Landscape and Urban Planning 218 (2022) 104283

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Growth of the wildland-urban interface within and around U.S. National Forests and Grasslands, 1990–2010

Miranda H. Mockrin [a,*], David Helmers [b], Sebastian Martinuzzi [b], Todd J. Hawbaker [c], Volker C. Radeloff [b]

[a] Northern Research Station, U.S.D.A Forest Service, 5523 Research Park Drive Suite 350, Catonsville, MD 21228, United States
[b] Department of Forest Ecology and Management, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, United States
[c] U.S. Geological Survey, Geosciences and Environmental Change Science Center, Denver, CO 80225, United States

HIGHLIGHTS

- Wildland-urban interface houses are common within and around National Forests.
- Land within and around National Forests experienced rapid WUI growth (1990–2010).
- Inholdings within National Forests had the fastest rates of WUI growth.
- More than 75% of private land within and around National Forests was not WUI in 2010.
- The amount of private land not WUI suggests that growth can continue.

ARTICLE INFO

Keywords:
WUI
Residential development
Sprawl
Public lands
Wildfire
Housing

ABSTRACT

The wildland-urban interface (WUI), where housing is in close proximity to or intermingled with wildland vegetation, is widespread throughout the United States, but it is unclear how this type of housing development affects public lands. We used a national dataset to examine WUI distribution and growth (1990–2010) in proximity to National Forests and created a typology to characterize each National Forest's combination of WUI area and housing growth. We found that National Forests are hotspots for WUI growth, with a 38% increase in WUI area and 46% growth in WUI houses from 1990 to 2010, in excess of WUI growth for the conterminous U.S. Growth within National Forests was higher than the surrounding area. Diffuse intermix WUI, where houses are intermingled with wildland vegetation, is common within National Forests, but WUI houses around National Forests were primarily in denser interface WUI areas, which lack substantial wildland vegetation. WUI was more prevalent within and around National Forests in the East, while National Forests in the West experienced higher rates of WUI growth. National Forests with the most challenging WUI issues—extensive WUI area and rapid growth in intermix and interface—were found primarily in the South and interior West. Given the diversity of WUI landscapes, effectively responding to current and future WUI challenges will require both engagement with individual homeowners dispersed throughout National Forests, as well as increased emphasis on mitigating denser interface development around National Forests. At a time when wildfire risks are expected to intensify due to climate change, and 75% of privately owned land within and around National Forests is not yet WUI, understanding WUI growth patterns in proximity to public lands is vital for land management and human well-being.

1. Introduction

The wildland-urban interface (WUI), those areas where houses meet or mingle with undeveloped wildland, is widespread across the United States and rapidly expanding (Radeloff et al., 2018). By 2010 WUI development made up 9.5% of the land area of the conterminous U.S. and 33% of all houses (Radeloff et al., 2018). WUI areas comprise two different types of development: "intermix" WUI where housing

* Corresponding author.
E-mail address: miranda.h.mockrin@usda.gov (M.H. Mockrin).

https://doi.org/10.1016/j.landurbplan.2021.104283
Received 23 December 2020; Received in revised form 28 September 2021; Accepted 9 October 2021
Available online 1 November 2021
0169-2046/Published by Elsevier B.V.

intermingled with wildland vegetation, and "interface" WUI, housing without substantial wildland vegetation, but found in proximity to a sizeable area of wildland vegetation (USDA and USDI, 2001). WUI housing, both adjacent to and intermingled with wildland vegetation, has widespread ecological and natural resource management effects, leading to higher populations of synanthropic and exotic species, declines in sensitive species, more challenging and costly wildfire management, decreased and fragmented wildlife habitat, and increasing pollution (Hansen et al., 2005; Bar-Massada, Radeloff, & Stewart, 2014; Wood et al., 2014; Pejchar, Reed, Bixler, Ex, & Mockrin, 2015). Although housing development occurs on privately owned lands, these broader ecological effects extend beyond boundaries onto public and other private lands. The effects of WUI growth are particularly important to understand in relation to public lands, given both the size of public lands and recent history of housing expansion in proximity to them (Wade & Theobald, 2010; Radeloff et al., 2010; Ager et al., 2019).

In the U.S., federal public lands cover over 2.5 million km^2 (640 million acres) and represent the vast majority of land protected for biodiversity conservation and natural resource management (Aycrigg et al., 2013; Vincent, Eliot Crafton, Comay, & Hoover, 2018). Public lands are critical for landscape-level ecosystem services including clean water, carbon storage, wildlife habitat, and recreation (Hansen & DeFries, 2007; Radeloff et al., 2010; Davis & Hansen, 2011; Hansen et al., 2014). However, human populations in proximity to public lands have increased in excess of national rates of growth (Wade & Theobald, 2010; Radeloff et al., 2010; Hamilton et al., 2013), as the U.S. population distribution has shifted (to the South and West) and deconcentrated, with growing exurban populations, particularly around public lands with desired amenities (Mockrin et al., 2018; Hjerpe, Hussain, & Holmes, 2020). Both natural amenities and wilderness areas can attract in-migration, particularly in rural areas (see more below) (Holmes et al., 2016; Hjerpe et al., 2020). For example, nationwide, housing within 1 km of protected areas grew by 20% in the 1990s in comparison to 13% housing growth for the entire U.S. (Radeloff et al., 2010). Similarly, around the largest National Parks (n = 57), housing densities grew well in excess of national averages from 1940 to 2000 (329% versus 210%) (Davis & Hansen, 2011). Such development has widespread ecological impacts and is particularly critical for wildfire management: development results in more wildfire ignitions, as fires are typically human caused, while also placing more homes at risk and making wildfire management more challenging (Moritz et al., 2014; Smith et al., 2016; Syphard, Keeley, Pfaff, & Ferschweiler, 2017).

Understanding residential development in proximity to public lands is therefore vital to maintain ecological functioning and manage wildfire risk across public and private lands. However, while the overall prevalence and growth of housing in close proximity to federal lands is known (Wade & Theobald, 2010; Radeloff et al., 2010; Davis & Hansen, 2011), additional characteristics of housing remain relatively unstudied. Although there are many different ways to examine extent and distribution of human modification on protected areas and forested lands (Theobald, 2013; Riitters, Schleeweis, & Costanza, 2020), we propose that examining the distribution and growth of WUI housing in relation to public lands is a fruitful way to track housing development with potentially substantial ecological and natural resource management effects. In particular, it is unclear if the housing development found in proximity to public lands meets vegetation and housing density thresholds to be classified as WUI, and what form of WUI development may be most common, intermix or interface (USDA and USDI, 2001; Bar-Massada et al., 2014) (Table 1).

Knowing WUI type—intermix or interface—can allow new insight into the management implications of such residential development in proximity to public lands. Intermix WUI is of particular ecological concern because vegetation is removed and fragmented when houses are built within wildland vegetation (Gonzalez-Abraham et al., 2007; Wilson & Brown, 2015; Olofsson, Holden, Bullock, & Woodcock, 2016). Dispersed development means individual houses create many separate

Table 1
Ecological and wildfire management concerns by wildland urban interface type.

	Interface	Intermix
Ecological/ biodiversity concerns:	• Developed areas create hard barriers, impeding connectivity. • Disturbances based on total number of people and domestic animals are greatest here (e.g., recreation pressure, noise, lights, disease transmission from domestic animals to wildlife).	• Fragmentation/habitat quality concerns for remaining vegetation. • Dispersed houses and infrastructure expand housing footprint and disturbance (e.g., light, noise, cats, invasive plants, septic pollution). • Concerns about biodiversity impacts of vegetation removal for fire risk reduction.
Fire-related concerns:	• Ignitions highest. • Fires losses highest; house to house transmission. • Fire spread poorly understood. • Fuel treatments may be more cost-effective given density of homes. • Emergency response/ smoke exposure reflect dense setting (more homes and infrastructure to protect, more people and facilities exposed to smoke, to evacuate).	• Fire occurrence highest. • Fewer homes to be protected, but larger area and remote setting increases expense and logistical challenges of fire suppression. Road design and access important. • Fuel treatments (including prescribed fire) more challenging with housing intermingled with vegetation and rural setting (terrain/access). • Need for vegetation management to reduce wildfire risk/restore fire regimes on individual properties. • Emergency response complicated by rural setting (limited road networks for evacuation, livestock to evacuate, limited water for fire suppression).

focal points for disturbance, including light, noise, and septic pollution (Longcore & Rich, 2004; Kaushal, Lewis, & McCutchan, 2006; Holgerson, Lambert, Freidenburg, & Skelly, 2018), introduction of exotic and invasive plant species (Gavier-Pizarro, Radeloff, Stewart, Huebner, & Keuler, 2010; Riitters et al., 2018), and wildlife predation from domestic animals (Loss, Will, & Marra, 2013) (Table 1). Wildfire is a concern here as there are both widespread ignitions (ignitions are primarily human-caused) and abundant wildland vegetation to burn (Syphard et al., 2007; Price & Bradstock, 2014; Evers, Ager, Nielsen-Pincus, Palaiologou, & Bunzel, 2019) (Table 1). In addition, when wildfires do occur suppression and emergency response are challenging because housing is dispersed (Gude, Jones, Rasker, & Greenwood, 2013; Hand, Thompson, & Calkin, 2016) (Table 1). Fuel treatments to buffer lower density homes from large areas of wildland vegetation are also challenging to implement given the larger area around dispersed homes requiring treatment and difficult terrain (Evers et al., 2019). Risk reduction instead emphasizes emergency preparedness and actions individuals can take on their properties (thinning vegetation, using fire-resistant building materials).

Interface areas hold substantial numbers of residents and houses, forming a hard border that may restrict connectivity between wildland areas (McGregor, Bender, & Fahrig, 2008; Kreling, Gaynor, & Coon, 2019). Interface areas both provide prized access to nearby wildland areas and serve as a focal source for disturbance, particularly those disturbances based on number of people (e.g., recreation pressure, disease transmission to wildlife, noise pollution) (Banks & Bryant, 2007; Carver et al., 2016; Mennitt & Fristrup, 2016; Kellner et al., 2017). Although natural vegetation is sparse in interface areas, when wildfires do occur, buildings themselves can become fuel and greater numbers of

buildings are at risk (Palaiologou, Ager, Nielsen-Pincus, Evers, & Day, 2019) (Table 1). For example, over 50% of all buildings lost to wildfire in California from 1985 to 2013 were in interface areas, although interface made up only 2% of fire perimeters by area (Kramer, Mockrin, Alexandre, & Radeloff, 2019). However, fuel treatments may be more cost effective here given the density and number of buildings that can be protected (Evers et al., 2019) (Table 1).

