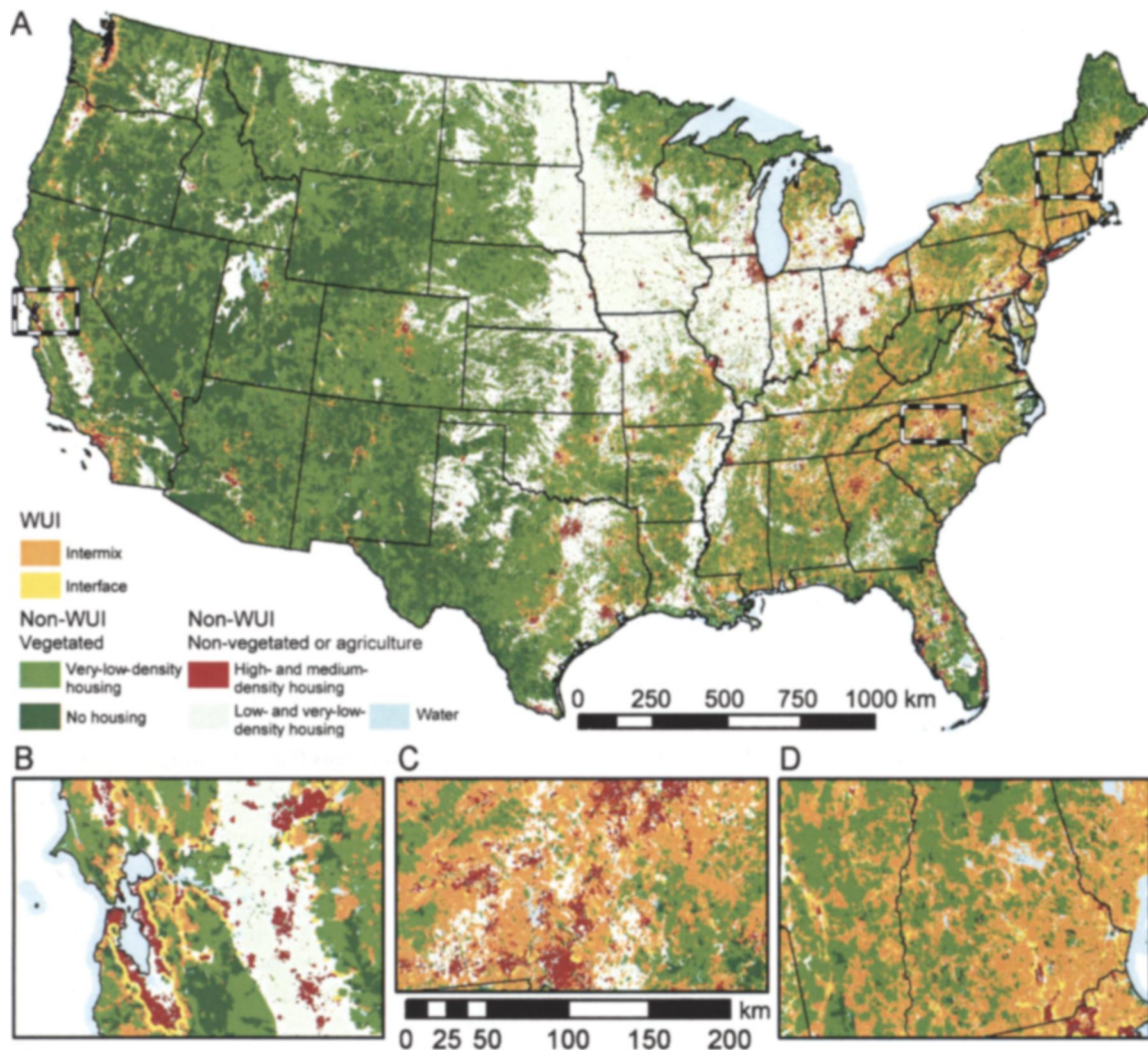


FIG. 1. The wildland-urban interface (WUI) in 2000 in (A) the conterminous United States, (B) the San Francisco Bay area, (C) North Carolina, and (D) New Hampshire. Housing density figures are as follows: very low,  $>0$ – $6.17$  housing units/ $\text{km}^2$ ; low,  $6.17$ – $49.42$ ; medium,  $49.42$ – $741.31$ ; and high,  $>741.31$  (USDA and USDI 2001).

minimum WUI estimate represents a housing density threshold of  $12.34$  housing units/ $\text{km}^2$ , an intermix vegetation threshold of  $75\%$ , an interface buffer distance of  $1.2$  km, and only forest vegetation classes. The maximum WUI estimate represents a housing density threshold of  $3.09$  housing units/ $\text{km}^2$ , an intermix vegetation threshold of  $25\%$ , an interface buffer distance of  $4.8$  km, and the original set of all wildland vegetation classes.

