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Changing large wildfire dynamics in the wildland–urban interface of the eastern United States

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ABSTRACT

Background. The recent increase in large wildfires in the eastern United States makes it crucial to examine the subsequent risk to human life and property. In the eastern US, the wildland–urban interface (WUI), where wildfire risk is greatest, has expanded tremendously over the last three decades. **Aims.** This study aimed to understand how increasing wildfires in the eastern US are manifesting in the WUI. **Methods.** We quantified WUI growth and characterised large (>200 ha) wildfire regimes inside and outside the WUI at multiple spatial scales across the eastern US between 1986 and 2021. **Key results.** WUI wildfires in the eastern US comprised 45% of all large wildfires and 55% of the area burned, were on average 46% larger than non-WUI wildfires, and are becoming more frequent in spring. Most increases in wildfire number and area burned occurred outside of the WUI. **Conclusion.** The WUI plays an important role in large wildfire dynamics in the eastern US; however, increases in the number of large wildfires have occurred primarily outside the WUI. **Implications.** Our findings highlight important interactions between human development and large wildfire occurrence in the eastern US and should be used to direct future region-specific assessments of changing wildfire risk.

Keywords: development, exposure, fire regime, housing growth, risk, sprawl, urbanisation, wildland fire, wildland–urban interface.

Introduction

The wildland–urban interface (WUI), which occurs at the intersection between human development and wildland vegetative fuels (Radeloff *et al.* 2005), remains a core focus for predicting and mitigating wildfire risk. Since the 1990s, the United States has experienced substantial growth in the total area of WUI (Radeloff *et al.* 2018, 2023*b*). The recent historical shift from an industrial economy to an informational one has allowed humans to live in more rural areas with easy access to outdoor recreation (Krannich *et al.* 2011; Matilainen *et al.* 2017). However, living in and building structures near wildland vegetation poses several economic and ecological problems (Radeloff *et al.* 2005), predominantly stemming from the 'edge effect' (Ranney 1977; Murcia 1995). The issues created by the WUI include habitat fragmentation, shifts in microclimates and the spread of exotic invasive species (Gehlhausen *et al.* 2000; Alston and Richardson 2006; Sanczuk *et al.* 2023). However, increased wildfire risk is arguably the most consequential problem posed by the WUI (Radeloff *et al.* 2005, 2018, 2023*b*). Increased wildfire risk in the WUI results from the interactions of multiple factors, including the WUI's proximity to human-caused ignition sources, the flammability of exotic invasive species and increased fuel loading (Mandle *et al.* 2011; Toman *et al.* 2011; Mietkiewicz *et al.* 2020).

Wildfires in the WUI require more suppression resources, destroy more homes and pose a greater threat to human life than wildfires elsewhere in the landscape (Radeloff *et al.* 2018; Swimley 2021; Modaresi Rad *et al.* 2023). Previous studies have shown that 32% of all wildfires in the conterminous US are started in the WUI, even though the WUI only makes up one-tenth of the country by area (Mietkiewicz *et al.* 2020). WUI wildfires result in greater property damage and pose logistical difficulties for firefighters because a large majority of the WUI (89%) is private property, thereby limiting access (Theobald and Romme 2007; Johnston *et al.* 2019; Haynes *et al.* 2020). In a 2021 report, the US Fire

Administration determined that wildfires in the WUI result in 14% more firefighter injuries and 20% more civilian casualties than urban structure fires (FEMA 2021). This increased wildfire risk in the WUI highlights the need to characterise wildfire regimes at finer scales in regions that contain high proportions of WUI area.

Large wildfire numbers are increasing in the eastern US (Donovan *et al.* 2023). It is crucial to understand how these increases in large wildfire interact with the WUI to better assess the risk of these changes to human life and infrastructure (Iglesias *et al.* 2022; Donovan *et al.* 2023). The eastern US contains a disproportionately large area of WUI relative to the rest of the country (Theobald and Romme 2007; Radeloff *et al.* 2018). Although wildfires in the eastern US currently result in fewer casualties and less property damage than in the West, the eastern US experiences frequent human-caused (~88%) wildfires that burn seven times more area of the WUI than western ones (Balch *et al.* 2017; Nagy *et al.* 2018; Mietkiewicz *et al.* 2020). On average, eastern wildfires in the WUI cost US \$18,300/km^2 to suppress (Mietkiewicz *et al.* 2020), and as the number of these fires continues to rise, suppression capacity will become strained. Additionally, as climate and land use alter wildfire regimes, the eastern US will continue to experience more human-caused wildfires originating in the WUI (Butsic *et al.* 2015; Abatzoglou and Williams 2016). Yet differences between WUI and non-WUI large wildfire regimes in this region of the country remain unclear, and as the WUI continues to expand, it becomes imperative to quantify changing wildfire risk to human life and structures.