Understanding the extent and distribution of WUI types near public lands can therefore provide insight into the ecological processes and wildfire management across public and private lands. However, at present, the relationships between WUI and public lands are unclear. Existing literature demonstrates the social complexity of human communities in WUI environments, using a variety of definitions for WUI (Paveglio, Brenkert-Smith, Hall, & Smith, 2015, Wigtil et al., 2016; Palaiologou et al., 2019). Other efforts examine housing densities and WUI types for communities near National Forests, with a focus on identifying communities in the West most likely to be exposed to wildfire originating within National Forest boundaries (Evers et al., 2019; Palaiologou et al., 2019). However, WUI landscapes are widespread throughout the United States, and management concerns extend beyond wildfire risk. Examining WUI distribution nationally is vital given the variation in distribution of native vegetation, land use history, and public lands across the US. For example, WUI is widespread across the naturally forested and densely developed East (Radeloff et al., 2018), but most federal public lands occur in the West, where WUI area is less extensive but recent WUI growth is more rapid. Nationally, intermix WUI is the most widespread WUI type in area, and the denser interface holds the majority of WUI houses (60.7% of all WUI houses in 2010) on a smaller footprint (Radeloff et al., 2018), but it is unclear how these patterns will change in proximity to federal lands, which are often in remote areas.

Accordingly, in this study we characterized WUI distribution and growth, both within and around a key type of federal lands, the National Forests and Grasslands (hereafter, National Forests). The Forest Service is an apt focus for this study as it is the largest federal land holder with holdings in both the East and West (Fig. 1), and is the primary federal agency that funds and manages wildfire suppression (Steelman, 2016). The Forest Service also has extensive private land inholdings with National Forest administrative boundaries, so that housing growth occurs both within and around National Forest perimeters.

To characterize WUI dynamics in relation to National Forests, we had several research objectives. ***Our first objective was to quantify WUI area and houses within and around National Forests (2010)***, examining both the prevalence of WUI and non-WUI areas and houses, and the proportion these WUI areas and houses represented of total WUI for the conterminous U.S. Assessing WUI distribution in proximity to National Forests in comparison to land area, WUI area, and WUI houses for the conterminous U.S. allowed us to determine if National Forests were a focal area for WUI distribution. We also compared WUI distribution within and around National Forests. WUI trends inside the boundaries of National Forests (i.e., in inholdings) are critical for natural resource managers, but we anticipated that more WUI development would be outside (i.e., around) National Forest boundaries, making it important to assess WUI in both locations. Measuring private land that remained non-

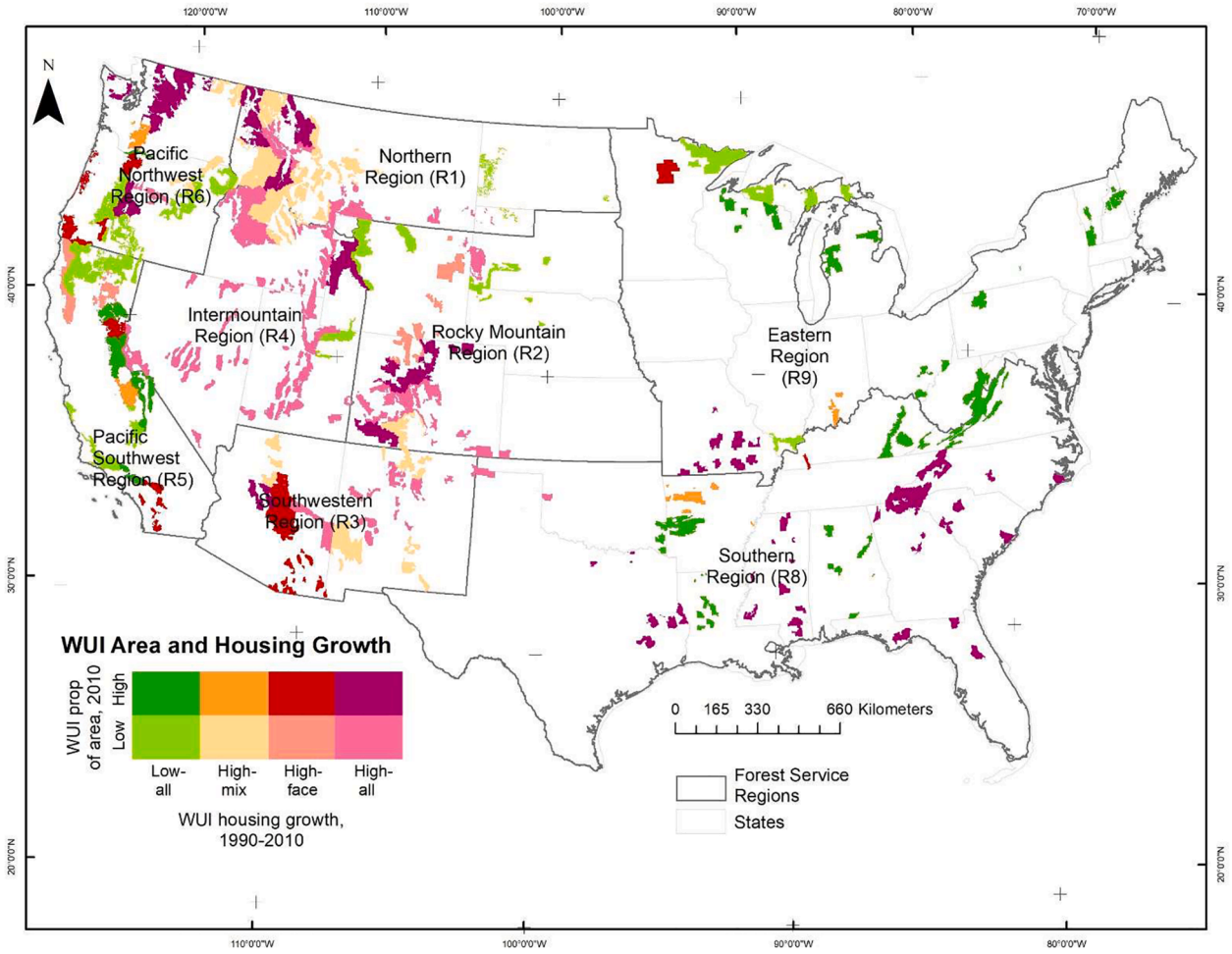

Fig. 1. Typology of wildland urban interface (WUI) area and growth for individual National Forests and regions, showing WUI area (2010) and level and type of WUI housing growth (1990–2010), for combined area within and around (10 km buffer).

WUI allowed us to consider how the WUI footprint can expand in proximity to National Forests in the future. Because National Forests span a diverse range of settings and conditions, as part of this objective we also examined WUI extent in relation to two different characteristics of National Forests: an index of natural amenities (McGranahan, 1999) and the proportion of land protected as a federal wilderness area. Federal wilderness areas are congressionally designated and managed to preserve natural conditions without permanent improvements or human influence (the highest level of protection; IUCN Protected Area category Ib) (Dudley, Shadie, & Stolton, 2013).

Our second objective was to determine growth rates of WUI area and houses within and around National Forests (1990–2010), comparing these increases to WUI growth for the remainder of the conterminous US. Given the distribution of and natural amenities offered by National Forests, we expected National Forests would be a focal area for WUI growth nationally, both within and around National Forests. As with objective 1 above, we also compared the rates of WUI interface and intermix housing growth to natural amenities (McGranahan, 1999) and the proportion of land protected as wilderness.

For both WUI distribution in 2010 (Obj. 1) and growth from 1990 to 2010 (Obj. 2), we compared findings for the eight Forest Service administrative regions across the U.S. (Fig. 1). Because of the diversity of land use history and public land distribution in the U.S., we expected to find varying WUI distribution and growth by region. Nationally, WUI is widespread in the East, but growth is most rapid in the West (Radeloff et al., 2018), and we expected this would hold true for areas within and around National Forests as well.

Finally, ***our third objective was to characterize the distribution and growth of WUI by types—intermix and interface***. Nationally, WUI intermix and interface make greater contributions to total WUI area and houses, respectively, but we anticipated these patterns would vary in the more remote settings in proximity to National Forests. Accordingly, we examined distribution and growth of WUI types for the National Forest network as a whole, and for each National Forest, creating a typology that combined current WUI area and recent housing growth to characterize the 108 National Forests. We used the individual National Forests in our typology classifications because they are the unit of management, and this forest-level information on WUI area and growth reveals the variety of management challenges and opportunities posed by WUI growth across the National Forest System. The individual National Forest perspective, combined with our analyses of WUI distribution and growth, offers a full portrait of WUI challenges at multiple scales.

2. Methods

2.1. Study area

National Forests are multiple-use public lands, supporting a range of activities including timber harvesting, recreation, grazing, mineral extraction, and hunting and fishing (Multiple-Use Sustained-Yield Act of 1960 [16 U.S.C §528]). The 108 National Forests across the conterminous U.S. are located in eight different administrative regions (Fig. 1) (USDA Forest Service. 2018, 2018). Over 75% of National Forest area is in in the West, with remaining National Forest land nearly equally divided between two regions in the East (Fig. 1). However, National Forests in the East are still larger than all other federal lands combined in this region (Hoover, 2016). National Forests in the East were established later than those in the West, often on tax delinquent land, and are intermixed with private lands (Roper, Capurso, Paroz, & Young, 2018). Catastrophic wildfire is less of a concern in the East, but small wildfires are common (Carlson, Sebasky, Peters, & Radeloff, 2021) and wildfire is an important ecosystem process in the Midwest and South, with prescribed fire use most common in the South (Melvin, 2020). In contrast, National Forests in the West were established earlier, have fewer inholdings, and are larger and typically fire prone, with less use of prescribed fire (Radeloff et al., 2010; Schoennagel et al., 2017; Ager et al., 2019). In our study, we used external National Forest boundaries to demarcate land within National Forests, which include publicly owned and managed land as well as private land inholdings. Since housing development is prohibited on land owned by the Forest Service, these privately owned inholdings are where housing development occurs within the external boundaries of National Forests.