#### RESULTS

Across the conterminous United States, the WUI covers  $719\,156$   $\text{km}^2$  ( $9.4\%$  of the land area) and contains  $44\,348\,628$  housing units ( $38.5\%$  of all housing units). All 48 states contain WUI areas, but the eastern United States has the greatest extent, especially in northern Florida, the southern Appalachians, and coastal areas of the Northeast (Fig. 1A in the Appendix; data

are publicly available online).<sup>6</sup> Major WUI areas are also located along the West Coast, the Colorado Front Range, southeast Texas, and the northern Great Lakes States. WUI is common at the fringe of major metropolitan centers such as Los Angeles, San Francisco (Fig. 1B), Seattle, Denver, Dallas, Atlanta, Washington D.C., New York, and Boston. WUI is also widespread in rural areas without major metropolitan centers that are rich in natural amenities, such as the Sierra Nevada foothills (Fig. 1B), the northern Great Lakes States, southern Appalachia (Fig. 1C), and rural New England (Fig. 1D).

State-level analysis shows that the number of homes in the WUI in a single state reaches up to  $5.1$  million (California), and the WUI land area up to  $55\,280$   $\text{km}^2$

<sup>6</sup> [http://www.silvis.forest.wisc.edu/projects/WUI\\_Main.asp](http://www.silvis.forest.wisc.edu/projects/WUI_Main.asp)

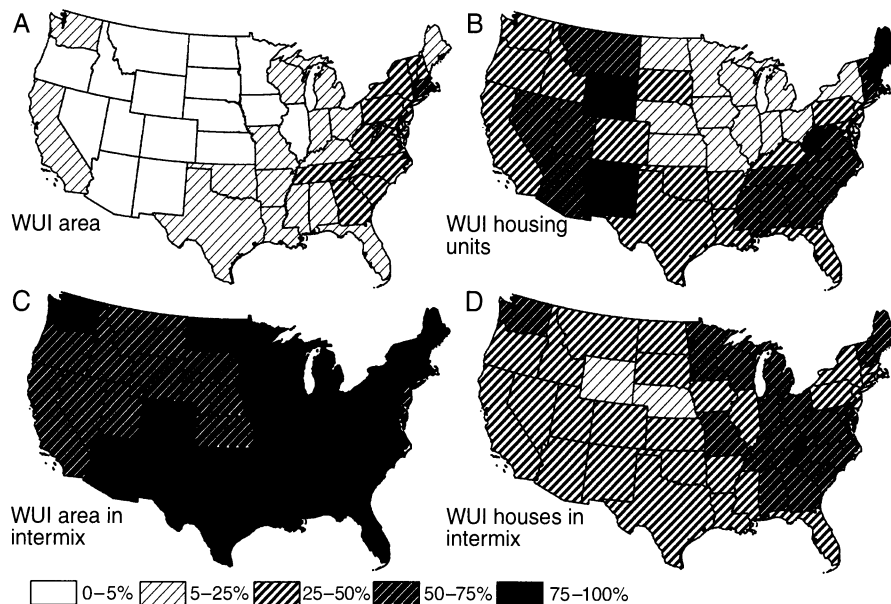


FIG. 2. WUI characteristics at the state level: (A) WUI area as a percentage of total land area, (B) WUI housing units as a percentage of all housing units, (C) percentage of the WUI area that is intermix WUI, and (D) percentage of WUI houses that are in intermix WUI.

(North Carolina). At the state level, the proportion of land area in the WUI reaches 72.4% (Connecticut), and the maximum proportion of housing units in the WUI is 83.5% (New Hampshire). WUI area by state shows a strong east–west gradient, with the highest proportions in the East (Fig. 2A). The proportion of homes in the WUI is high in both the East and the West. In the Midwest, <25% of homes are found in the WUI because wildland vegetation is not as common in these agriculturally dominated states (Fig. 2B). Extensive metropolitan areas also tend to limit the proportion of a state's homes in the WUI even though the absolute number of homes in the WUI can be high (e.g., California).