2.2. Data

Radeloff et al. (2018) mapped the WUI from 1990 to 2010 based on definitions from the Federal Register (USDA and USDI, 2001), combining information on housing units and population at the census block level from the 1990, 2000, and 2010 decennial censuses with wildland vegetation from 1992, 2001, and 2011 from the National Land Cover Database (wildland includes forests (classes 41–43), shrublands (classes 51 and 52), grasslands (class 71), and woody wetlands (class 90)) (Radeloff et al., 2018). Because census block boundaries change from each decennial census housing units and population from 1990 and 2000 were allocated into 2010 census block geometries (Radeloff et al., 2018). All WUI areas have $\geq$1 house/40 acres (6.17 houses/km^2), with housing densities calculated by excluding any public lands in the census block, using Protected Area Database (PAD), version 2 (Institute, 2012). Intermix areas have $\geq$50% wildland vegetation. Interface areas have $\leq$50% vegetation but are within 1.5 miles (2.4 km) of a sizeable area of wildland vegetation ($\geq$5 km^2 with $\geq$75% wildland vegetation) (USDA and USDI, 2001). Unfortunately, 2020 WUI data were not available at time of submission. For more detail on WUI data please see Radeloff et al. (2018).

We analyzed geospatial data on National Forests from the USDA Forest Service in order to group land areas by National Forest name. We did so by combining an ownership data layer that identified lands owned by the Forest Service (USDA Forest Service. 2019, 2019) with an administrative boundaries data set (USDA Forest Service. 2018, 2018). The combined data sets included 3,263 polygons that belonged to the 108 National Forests. During data exploration we found some small polygons owned by the Forest Service but used for administration and detached from the rest of land holdings (e.g., offices, infrastructure for vehicles or communications). Although small in size, these polygons were erroneously enlarging buffers around National Forests. We removed all small polygons (smaller than 15 acres, or 0.06 km^2) that were more than 5 km away from other National Forest polygons. For the remaining small polygons ($<$0.06 km^2 in closer proximity to National Forest lands) we retained only those with wildland vegetation (n = 413), yielding a final set of National Forest polygons (n = 2,760) for the 108 National Forests. We then used the Protected Area Database, version 2 (Institute, 2012) to determine area of public and private land, excluding water, inside and around each National Forest. We used these broader public lands data because they include local, state, and federal lands; particularly in the West, National Forests were often adjacent to other public lands. We used these data to calculate the proportion of public land in wilderness, for each National Forest and 10 km buffer.

Data on natural amenities came from McGranahan (1999) natural amenity index, which combines topographic variation, water area, and four measures of climate to rank each county in the U.S., ranging from one for the lowest amenity counties to seven for the most amenity-rich counties. This index is widely used in the literature, and consistently associated with population growth in rural areas (Chi & Marcouiller, 2013; Hjerpe et al., 2020; McGranahan, 1999). For each National Forest, we assigned a weighted mean amenity score, based on proportion of National Forest per county (Supplemental Fig. 1). Data on wilderness areas came from the Protected Area Database, version 2 (Institute, 2012). We calculated the total and proportional area of federal wilderness intersecting National Forests within each forest boundary and for their surrounding 10 km buffer zones (Supplemental Fig. 2).

2.3. Analyses

Based on administrative boundaries, we calculated WUI area and houses within National Forests and in around a 10 km buffer around National Forests. Within National Forests we had 853,765 km^2 of land, of which 705,779 km^2 (82.7%) was public and 147,987 km^2 (17.3%) private. Our 10 km buffer around National Forests was similar in size to land area within administrative boundaries but was primarily privately-owned: a total of 824,020 km^2 in the 10 km buffer surrounding National Forests, 590,400 km^2 (71.6%) of which was private land and 233,620 km^2 (28.4%) public land. In total, the 1.6 million km^2 land area found around and within National Forests represented just over 20% of the area of the conterminous U.S. We summarized WUI houses and area within and around National Forests at three levels: nationally (entire National Forest System), for each region, and for each individual National Forest (Fig. 1). We focused on WUI housing rather than WUI population because houses directly reflect development history, particularly in amenity areas where seasonal population counts can vary.

Calculating WUI area and houses required additional processing when our National Forest and buffer perimeters bisected 2010 Census blocks. In each case we estimated private area and houses within bisected 2010 Census blocks based on area weighting. If perimeters intersected with blocks that contained both public and private land, WUI processing had already allocated houses in the privately owned portion of the block. For all blocks, we were therefore able to area-weight and summarize WUI/non-WUI housing units, public/private area, and WUI/non-WUI area. If a block was entirely on public land but contained houses, we assumed that they were located on an inholding too small to be mapped as private land by the PAD. We included these houses and area in WUI and non-WUI totals, but not in our totals of private land within National Forests. It was extremely rare to find such WUI blocks completely within land designated as public: they made up less than 2% of WUI area and houses within and around National Forests.

Because buffers for adjacent National Forests overlapped, we performed GIS analyses of WUI data separately for each three geographic levels (all National Forests combined, each region's National Forests, and each individual National Forest). For each level we calculated WUI houses and area, for intermix and interface, for 1990, 2000, and 2010. National studies of WUI change found that trends were consistent across the 1990s and 2000s (Radeloff et al., 2018), so we calculated change only for the entire time period, 1990–2010. To better characterize National Forests, we correlated different measures of WUI (proportion of private land in WUI area in 2010, percent growth in WUI intermix and interface housing and area from 1990 to 2010) by both natural amenities and proportion of public land in wilderness. After examining data for normality using exploratory plots and Shapiro-Wilk tests, we used Spearman's correlation to quantify relationships between WUI extent and growth and amenity and wilderness settings for National Forests. We analyzed the combined area within and around a National Forest for these analyses.

In order to characterize variation in WUI area and growth by type below the national level we created a typology of WUI area and growth, cross walking WUI area in 2010 with growth rate in WUI housing units from 1990 to 2010. We simplified our analyses by including the entire area within and around a National Forest together as one unit. We focused on the housing growth rate because WUI housing is increasing at a faster rate than WUI area nationally (Radeloff et al., 2018). For WUI housing growth, we placed each National Forest into one of four categories: low housing growth for both interface and intermix (0-50th percentile for both); high housing growth for both interface and intermix (50th–99th percentile for both); and high housing growth for only one WUI type (50–99th percentile for one type, but 0–50th for the other). For WUI area we separated National Forests with small (0–50th percentile) and large (50–99th percentile) WUI area. This typology allowed us to identify National Forests facing the most pressing WUI challenges (most extensive WUI area and rapid WUI housing growth), and those with lower priority WUI concerns (smaller WUI area and slower recent WUI housing growth), and consider management challenges across the full range of WUI conditions.

3. Results

3.1. WUI area and houses within and around National Forests (2010)

By 2010, there were 133,261 km^2 of WUI within and around National Forests, containing 7.1 million houses (Table 2). Most WUI area and houses were around National Forests as opposed to within: there were 98,631 km^2 of WUI and 5.7 million WUI houses in the 590,400 km^2 private land around National Forests (Table 2). Within National Forests there were 147,987 km^2 of private land, of which 34,630 km^2 was WUI, containing more than 1.3 million WUI houses (Table 2). Both within and around National Forests, the majority of housing was in WUI-designated census blocks, particularly within National Forests: 85.5% of all houses were in WUI-designated census blocks within National Forests in comparison to 65.7% of houses around National Forests and 30.1% of houses in the rest of the conterminous U.S. (Table 2).

Both within and around National Forests, WUI areas remained a small proportion of privately owned land (Table 2). The proportion of privately owned land in WUI was higher within National Forests than around: 23.4% of the privately owned land within National Forest boundaries and 16.7% of privately owned lands around National Forests were WUI as of 2010 (within: 34,630 km^2 WUI/147,987 km^2 private land; around: 98,631 km^2 WUI/590,400 km^2 private) (Table 2). Most privately owned land thus remained non-WUI (77.7% within and 83.4% around). Non-WUI blocks were typically those with no housing or low housing densities. In total, the WUI area and houses found within and around National Forests were a small portion of the nation's total WUI. The area within and around National Forests was just over 20% of all land area in the U.S., and by 2010, held 17.3% of all WUI area nationally (133,261 km^2 WUI within and around National Forests out of 770,301 km^2 WUI in the U.S.) and 16.3% of all WUI houses (7.1 million WUI houses within and around National Forests out of 43.4 million WUI houses for the U.S.) (Table 2).

As expected, National Forest administrative regions varied in the distribution of WUI area and houses. Considering the area within and around National Forests together, twice as much WUI area was in proximity to National Forests in the East than in the West (Fig. 2a). WUI was a larger proportion of privately owned land within and around National Forests in the East: WUI comprised 37.3% of all privately owned land within National Forests in the Southern Region (R8) and 26.8% for the Eastern Region (R9) (and 31.9% and 23.7% of all privately owned land around National Forests, for Southern Region (R8) and Eastern Region (R9), respectively) (Table 3). In contrast, in the West, land within and around National Forests was less likely to be WUI (ranging from 7.1% to 16.3% of privately owned land within and 6.7%-18.3% of land around) (Table 3). In absolute numbers, the greatest numbers of WUI houses within and around National Forests were located in the East and in the Pacific Southwest Region (R5) (Fig. 2b).

National Forests' contribution to regional totals in WUI area and houses also varied between East and West. National Forests were a focal area for WUI in the West, particularly the interior West, where WUI area and houses were likely to be within and around National Forests. For example, for the Northern Region (R1), 64.0% of the region's WUI houses and 73.4% of the region's WUI area were located within and around National Forests, and for the Intermountain Region (R4), more than half of the regions' WUI area and houses were within and around National Forests (Table 3). The remaining regions in the West had less of the regions' WUI area within and around National Forests, but still higher proportions than in the East, where under 16% of regions' WUI area and less than 12% of WUI homes were within and around National Forests (Table 3).

While amount and distribution of WUI differed across regions, many

Table 2
Area, housing units, and population in the wildland urban interface (WUI), within and around (10 km buffer) National Forests and Grasslands (National Forests), and rest of conterminous United States and 1990–2010.

	Area (km^2)			Housing units			Absolute change 1990–2010		Percent change 1990–2010	
	1990	2000	2010	1990	2000	2010	Area (km^2)	Hous.	Area	Hous.
Within and Around National Forests (10 km)[#]										
WUI	96,563	116,491	133,261	4,868,063	5,975,105	7,097,870	36,698	2,229,807	38	45.8
Interface	18,792	22,421	24,576	2,957,942	3,597,428	4,248,389	5,783	1,290,447	30.8	43.6
Intermix	77,770	94,071	108,685	1,910,121	2,377,677	2,849,481	30,915	939,360	39.8	49.2
Non-WUI, priv	643,477	623,871	607,390	2,618,544	2,906,732	3,234,097	−36,087	615,553	−5.6	23.5
Within National Forests[^]										
WUI	24,521	30,033	34,630	901,842	1,115,000	1,327,011	10,109	425,169	41.2	47.1
Interface	2,566	3,034	3,285	369,872	445,874	514,425	719	144,553	28	39.1
Intermix	21,955	26,999	31,345	531,970	669,126	812,586	9,390	280,616	42.8	52.8
Non-WUI, priv	124,600	119,332	114,929	213,404	219,610	225,579	−9,671	12,175	−7.8	5.7
Around National Forests (10 km)*										
WUI	72,042	86,458	98,631	3,966,221	4,860,105	5,770,859	26,589	1,804,638	36.9	45.5
Interface	16,226	19,386	21,291	2,588,070	3,151,554	3,733,964	5,065	1,145,894	31.2	44.3
Intermix	55,815	67,072	77,340	1,378,151	1,708,551	2,036,895	21,525	658,744	38.6	47.8
Non-WUI, priv	518,877	504,538	492,460	2,405,140	2,687,122	3,008,518	−26,416	603,378	−5.1	25.1
Rest of United States (outside study areas)										
WUI	484,269	572,038	637,040	25,914,619	30,971,755	36,336,242	152,771	10,421,623	31.5	40.2
Interface	106,925	124,168	138,070	15,477,010	18,339,600	22,136,582	31,146	6,659,572	29.1	43.0
Intermix	377,345	447,869	498,970	10,437,609	12,632,155	14,199,660	121,625	3,762,051	32.2	36.0
Non-WUI, all	6,857,577	6,769,486	6,704,195	68,240,027	75,329,528	84,210,046	−153,382	15,970,019	−2.2	23.4

#Within and around National Forests public and private land were 939,399 km^2 and 738,387 km^2, respectively.
^Within National Forests public and private land were 705,779 km^2 and 147,987 km^2, respectively.
*Around National Forests public and private land were 233,620 km^2 and 590,400 km^2, respectively.

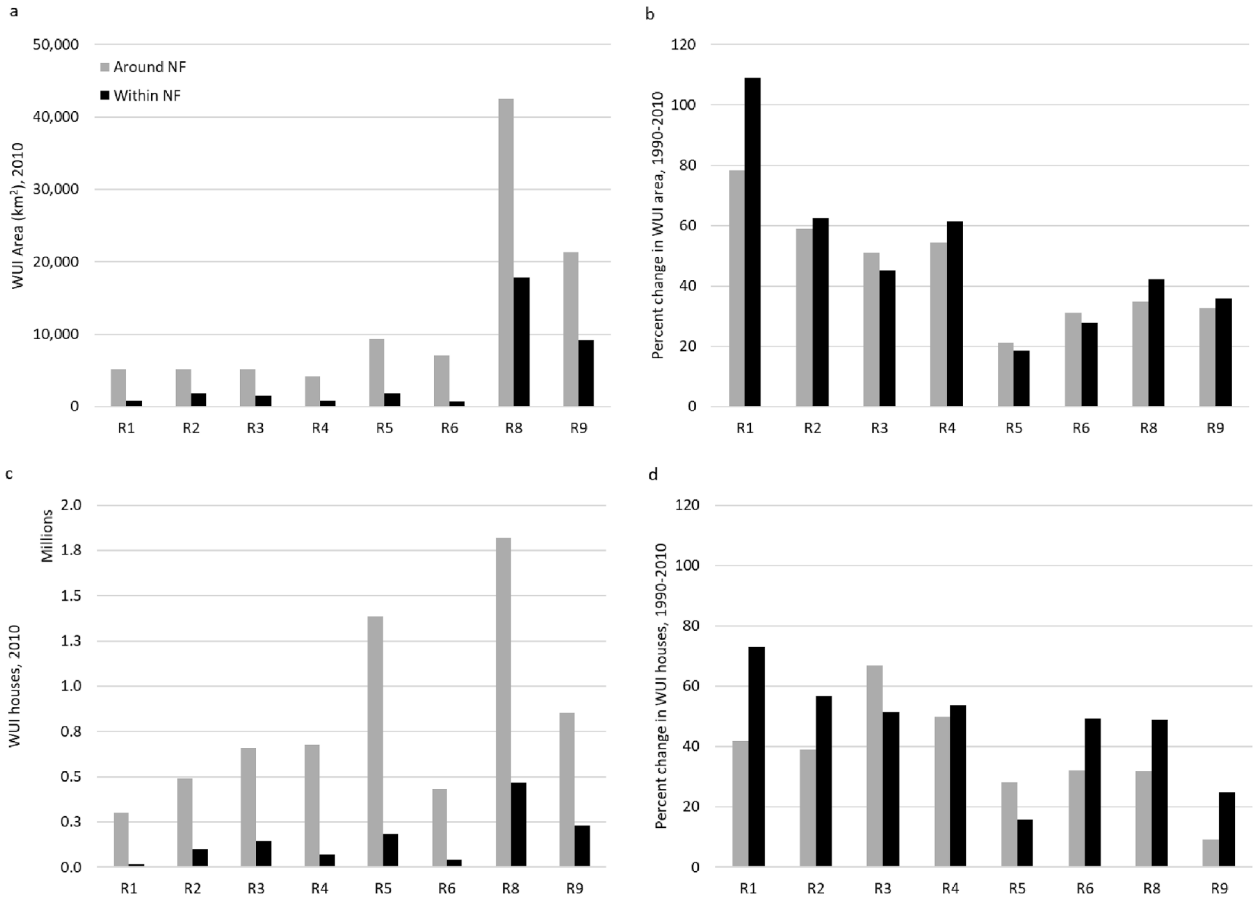

Fig. 2. WUI within and around National Forests (NFs), by administrative region: a) wildland urban interface (WUI) area, 2010, b) percent growth in WUI area (1990–2010), c) WUI housing units, 2010, and d) percent growth in WUI housing units (1990–2010).

Table 3
Distribution of wildland urban interface (WUI) and non-WUI area and houses within and around National Forests (NFs), relative to each Region's housing and area. All data from 2010, except for % growth from 1990 to 2010.

	WUI km^2				Non-WUI area, privately owned (km^2), 2010			% private land in WUI			% of region's WUI area found:		
	Region total	Within and Around NFs	Around NFs (% growth)	Within NFs (% growth)	With & Around NFs	Around NFs	With NFs	With & Around NFs	Around NFs	With NFs	With & Around NFs	Around NFs	With NFs
Northern R1	8,079	5,928	5,136 (78.4%)	792 (108.9%)	80,994	71,205	9,789	6.7	6.7	7.1	73.4	63.6	9.8
Rocky Mountain R2	16,330	6,940	5,098 (59.1%)	1,841 (62.6%)	89,286	69,220	20,066	7.0	6.8	7.9	42.5	31.2	11.3
Southwestern R3	15,651	6,660	5,106 (50.9%)	1,555 (45.2%)	58,697	51,177	7,519	9.9	8.9	16.3	42.6	32.6	9.9
Intermountain R4	8,861	5,004	4,158 (54.5%)	846 (61.5%)	52,554	44,848	7,706	8.0	7.9	8.5	56.5	46.9	9.5
Pacific Southwest R5	26,967	11,116	9,274 (21.3%)	1,842 (18.7%)	52,816	41,127	11,690	17.0	18.3	12.2	41.2	34.4	6.8
Pacific Northwest R6	23,197	7,700	6,997 (31.2%)	703 (27.9%)	66,418	61,875	4,544	10.2	10.1	11.9	33.2	30.2	3
Southern R8	389,783	60,334	42,507 (35%)	17,828 (42.3%)	119,335	90,809	28,526	33.3	31.9	37.3	15.5	10.9	4.6
Eastern R9	277,760	30,522	21,298 (32.8%)	9,223 (36%)	93,422	68,333	25,090	24.6	23.7	26.8	11.0	7.7	3.3

	WUI houses				Non-WUI houses			% of houses in WUI			% of region's WUI houses found:		
	Region total	Within and Around NFs	Around NFs (% growth)	Within NFs (% growth)	With & Around NFs	Around NFs	With NFs	With & Around NFs	Around NFs	With NFs	With & Around NFs	Around NFs	With NFs
Northern R1	465,328	297,592	277,085 (41.8%)	20,507 (73.0%)	144,902	135,751	9,151	68.9	68.9	69.1	64.0	59.5	4.4
Rocky Mountain R2	1,494,522	530,026	431,662 (38.8%)	98,364 (56.6%)	176,704	162,711	13,993	77.0	75.1	87.5	35.5	28.9	6.6
Southwestern R3	1,925,223	734,108	590,550 (66.9%)	143,558 (51.4%)	305,757	298,201	7,556	72.4	68.9	95.0	38.1	30.7	7.5
Intermountain R4	1,228,638	692,997	621,065 (49.8%)	71,932 (53.5%)	479,009	431,140	47,869	61.0	61.1	60.0	56.4	50.5	5.9
Pacific Southwest R5	4,424,422	1,438,550	1,254,328 (28.1%)	184,222 (15.8%)	952,210	942,592	9,618	62.2	59.5	95.0	32.5	28.4	4.2
Pacific Northwest R6	1,521,369	415,460	375,031 (32.0%)	40,429 (49.3%)	266,881	256,712	10,169	64.0	62.8	79.9	27.3	24.7	2.7
Southern R8	18,064,964	2,086,692	1,620,147 (31.9%)	466,545 (49.1%)	853,296	780,998	72,298	72.8	70.0	86.6	11.6	9.0	2.6
Eastern R9	13,802,916	977,170	744,267 (9.3%)	232,903 (24.9%)	461,854	406,929	54,925	70.2	67.7	80.9	7.1	5.4	1.7

patterns observed nationally for WUI distribution also held true for regions. For example, for all regions WUI area was larger and WUI houses more numerous around National Forests than within (Fig. 2). In all regions the majority of houses found within and around National Forests were in WUI-designated census blocks (60.0%-95.0% of all houses within National Forests and 59.5%-75.1% of all houses around National Forests were WUI houses) (Table 3). For all regions, the majority of land within and around National Forests remained non-WUI (Table 3).

At the level of the National Forest (n = 108), the proportion of area in WUI was not correlated with natural amenities nor with percent wilderness area (for combined area within and around each National Forest) (Fig. 3). Total WUI area (km^2) in 2010 was weakly negatively correlated with amenity and percent wilderness, most likely because National Forests in the East contain more WUI area but have lower amenity scores and less wilderness area (Supplemental Fig. 1,2, Supplemental Table 1). Similarly, intermix housing units in 2010 were weakly negatively correlated with percent wilderness, with no relationship between other measures of WUI housing, wilderness, and amenities (Supplemental Figs. 1, 2, Supplemental Table 1).