When we break the WUI into its two components, intermix accounts for the majority of WUI area nationally (80.7%; Fig. 2C). Interface WUI is commonly limited to a ring separating non-WUI urban centers from outlying intermix areas (Fig. 1B). However, interface WUI does not occur around all urban centers, as illustrated by its absence around cities of the Southeast (Fig. 1C). Across the conterminous United States, housing units are almost evenly split between interface and intermix WUI (53.4% vs. 46.6%) partly because housing densities are higher in the interface. In most southeastern states, WUI housing units are predominantly in intermix WUI (Fig. 2D). Interface WUI is more common in western states, occupying up to a third of the WUI area and containing up to two-thirds of the WUI houses.

#### *Sensitivity analysis*

Results of the sensitivity analysis show that the WUI assessment is fairly robust (Table 1). Major changes in

single variables (e.g., +100%, –50%) generally result in <50% change in WUI area or WUI housing units. The only exception to this rule is California, where WUI houses decline by 88% if wildland vegetation is limited to forests, and shrublands are excluded. However, given the high frequency and intensity of fire in chaparral communities, shrublands must be included in any realistic definition of wildland vegetation.

In all three states, WUI area is most sensitive to the housing-density threshold. The number of WUI housing units is most sensitive to changes in the buffer distance that defines interface WUI (California, New Hampshire) or the intermix vegetation threshold (North Carolina). Under the maximum WUI scenario (Table 1), both WUI area and WUI housing units increase by up to 60%, and even under the minimum WUI scenario, there are 384 000 housing units in the WUI in California. The ranking of the states in terms of their WUI area and WUI houses remains constant across all scenarios, suggesting that the general spatial pattern, for example, of more abundant WUI in the East as compared to the West, are not an artifact of the WUI definition that we employed.

#### DISCUSSION

Housing development in or near wildland vegetation is widespread: about one-tenth of the area and one-third of the housing units of the conterminous United States are located in the WUI. The pervasiveness of the WUI has immediate relevance in the current U.S. debate on wildland fire, fuel treatments, and the restoration of fire dependent forest ecosystems (Covington 2000, Service 2003). The WUI is where wildland fires destroy the most structures when fuels and weather are

TABLE 1. Changes in the wildland-urban interface (WUI) area and WUI housing units in California, North Carolina, and New Hampshire, USA, in response to changes in the WUI definition thresholds tested in the sensitivity analysis.

Variable	California		North Carolina		New Hampshire	
	Area (1000s km <sup>2</sup> )	Houses (100 000s housing units)	Area (1000s km <sup>2</sup> )	Houses (100 000s housing units)	Area (1000s km <sup>2</sup> )	Houses (100 000s housing units)
Federal Register definition†	29.3	50.9	55.3	23.2	9.6	4.5
Housing density						
>3.09‡	41.1	51.4	74.0	24.1	13.5	4.6
>12.34	20.7	50.1	33.5	21.3	5.9	4.1
Intermix vegetation						
>25%	30.7	58.0	62.8	27.9	9.7	4.6
>75%	28.6	49.0	47.5	20.6	9.5	4.4
Interface distance						
<4.8 km	33.0	74.7	59.3	28.3	9.7	5.2
<1.2 km	26.4	35.2	52.3	19.8	9.4	3.9
Wildland vegetation						
Upland only†	29.1	50.5	45.4	18.8	9.4	4.0
Forest only†	10.0	6.2	44.8	18.5	9.4	4.0
Minimum WUI†	4.6	3.8	5.0	2.8	5.0	2.8
Maximum WUI†	46.5	79.1	83.1	28.1	13.6	5.4

† See *Methods: WUI definition and assessment* for definition.‡ Housing units per km<sup>2</sup>.

conductive to fire (Covington 2000) and where human-caused fire ignitions are most common (Cardille et al. 2001). The southern California fires of 2003 highlighted the devastating effects that wildland fires can have in WUI areas. Yet, these fires, despite setting records, burned only a small portion of the WUI of southern California, leaving extensive areas of the WUI at risk for future fires. This emphasizes the magnitude of the task that is at hand and suggests that sprawl-limiting policies may have to be paired with fuel treatments to substantially lower the fire threat to homes in the long term.