3.2. WUI growth within and around National Forests (1990–2010)

WUI growth rates within and around National Forests exceeded rates of WUI growth for the rest of the US and were highest within National Forests (47.1% increase in WUI houses and 41.2% in WUI area inside National Forests over the past two decades) (Table 2). During the same time period, there was a 45.5% increase in WUI houses and 36.9% growth in WUI area around National Forests, still higher than rates of WUI growth for the rest of the U.S. (40.2% increase in WUI houses, 31.5% in WUI area for the rest of the conterminous U.S.).

As with WUI distribution in 2010, WUI growth rates varied by region. WUI growth rates in area were highest for National Forests in the interior West (R1-4) with increases of 50% or more in WUI area for the combined area within and around National Forests (Fig. 2). For all regions, WUI growth rates exceeded rates of WUI growth for the rest of the conterminous U.S. Notably, although WUI area was extensive within and around National Forests in the East by 1990, WUI area in the East still expanded faster than WUI area for the rest if conterminous U.S. (i.e., 37.1% increase in area in Southern Region (R8) and 33.7% increase in area in Eastern Region (R9) for area within and around National Forests from 1990 to 2010, in comparison to 31.5% increase in WUI area for the

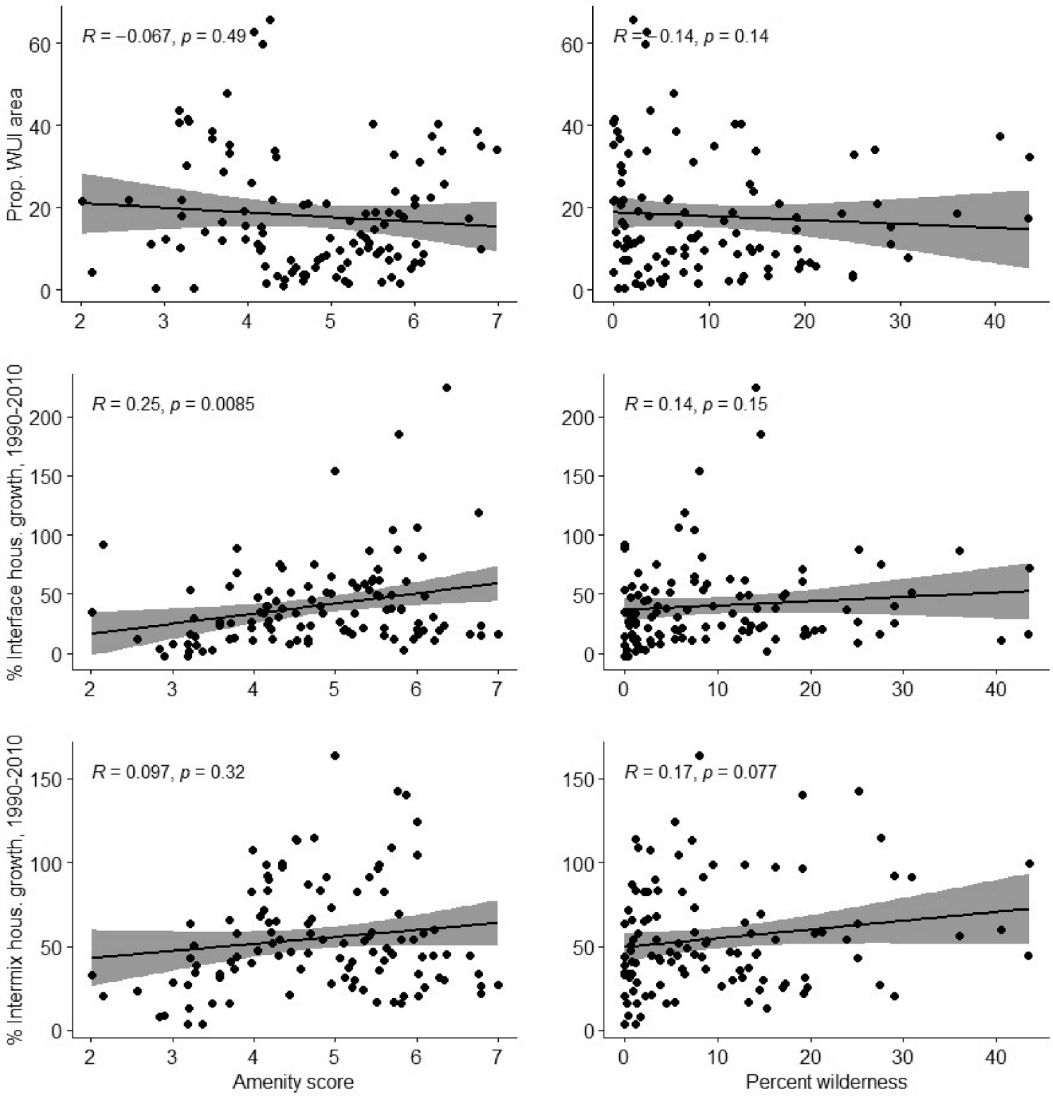

Fig. 3. Plots and Spearman's correlations of wildland urban interface (WUI) extent, 2010, and growth, 1990–2010, with amenity score and percent wilderness, for National Forests and surrounding 10 km buffers.

rest of conterminous U.S. during the same time period) (Table 2, Fig. 2). WUI housing growth was above 50% for most regions, except for the Pacific Southwest (R5) and Eastern Region (R9), both of which had higher total numbers of WUI houses in 1990. WUI housing growth within and around National Forests in the Southern Region (R8) was particularly notable, considering the number of WUI houses already present by 1990 (Fig. 2).

For most regions, growth in WUI area and houses within National Forests was higher than around, the same as trends for the National Forest System as a whole, but the West had some exceptions. The Southwestern Region (R3) and Pacific Southwest Region (R5) grew faster in WUI area and houses around National Forests, while Pacific Northwest (R6) grew fastest in WUI area around National Forests (Table 3).

3.3. WUI types (intermix, interface) within and around National Forests (1990–2010)

Both within and around National Forests, WUI area was primarily intermix, making up 90% of WUI area within National Forests and 78.4% of WUI area around National Forests in 2010 (Table 2). WUI houses were primarily intermix within National Forests (61.2% of all WUI houses), but around National Forests WUI interface houses were most common (64.7% of all WUI houses). Around National Forests therefore distribution of houses and area by WUI type was similar to WUI composition across the U.S. (for the entire U.S. in 2010, 78.8% of WUI area was intermix, and 60.7% of all WUI houses were interface) (Table 2). WUI within National Forests differed from these national patterns, with more area and houses in intermix (Table 2).

From 1990 to 2010 intermix also grew rapidly within and around National Forests, both in area and houses (Table 2). Growth in intermix houses and area was especially elevated within National Forests, above rates of intermix growth for the rest of the conterminous U.S. (i.e., within National Forests, 52.8% growth in intermix houses and 42.8% growth in intermix area in comparison to 36.0% growth in intermix houses and 32.2% in intermix area for the rest of the conterminous U.S.) (Table 2). Rates of intermix growth for area and houses were lower around National Forests, but still higher than intermix growth for the rest of conterminous U.S. (Table 2). In contrast, interface area growth within National Forests was slightly slower than rates of growth for the rest of the conterminous U.S., but slightly higher around National Forests (Table 2). Interface housing similarly grew slightly higher around National Forests than for the rest of the conterminous U.S., with the slowest interface housing growth within National Forests (Table 2).

Elevated rates of WUI growth within National Forests reflect the smaller starting values in 1990, but examining absolute change in WUI area and houses, relative to private land available, also demonstrates the relative scope of WUI growth by type. Although private land outside National Forests was larger than private land inside by 4:1, the intermix area and housing units added during this time period were distributed 2.3:1 around National Forests relative to within (Table 2). Conversely, absolute change in interface housing units and area was greater around National Forest than within: although private land was more prevalent outside National Forests than within by 4:1, the interface area and housing units added during this time period were distributed more than 7:1 around National Forests relative to within (Table 2).

At the level of individual National Forests (n = 108), growth rates of intermix and interface houses were not related to percentage of wilderness, and there was also no relationship between natural amenity score and growth rate for intermix houses (analyses for combined area within and around National Forests). Only growth rate in WUI interface houses was weakly positively related to natural amenity scores (Fig. 3). Growth in WUI interface and intermix area was not related to amenity scores or proportion of public land in wilderness areas (Supplemental Table 1).

3.4. WUI typology of distribution and growth for individual National Forests (1990–2010)

We used our typology to further characterize individual National Forests, combining proportion of WUI area (2010) relative to private land (hereafter, percent private land in WUI) and type and rate of housing growth (1990–2010) (Fig. 1, Supplemental Table 2). The proportion of area in WUI in 2010 was not correlated with growth in WUI housing over the two previous decades. Trends in intermix and interface housing growth were similar though; 70% of all National Forests had either low or high growth for both (Fig. 1, Supplemental Table 2).

The typology results highlight National Forests with the most pressing and complex WUI concerns, those National Forests with both greater proportion in WUI area and rapid recent housing growth in intermix and interface (n = 20) (Fig. 1, Supplemental Table 2). Over half of these National Forests were found in the West, either Interior West (R1-4) (n = 8) or Pacific Northwest (R6) (n = 4), and 40% were found in the Southern Region (R8) (n = 8) (Fig. 1, Supplemental Table 2). Conversely, 19 National Forests had smaller percent of private land in WUI and lower growth in both intermix and interface housing, nearly all in the West, more than half of which were in the Pacific Northwest Region (R6) and Pacific Southwest Region (R5).

Individual administrative regions often contained a highly variable portfolio of WUI classifications, however, particularly in the West (Fig. 1). Even adjacent National Forests could fall into different categories in our WUI typology. For example, the two regions along the West Coast, the Pacific Southwest Region (R5) and Pacific Northwest (R6), had National Forests with all combinations of WUI area and growth, as well as the greatest number of National Forests that had experienced rapid interface growth alone (high interface housing growth but low intermix growth). The interior West (R1-4) also had a diverse range of classifications in our typology: National Forests here with smaller proportion of WUI area in 2010 had experienced every categorization of WUI housing growth in the past two decades (Fig. 1, Supplemental Table 1). National Forests in the interior West with larger proportion of WUI area by 2010 had all experienced rapid WUI housing growth in the previous two decades (usually both types, with a few National Forests in the Southwestern Region (R3) experiencing only high interface housing growth) (Fig. 1, Supplemental Table 2).

In contrast, National Forests in the East were more similar to each other, because WUI area was more consistently a large proportion of private land for these forests in 2010. Nearly all of the Eastern Region (R9)'s National Forests had experienced lower recent WUI housing growth, although a large proportion of private land was classified as WUI for more than half of them. WUI in these National Forests is thus widespread in area today but is typically older, with slower growth since the 1990s. In the Southern Region (R8), National Forests consistently had extensive proportion of area in WUI as of 2010, with most experiencing rapid WUI housing growth (typically high growth in both intermix and interface) (Fig. 1, Supplemental Table 2).

4. Discussion

Over the last several decades there has been growing concern about the ecological and wildfire management implications of housing development in close proximity to public land (Radeloff et al., 2010; Theobald, Crooks, & Norman, 2011; Ager et al., 2019). We found that this housing development is overwhelmingly WUI housing, making up nearly 70% of all houses found within and around National Forests. While it is unsurprising that housing within and around National Forests is in proximity to wildland vegetation, the finding that such development is typically meeting and exceeding housing density thresholds for WUI classification is novel. Furthermore, National Forests are a focal area for WUI growth: within and around National Forests, rates of WUI growth were higher than WUI growth in the rest of the conterminous U. S. Growth was particularly high within National Forests, driven by WUI intermix growth. In addition, more than 75% of private land within and around National Forests is not yet WUI because it has low or no housing. Although accessibility of the remaining land (e.g., road access and topography) may limit development in some cases, the amount of privately-owned land not yet in WUI status suggests opportunity for continued WUI expansion.

While WUI challenges are widespread for the National Forest system, we found variations over our levels of analysis, by region and within vs. around National Forests. In several ways WUI trends were most pronounced inside National Forests, which is striking given the management challenges created by such inholdings. Within National Forests, WUI area made up a higher proportion of privately owned land, and WUI growth rates were highest here, driven by the typically lower-density and more diffuse intermix. Notably, WUI growth rates within National Forests were higher than rates of growth for the conterminous U.S., where WUI expanded faster than any other land use or land cover from 1990 to 2010 (Radeloff et al., 2018). As predicted, however, the total area of WUI and number of WUI houses was smaller within than around National Forests, which follows from the relatively greater area of private land found outside National Forests. The area around National Forests therefore still hold the greatest total amount of WUI area and houses found in proximity to National Forests. The incidence of interface housing is similar to trends for the conterminous U.S. and means that the majority of WUI homes around National Forests were found in interface. National Forests are large public lands, but they are not isolated from WUI interface development, which is typically higher density and lacks wildland vegetation.

As anticipated, WUI trends also varied between administrative regions, most clearly seen in differences between the National Forests in the East and the West, reflecting the regions' variable land use histories and development trends. WUI challenges in the eastern United States have not received the same level of recent study as those in the West, but our findings demonstrate substantial WUI presence: National Forests in the East contained the most WUI area and houses in absolute numbers, and had a far greater proportion of privately owned land within and around National Forests falling into WUI designations. The Southern Region (R8) emerged as a focal region facing WUI management challenges, with the greatest number of National Forests having both large WUI area and rapid intermix and interface housing growth. However, housing development and forest cover are widespread in the East, so that National Forests only made up a smaller portion of the regions' WUI challenges.

In the West, however, National Forests were critical areas for WUI development. In particular, in the interior West, WUI areas were

primarily found in proximity to or within National Forests. National Forests in the Interior West had also experienced the fastest rates of WUI growth in housing and area. However, throughout the West, our typology of individual National Forests showed that WUI extent and growth were highly variable. Indeed, those National Forests with smaller WUI area and lower WUI housing growth were found primarily in the West. The West has been a consistent focus of studies on public lands and amenity growth, but our analyses concur with others showing that such growth is unevenly distributed (Winkler et al., 2007; Hjerpe et al., 2020). Indeed, despite the concentration of both natural amenities and wilderness areas in the West, our analyses showed no clear relationship between WUI extent and growth and amenity and wilderness attributes at the National Forest scale. The lack of consistent relationship between natural amenities and wilderness at the individual National Forest level reflects both the long history of land use and development in the East (where natural amenity scores are lower and wilderness areas are less common), and the lack of other contextual factors about economic conditions and development legacies in our analyses. For example, in a study of northern Wisconsin the largest effect of natural amenities on in-migration was in rural areas adjacent to larger developed metropolitan areas (Chi & Marcouiller, 2013). Additional data and studies, which incorporate economic and housing data at the county or sub-county scale (e.g., Gustafson et al., 2005, Chi & Marcouiller, 2013; Hjerpe et al., 2020) can further explore the role of natural amenities and wilderness status in relation to population change and WUI interface and intermix trends.

4.1. Considerations for management and future research

Given the variation in WUI distribution and growth within the National Forest System, no one intervention is likely to help mitigate the ecological and wildfire management effects of residential development on public lands. On the ground forest and wildfire management will be diverse, reflecting local priorities and resources, including fire regimes, past fire history, and socioeconomic characteristics of local populations (Nielsen-Pincus, Ribe, & Johnson, 2015; Ager et al., 2019; Palaiologou et al., 2019). However, our national analyses emphasize the importance of engaging across public and private lands to consider the design and effects of housing development while it is ongoing—nearly 2/3rds of National Forests had rapid intermix or interface growth in the past two decades (or both). The type of WUI present also provides insight into management priorities.

We found WUI intermix is widespread within National Forests, a diffuse footprint that can lead to challenging issues with infrastructure and open space at the landscape-level. Coordination between Forest Service, local government, and developers when housing is being planned can contribute to thoughtful consideration of road and infrastructure design. Local governments make land use planning and regulation decisions, but National Forest staff can contribute data and expertise to these efforts (Carr & Stein, 2014). For example, Carr and Stein (2014) describe Forest Service managers successfully working with a subdivision developer to link development with existing recreational trails, rather than creating new trails that would have led to a critical riparian area on Forest Service land. For wildfire concerns, maintaining open space within developments can allow local communities to control and manage the defensible space around their homes while also providing recreational benefits. Beyond the level of the individual subdivision, planning and discussions at the landscape and regional level can also help public and private stakeholders better anticipate future development (Shafer, 2015). Even in rural settings where there may be fewer resources for and public interest in broad land use planning efforts (Chase, 2015; Paveglio et al., 2015), concerns about emergency response and fire suppression can provide entrées into these discussions (Mockrin, Fishler, & Stewart, 2020).

Once homes are built in WUI intermix areas, there are many dispersed homes at risk of potential wildfire and contributing to a variety of disturbances (e.g., light, invasives, septic, ignitions). Extension and outreach programs can work directly with homeowners on minimizing disturbance and reducing wildfire risk (Gill & Stephens, 2009; Syphard et al., 2016, Mowery, Read, Johnston, & Wafaie, 2019). Given the complexity of WUI landscapes and a changing climate, outreach that considers multiple natural resource goals will be increasingly important—for example, if wildfire-related recommendations for landscaping can also consider drought/water conservation, wildlife viewing, and aesthetic goals (e.g., Bethke et al., 2016) they are more likely to be embraced by homeowners as well as successful over the long-term (Nelson, Monroe, Johnson, & Bowers, 2004; Peterson & Vaske, 2017). Balancing these different natural resource management goals, at the home and landscape-level, will require additional research on multiple objectives and their tradeoffs (Syphard, Brennan, & Keeley, 2014, 2016).

Understanding and refining best practices of science delivery will also be important to reaching intermix residents and collectively addressing wildfire or other management concerns, given that housing here is dispersed, and many residents are seasonal (Petrzelka, Ma, & Malin, 2013; Paveglio, Nielsen-Pincus, Abrams, & Moseley, 2017). Homeowners associations and road associations can help coordinate natural resource management issues within developments, by coordinating recreation use, right-of-way permits and road maintenance, or facilitating information sharing about wildfire management and forest restoration activity on private and public land. Finally, land exchanges, acquisitions, and broader connectivity to other public lands may also be a higher priority in intermix areas where wildland vegetation is more widespread. Such land exchanges and acquisitions recently received a permanent source of funding through the Act (2020) which fully funds the Land and Water Conservation Fund, the primary federal funding source for these efforts. In addition, a 2021 executive order has led to stakeholder engagement across public and private owners about land conservation, with a goal of conserving at least 30 percent of land area in the U.S. by 2030 (Exec. Order No. 14008, 2021).

Interface housing development poses different opportunities and challenges, and primarily occurs around National Forests, where it is found in similar prevalence to the rest of the conterminous U.S. Here, formal efforts to manage development may be more successful, such as wildfire codes, noise, or light ordinances, or similar efforts undertaken by groups such as homeowners associations (Paveglio et al., 2015). Where interface development is occurring, higher population density means that recreational use on National Forests will be high, and monitoring changing ecological conditions in close proximity to these areas will be critical to mitigating and reversing impacts. Land exchange or acquisition in these areas may focus on smaller, more valuable land critical for supporting recreation and maintaining landscape connectivity. From a wildfire perspective, education may be particularly important in interface as residents and local governments may not yet appreciate wildfire risk (Kramer et al., 2019; Mowery et al., 2019). Fuel treatments could be more cost-effective in such areas with dense development, although their use will depend on native vegetation and fire regimes. For example, an analysis of wildfire exposure from National Forests into WUI communities in the West suggests that interface communities with the highest exposure to wildfire (e.g., southern California, Wasatch Front, Utah) are also in vegetation communities where prescribed fire and fuel treatments may not be as effective in reducing wildfire risk (Evers et al., 2019). For both wildfire and other ecological interests, many best practices for managing and planning housing development were developed with an emphasis on housing that is dispersed within wildland vegetation, so that best management practices for interface development are less understood (Schneider, Fischer, & Miller, 2015; Carver et al., 2016; Kramer et al., 2019).

For many National Forests, these intermix and interface concerns are combined, with extensive intermix and rapid recent WUI growth, including denser interface around National Forest boundaries. We identified two areas in the US that are hotspots for such conditions—the

interior West and in the South. Cross-site research to identify "common patterns in diverse settings" could be a powerful way to elucidate commonalities and differences in WUI effects on natural resources across ecoregions, given that such studies are typically restricted to a single site (Glennon, Kretser, & Hilty, 2015). WUI development also interacts with other ecological stressors, leading to unprecedented challenges to public lands (Hansen et al., 2014; Sun et al., 2015; Buxton et al., 2017; Riitters et al., 2018; Martinuzzi et al., 2019). Monitoring future WUI growth, and considering it in combination with climate change impacts, especially increasing wildfire occurrence and severity (e.g., Kerns, Kim, Kline, & Day, 2016; Martinuzzi et al., 2019), will be critical to understanding the impacts of this development into the future. With results from the 2020 census available, and long-term effects of the COVID-19 pandemic on amenity migration emerging over the next decade, it will be a valuable time to re-assess these patterns of WUI growth. Such efforts can extend beyond National Forest land to consider other public and privately owned land, particularly in the East where states and corporate owners manage sizeable areas of forest cover (Sass, Butler, & Markowski-Lindsay, 2020).