When interpreting our results with respect to fire, it is important to remember that the Federal Register WUI definition we used is a general one and does not assess wildland fire risk specifically. For example, WUI areas in southern California that are dominated by chaparral communities with short fire-return intervals are perhaps the most prone to fire of all WUI areas in the United States. (Minnich 1983, Keeley et al. 1999, Fried et al. 2004). Conversely, WUI areas in New Hampshire that are located in mesic hardwood forests are much less likely to experience wildland fire (Fig. 1D; Foster and Zebryk 1993). In addition to fire frequency, WUI areas differ in their fire regimes (e.g., frequent but low-intensity surface fire vs. infrequent but catastrophic crown fire) depending on weather patterns, vegetation structure, fuel loads, and topography (Heinselman 1981). And whether a home will burn in the event of a wildfire will depend on its building materials (e.g., cedar shingles vs. sheet-metal roofing), landscaping features, and accessibility to firefighting equipment (Cohen 2000). Our WUI assessment needs to be inte-

grated with spatially detailed data on these factors to estimate fire threat in the United States WUI. Such data are not yet available across the United States, but we have conducted a fire threat ranking for smaller regions (Haight et al. 2004).

The WUI assessment also raises broader issues that reach beyond wildland fire. Numerous case studies show that housing in or near wildland vegetation (and correlates, such as human populations and roads) have profound effects on biodiversity and ecosystems, and that these effects are largely negative (McKinney 2002). Areas with high housing and road densities exhibit lower populations of neotropical migrant birds (Friesen et al. 1995, Cam et al. 2000, Kluza et al. 2000), wolves (Mladenoff et al. 1995), and other large carnivores (Rasker and Hackman 1996). Species richness of butterflies (Blair 1999), birds (Clergeau et al. 1998, Germaine et al. 1998), and mammals (Joly and Myers 2001) is lower where human population density is high. Accordingly, the number of endangered species tends to be higher where human activities are more prevalent (Czech et al. 2000, Sechrest et al. 2002).

At the landscape scale, housing development is a major cause of habitat loss and fragmentation (Theobald et al. 1997, Swenson and Franklin 2000, Radeloff et al. 2005), due in part to new roads built to access homes (Hawbaker and Radeloff 2004). Fragmentation, in turn, causes local extinction and biodiversity declines by reducing the size of habitat patches and of remnant populations (Andrén 1994).

However, not all species decline in response to housing growth. Both human commensals and exotic species may thrive in the WUI (Allen and O'Connor 2000,



Johnson 2001, Langton et al. 2001, Odell and Knight 2001). During construction, habitat conditions favor disturbance-adapted species, and subsequent landscaping around houses often introduces exotic plant species to neighboring ecosystems (Suarez et al. 1998, Pysek et al. 2002). The facilitation of exotic species spread is one of the major processes through which humans affect ecosystems (Vitousek et al. 1997).

There is ample evidence that WUI housing profoundly affects the environment, yet much of what we know about the impacts of housing development has been learned by studying environmental response along urban-to-rural gradients (McDonnell and Pickett 1990). Our results suggest the need for additional research focused on the dispersed housing development typical of intermix type WUI, which covers an extensive and growing area of the U.S. Human-environment conflicts in the WUI are likely to increase in the future, especially if past housing-growth trends continue in rural areas that are rich in natural amenities (Theobald 2001, Hammer et al. 2004, Radeloff et al. 2005). Given these problems, the WUI should be a focus of national discussions on natural resource issues and policies. The pervasiveness of the WUI highlights the value of protected areas, and the need to quickly identify and secure priority sites for conservation in the face of strong development pressure in rural areas. In addition, our results highlight the importance of extending conservation efforts to private lands (Norton 2000), and integrating ecological principles in land-use planning (Broberg 2003) and zoning decisions to maintain key habitats and the corridors that connect protected areas. Solving both wildfire and conservation problems will require landscape-level planning across ownership boundaries, and a broad vision for the future of wildlands and rural areas.

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## APPENDIX

A table showing the amount and the relative abundance of wildland-urban interface (WUI) area and WUI houses (both in the intermix and the interface WUI type) in each state of the conterminous United States is available in ESA's Electronic Data Archive: *Ecological Archives* A015-020-A1.