National Forests on the leading edge of WUI growth may also share similarities in land use planning and management processes that can be shared across sites. For example, the South has widespread WUI areas and also a long tradition of prescribed fire on public and private lands (Melvin, 2020). Understanding the social components of successful prescribed fire use in the South, including public communications and outreach with residents, may offer management insight for WUI areas in the West, where managers aim to increase prescribed and wildland fire use. Across settings, more information about demographic and economic change associated with WUI development, and changing opportunities for land use planning, collaboration across public and private owners, diversity and visitation patterns on the National Forests (Burow, McConnell, & Farrell, 2019; Stoker, Rumore, Romaniello, & Levine, 2020) will also be valuable to enhance public land management. Ultimately, the long history of residential development spurring land use change in the US, the extent and growth of WUI documented in this study, combined with the fact that more than 75% of privately owned land within and around National Forests is not yet WUI, lead us to conclude that the impacts of such development will continue to be important to track and mitigate into the future.

5. Conclusion

This study examined the distribution and growth of the wildland-urban interface (WUI), where houses are adjacent and intermingled to wildland vegetation, in proximity to the National Forests, critical type of federal public lands in the United States. We used a national dataset to document WUI distribution and growth within and around National Forests and created a typology to characterize each National Forest's combination of WUI area and housing growth. Our findings revealed that **WUI housing is widespread within and around National Forests** (up 86% of all housing within National Forests). National Forests are also a focal area for WUI growth, with **inholdings within National Forests experiencing the highest rate of WUI expansion and housing growth** from 1990 to 2010. More than 75% of private land within and around National Forests is not yet WUI because it has low or no housing, suggesting that there is opportunity for this WUI growth to continue. The typology developed in this study incorporates WUI extent and growth to inform management and planning priorities for individual National Forests. Those National Forests with the most challenging WUI issues—extensive WUI area and rapid growth in intermix and interface—were found primarily in the South and interior West. Responding to these current and future challenges will require a variety of policy responses.

CRediT authorship contribution statement

Miranda H. Mockrin: Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing. **David Helmers:** Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sebastian Martinuzzi:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Todd J. Hawbaker:** Writing – original draft, Writing – review & editing. **Volker C. Radeloff:** Conceptualization, Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104283.

References

Ager, A. A., M. A., Day, P., Palaiologou, R. M., Houtman, C. Ringo, Evers, C. R. 2019. Cross-boundary wildfire and community exposure: A framework and application in the western U.S. Gen. Tech. Rep. RMRS-GTR-392. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 36 p.

Aycrigg, J. L., Davidson, A., Svancara, L. K., Gergely, K. J., McKerrow, A., Scott, J. M., & Van Niel, K. P. (2013). Representation of ecological systems within the protected areas network of the continental United States. *PloS one, 8*, e54689.

Banks, P. B., & Bryant, J. V. (2007). Four-legged friend or foe? Dog walking displaces native birds from natural areas. *Biology Letters, 3*, 611–613.

Bar-Massada, A., Radeloff, V. C., & Stewart, S. I. (2014). Biotic and abiotic effects of human settlements in the wildland–urban interface. *Bioscience, 64*, 429–437.

Bethke, J., Bell, C., Gonzales, J., Lima, L., Long, A., & McDonald, C. J. (2016). Research literature review of plant flammability testing, fire-resistant plant lists and relevance of a plant flammability key for ornamental landscape plants in the Western States. *Final report. Farm and Home Advisor's Office University of California Cooperative Extension County of San Diego 92123:176*.

Burow, P. B., McConnell, K., & Farrell, J. (2019). Social scientific research on the American West: Current debates, novel methods, and new directions. *Environmental Research Letters, 14*, 125012.

Buxton, R. T., McKenna, M. F., Mennitt, D., Fristrup, K., Crooks, K., Angeloni, L., & Wittemyer, G. (2017). Noise pollution is pervasive in U.S. protected areas. *Science, 356*, 531–533.

Carlson, A. R., Sebasky, M. E., Peters, M. P., & Radeloff, V. C. (2021). The importance of small fires for wildfire hazard in urbanised landscapes of the northeastern US. *International Journal of Wildland Fire, 30*, 307.

Carr, M., & Stein, S. M. (2014). *Across the green line: how forest service employees can support local land use planning efforts*. Washington DC: USDA Forest Service.

Carver, S., Bevins, S. N., Lappin, M. R., Boydston, E. E., Lyren, L. M., Alldredge, M., … VandeWoude, S. (2016). Pathogen exposure varies widely among sympatric populations of wild and domestic felids across the United States. *Ecological Applications, 26*, 367–381.

Chase, J. (2015). Bending the rules in the foothills—county general planning in exurban Northern California. *Society & Natural Resources*, 1–16.

Chi, G., & Marcouiller, D. W. (2013). Natural amenities and their effects on migration along the urban–rural continuum. *The Annals of Regional Science, 50*, 861–883.

Davis, C. R., & Hansen, A. J. (2011). Trajectories in land use change around US National Parks and challenges and opportunities for management. *Ecological Applications, 21*, 3299–3316.

Dudley, N., Shadie, P., & S. Stolton. 2013. Guidelines for applying protected area management categories including IUCN WCPA best practice guidance on recognising protected areas and assigning management categories and governance types. Best practice protected area guidelines series.

Evers, C. R., Ager, A. A., Nielsen-Pincus, M., Palaiologou, P., & Bunzel, K. (2019). Archetypes of community wildfire exposure from national forests of the western US. *Landscape and Urban Planning, 182*, 55–66.

Exec. Order No. 14008. 2021. Tackling the climate crisis at home and abroad Sec. 216. Conserving Our Nation's Lands and Waters Signed: January 27, 2021; Vol. 86, No. 19, 7619-7633.

Gavier-Pizarro, G. I., Radeloff, V. C., Stewart, S. I., Huebner, C. D., & Keuler, N. S. (2010). Housing is positively associated with invasive exotic plant species richness in New England, USA. *Ecological Applications, 20*, 1913–1925.

Gill, A. M., & Stephens, S. L. (2009). Scientific and social challenges for the management of fire-prone wildland–urban interfaces. *Environmental Research Letters, 4*, 034014. https://doi.org/10.1088/1748-9326/4/3/034014

Glennon, M. J., Kretser, H. E., & Hilty, J. A. (2015). Identifying common patterns in diverse systems: Effects of exurban development on birds of the Adirondack Park and the Greater Yellowstone Ecosystem, USA. *Environmental Management, 55*, 453–466.

Gonzalez-Abraham, C. E., Radeloff, V. C., Hawbaker, T. J., Hammer, R. B., Stewart, S. I., & Clayton, M. K. (2007). Patterns of houses and habitat loss from 1937 to 1999 in northern Wisconsin, USA. *Ecological Applications, 17*, 2011–2023.

Great American Outdoors Act. 2020. 54 USC 100101 §§ 682-686. https://www.congress.gov/116/plaws/publ152/PLAW-116publ152.pdf.
Gude, P. H., Jones, K., Rasker, R., & Greenwood, M. C. (2013). Evidence for the effect of homes on wildfire suppression costs. *International Journal of Wildland Fire, 22*, 537–548.
Gustafson, E. J., Hammer, R. B., Radeloff, V. C., & Potts, R. S. (2005). The relationship between environmental amenities and changing human settlement patterns between 1980 and 2000 in the Midwestern USA. *Landscape Ecology, 20*(7), 773–789.
Hamilton, C. M., Martinuzzi, S., Plantinga, A. J., Radeloff, V. C., Lewis, D. J., Thogmartin, W. E., … Van Niel, K. P. (2013). Current and future land use around a nationwide protected area network. *PloS one, 8*, e55737.
Hand, M. S., Thompson, M. P., & Calkin, D. E. (2016). Examining heterogeneity and wildfire management expenditures using spatially and temporally descriptive data. *Journal of Forest Economics, 22*, 80–102.
Hansen, A. J., & DeFries, R. (2007). Ecological mechanisms linking protected areas to surrounding lands. *Ecological Applications, 17*, 974–988.
Hansen, A. J., Knight, R. L., Marzluff, J. M., Powell, S., Brown, K., Gude, P. H., & Jones, K. (2005). Effects of exurban development on biodiversity: Patterns, mechanisms, and research needs. *Ecological Applications, 15*, 1893–1905.
Hansen, A. J., Piekielek, N., Davis, C., Haas, J., Theobald, D. M., Gross, J. E., … Running, S. W. (2014). Exposure of US National Parks to land use and climate change 1900–2100. *Ecological Applications, 24*, 484–502.
Hjerpe, E., Hussain, A., & Holmes, T. (2020). Amenity migration and public lands: Rise of the protected areas. *Environmental Management, 66*, 56–71.
Holgerson, M. A., Lambert, M. R., Freidenburg, L. K., & Skelly, D. K. (2018). Suburbanization alters small pond ecosystems: Shifts in nitrogen and food web dynamics. *Canadian Journal of Fisheries and Aquatic Sciences, 75*, 641–652.
Holmes, T. P., Bowker, J. M., Englin, J., Hjerpe, E., Loomis, J. B., Phillips, S., & Richardson, R. (2016). A synthesis of the economic values of wilderness. *Journal of Forestry, 114*, 320–328.
Hoover, K. 2016. National Forest System Management: Overview, appropriations, and issues for Congress. R43872. Library of Congress, Congressional Research Service.
Kaushal, S. S., Lewis, W. M., Jr, & McCutchan, J. H., Jr. (2006). Land use change and nitrogen enrichment of a Rocky Mountain watershed. *Ecological Applications, 16*, 299–312.
Kellner, A., Carver, S., Gramza, A., Lewis, J. S., VandeWoude, S., & Crooks, K. R. (2017). Outdoor recreation at the wildland—Urban interface: Examining human activity patterns and compliance with dog management policies. *Natural Areas Journal, 37*, 515–529.
Kerns, B. K., Kim, J. B., Kline, J. D., & Day, M. A. (2016). US exposure to multiple landscape stressors and climate change. *Regional Environmental Change, 16*, 2129–2140.
Kramer, H. A., Mockrin, M. H., Alexandre, P. M., & Radeloff, V. C. (2019). High wildfire damage in interface communities in California. *International Journal of Wildland Fire, 28*, 641. https://doi.org/10.1071/WF18108
Kreling, S. E. S., Gaynor, K. M., & Coon, C. A. C. (2019). Roadkill distribution at the wildland-urban interface. *The Journal of Wildlife Management, 83*, 1427–1436.
Longcore, T., & Rich, C. (2004). Ecological light pollution. *Frontiers in Ecology and the Environment, 2*, 191–198.
Loss, S. R., Will, T., & Marra, P. P. (2013). The impact of free-ranging domestic cats on wildlife of the United States. *Nature Communications, 4*, 1–8.
Martinuzzi, S., Allstadt, A. J., Pidgeon, A. M., Flather, C. H., Jolly, W. M., & Radeloff, V. C. (2019). Future changes in fire weather, spring droughts, and false springs across U.S. National Forests and Grasslands. *Ecological Applications, 29*.
McGranahan, D. A. 1999. Natural amenities drive rural population change. Agricultural Economic Report No. 781. US Department of Agriculture, Economic Research Service, Washington DC.
McGregor, R. L., Bender, D. J., & Fahrig, L. (2008). Do small mammals avoid roads because of the traffic? *Journal of Applied Ecology, 45*, 117–123.
Melvin, M. 2020. National prescribed fire use report. Technical Bulletin 04-20. Coalition of Prescribed Fire Councils, Inc., 2020.
Mennitt, D. J., & Fristrup, K. M. (2016). Influence factors and spatiotemporal patterns of environmental sound levels in the contiguous United States. *Noise Control Engineering Journal, 64*, 342–353.
Mockrin, M. H., Fishler, H. K., & Stewart, S. I. (2020). After the fire: Perceptions of land use planning to reduce wildfire risk in eight communities across the United States. *International Journal of Disaster Risk Reduction, 45*, 101444. https://doi.org/10.1016/j.ijdrr.2019.101444
Mockrin, M. H., Stewart, S. I., Matonis, M. S., Johnson, K. M., Hammer, R. B., & Radeloff, V. C. (2018). Sprawling and diverse: The changing US population and implications for public lands in the 21st Century. *Journal of environmental management, 215*, 153–165.
Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., … Syphard, A. D. (2014). Learning to coexist with wildfire. *Nature, 515*, 58–66.
Mowery, M., Anna Read, Kelly Johnston, and Tareq Wafaie. 2019. Planning the Wildland-Urban Interface PAS Report 594. pp 194 https://www.planning.org/publications/report/9174069/.
Nelson, K. C., Monroe, M. C., Johnson, J. F., & Bowers, A. (2004). Living with fire: Homeowner assessment of landscape values and defensible space in Minnesota and Florida, USA. *International Journal of Wildland Fire, 13*, 413. https://doi.org/10.1071/WF03067
Nielsen-Pincus, M., Ribe, R. G., & Johnson, B. R. (2015). Spatially and socially segmenting private landowner motivations, properties, and management: A typology for the wildland urban interface. *Landscape and Urban Planning, 137*, 1–12.
Olofsson, P., Holden, C. E., Bullock, E. L., & Woodcock, C. E. (2016). Time series analysis of satellite data reveals continuous deforestation of New England since the 1980s. *Environmental Research Letters, 11*, 064002. https://doi.org/10.1088/1748-9326/11/6/064002
Palaiologou, P., Ager, A. A., Nielsen-Pincus, M., Evers, C. R., & Day, M. A. (2019). Social vulnerability to large wildfires in the western USA. *Landscape and Urban Planning, 189*, 99–116.
Paveglio, T. B., Brenkert-Smith, H., Hall, T., & Smith, A. M. S. (2015a). Understanding social impact from wildfires: Advancing means for assessment. *International Journal of Wildland Fire, 24*, 212. https://doi.org/10.1071/WF14091
Paveglio, T. B., Nielsen-Pincus, M., Abrams, J., & Moseley, C. (2017). Advancing characterization of social diversity in the wildland-urban interface: An indicator approach for wildfire management. *Landscape and Urban Planning, 160*, 115–126.
Paveglio, T. B., Moseley, C., Carroll, M. S., Williams, D. R., Davis, E. J., & Fischer, A. P. (2015b). Categorizing the social context of the wildland urban interface: Adaptive capacity for wildfire and community "archetypes". *Forest Science, 61*, 298–310.
Pejchar, L., Reed, S. E., Bixler, P., Ex, L., & Mockrin, M. H. (2015). Consequences of residential development for biodiversity and human well-being. *Frontiers in Ecology and the Environment, 13*, 146–153.
Peterson, C. L., & Vaske, J. J. (2017). Colorado residents' familiarity, aesthetic evaluations, and approval of forest management practices. *Journal of Forestry, 115*, 10–15.
Petrzelka, P., Ma, Z., & Malin, S. (2013). The elephant in the room: Absentee landowner issues in conservation and land management. *Land Use Policy, 30*, 157–166.
Price, O., & Bradstock, R. (2014). Countervailing effects of urbanization and vegetation extent on fire frequency on the Wildland Urban Interface: Disentangling fuel and ignition effects. *Landscape and Urban Planning, 130*, 81–88.
Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., … Stewart, S. I. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences, 115*, 3314–3319.
Radeloff, V. C., Stewart, S. I., Hawbaker, T. J., Gimmi, U., Pidgeon, A. M., Flather, C. H., … Helmers, D. P. (2010). Housing growth in and near United States protected areas limits their conservation value. *Proceedings of the National Academy of Sciences, 107*, 940–945.
Riitters, K., Potter, K., Iannone, B., Oswalt, C., Guo, Q., & Fei, S. (2018). Exposure of protected and unprotected forest to plant invasions in the eastern United States. *Forests, 9*, 723. https://doi.org/10.3390/f9110723
Riitters, K., Schleeweis, K., & Costanza, J. (2020). Forest area change in the shifting landscape mosaic of the continental United States from 2001 to 2016. *Land, 9*, 417. https://doi.org/10.3390/land9110417
Roper, B. B., Capurso, J. M., Paroz, Y., & Young, M. K. (2018). Conservation of aquatic biodiversity in the context of multiple-use management on National Forest System lands. *Fisheries, 43*, 396–405.
Sass, E. M., Butler, B.J., & Markowski-Lindsay, M. 2020. Distribution of forest ownerships across the conterminous United States, 2017. Res. Map NRS-11. Madison, WI: US Department of Agriculture, Forest Service, Northern Research Station 11.
Schneider, S. C., Fischer, J. D., & Miller, J. R. (2015). Two-sided edge responses of avian communities in an urban landscape. *Urban Ecosystems, 18*, 539–551.
Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., … Whitlock, C. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences, 114*, 4582–4590.
Shafer, C. L. (2015). Land use planning: A potential force for retaining habitat connectivity in the Greater Yellowstone Ecosystem and Beyond. *Global Ecology and Conservation, 3*, 256–278.
Smith, A. M., Kolden, C. A., Paveglio, T. B., Cochrane, M. A., Bowman, D. M., Moritz, M. A., … Hoffman, C. M. (2016). The science of firescapes: achieving fire-resilient communities. *BioScience, 66*, 130–146.
Steelman, T. (2016). US wildfire governance as social-ecological problem. *Ecology and Society, 21*.
Stoker, P., Rumore, D., Romaniello, L., & Levine, Z. (2020). Planning and development challenges in western gateway communities. *Journal of the American Planning, 87*, 21–33.
Sun, S., Sun, G.e., Caldwell, P., McNulty, S., Cohen, E., Xiao, J., & Zhang, Y. (2015). Drought impacts on ecosystem functions of the US National Forests and Grasslands: Part II assessment results and management implications. *Forest Ecology and Management, 353*, 269–279.
Syphard, A., Butsic, V., Bar-Massada, A., Keeley, J., Tracey, J., & Fisher, R. (2016). Setting priorities for private land conservation in fire-prone landscapes: Are fire risk reduction and biodiversity conservation competing or compatible objectives? *Ecology and Society, 21*.
Syphard, A. D., Brennan, T. J., & Keeley, J. E. (2014). The role of defensible space for residential structure protection during wildfires. *International Journal of Wildland Fire, 23*, 1165.
Syphard, A. D., Keeley, J. E., Pfaff, A. H., & Ferschweiler, K. (2017). Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences, 114*, 13750–13755.
Syphard, A. D., Radeloff, V. C., Keeley, J. E., Hawbaker, T. J., Clayton, M. K., Stewart, S. I., & Hammer, R. B. (2007). Human influence on California fire regimes. *Ecological Applications, 17*, 1388–1402.
The Conservation Biology Institute. 2012. PAD-US 2. Corvallis, Oregon http://consbio.org/products/projects/pad-us-cbi-edition.
Theobald, D. M. (2013). A general model to quantify ecological integrity for landscape assessments and US application. *Landscape Ecology, 28*, 1859–1874.

Theobald, D. M., Crooks, K. R., & Norman, J. B. (2011). Assessing effects of land use on landscape connectivity: Loss and fragmentation of western US forests. *Ecological Applications, 21*, 2445–2458.

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

USDA Forest Service. 2018. Administrative Forest Boundaries https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.AdministrativeForest.xml. Washington D.C.

USDA Forest Service. 2019. Surface Ownership Parcels, detailed https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.SurfaceOwnership.xml. Washington D.C.

Vincent, C. H., Eliot Crafton, R., Comay, L. B., & Hoover, K. (2018). *Federal land ownership: Acquisition and disposal authorities. RL34273*. Library of Congress, Congressional Research Service.

Wade, A. A., & Theobald, D. M. (2010). Residential development encroachment on U.S. protected areas. *Conservation Biology, 24*, 151–161.

Wigtil, G., Hammer, R. B., Kline, J. D., Mockrin, M. H., Stewart, S. I., Roper, D., & Radeloff, V. C. (2016). Places where wildfire potential and social vulnerability coincide in the coterminous United States. *International Journal of Wildland Fire, 25*, 896. https://doi.org/10.1071/WF15109

Wilson, C. R., & Brown, D. G. (2015). Change in visible impervious surface area in southeastern Michigan before and after the "Great Recession:" spatial differentiation in remotely sensed land-cover dynamics. *Population and Environment, 36*, 331–355.

Winkler, R., Field, D., Luloff, A. E., Krannich, R., & Williams, T. (2007). Social landscapes of the intermountain West: a comparison of "Old West" and "New West" communities. *Rural Sociology, 72*, 478–501.

Wood, E. M., Pidgeon, A. M., Radeloff, V. C., Helmers, D., Culbert, P. D., Keuler, N. S., & Flather, C. H. (2014). Housing development erodes avian community structure in US protected areas. *Ecological Applications, 24*, 1445–1462.