We examined how changes in large wildfire regimes across the eastern US are manifesting in the WUI. Specifically, we aimed to (1) assess temporal changes in the WUI; (2) contrast characteristics of WUI versus non-WUI large (>200 ha) wildfire regimes; and (3) assess temporal trends in WUI versus non-WUI large wildfire regime characteristics across the eastern US at multiple spatial scales. As the eastern US is a large area that contains regions with vastly different ecological properties, a multiscale assessment is needed to understand changes in fire regimes. We combine spatio-temporal large wildfire perimeter data and decadal WUI maps across the Eastern Temperate Forests Level I Environmental Protection Agency (EPA) ecoregion and within 31 Level III ecoregions that subdivide the eastern US. We characterise spatial and temporal characteristics of wildfire regimes inside and outside the WUI using six fundamental components of fire regimes: average wildfire size, number, total area burned within an ecoregion, annual probability of occurrence, seasonality and ignition source.

Materials and methods

Data

We used the US EPA ecoregions to designate and subdivide our study region. We used the Level I (L1) Eastern Temperate Forests ecoregion (hereafter referred to as the 'eastern US') to characterise the eastern US (Supplementary Fig. S1). This area is characterised by high population and housing density compared with the rest of the US (Theobald 2005; Radeloff *et al.* 2018). The eastern US is ecologically distinct from the rest of the country because of its high humidity, high precipitation (100–150 cm annually), and gradient of mild to cold winters (Gilliam 2016). Forests of the eastern US are mostly hardwoods in the north and mixed pines and hardwoods in the south (Woodbridge *et al.* 2022). We further subdivided the eastern US using Level III (L3) ecoregions ($n = 31$) (EPA 2013; Omernik and Griffith 2014). The EPA has created Level I through IV ecoregions as a framework for spatially subdividing the United States hierarchically, with Level I ecoregions being the largest scale and Level IV ecoregions being the finest scale. Ecoregions are areas with fairly homogeneous landscapes and similar environmental resources (Bryce *et al.* 1999; EPA 2013).

We used the USDA's decadal WUI maps from 1990 to 2020 (Radeloff *et al.* 2023*a*). Census block polygons in this dataset are classified as intermix WUI, interface WUI or non-WUI according to the Federal Register definition (USDA and USDI 2001; FMB 2019). Intermix WUI is any area containing at least 6.17 housing units km^{-2} and 50% vegetation. Interface WUI is any area containing more than 6.17 housing units km^{-2} and less than 50% vegetation but is within 2.4 km of a highly vegetated area larger than 5 km^2 (USDA and USDI 2001; Radeloff *et al.* 2005).

Wildfire data were collected from the 'Burned Areas Boundary Dataset' from the Monitoring Trends in Burn Severity (MTBS) database (Eidenshink *et al.* 2007; MTBS 2023). Among the categories of fires (Prescribed Fire, Unknown, Wildfire and Wildland Fire Use), we only included fires greater than 200 ha classified as 'Wildfires' between 1986 and 2021 for our assessment ($n = 2388$) (Nagy *et al.* 2018). MTBS defines a wildfire as any fire initiated from an unplanned ignition, whether a human cause, a natural cause, or an uncontrolled prescribed burn (FMB 2019). We joined ignition source data from the USDA's Fire Program Analysis Fire Occurrence database with wildfire perimeters where corresponding MTBS identifiers existed ($n = 1749$) (Short 2022). For analysing ignition patterns, we only used fires with known ignition causes ($n = 1652$). This dataset only contains wildfires between the years 1992 and 2020.

Temporal patterns in the WUI

To assess temporal changes in the WUI across the eastern US, we summarised the proportion of area for interface and intermix WUI within each L3 ecoregion for the years 1990, 2000, 2010 and 2020. We also summarised the proportion of vegetated and non-vegetated or agricultural areas within each ecoregion for each of the 4 years. We calculated the relative change in intermix WUI, interface WUI, vegetated and unvegetated/agricultural areas from 1990 to 2020 across L3 ecoregions (Fig. 1, Supplementary Table S1).

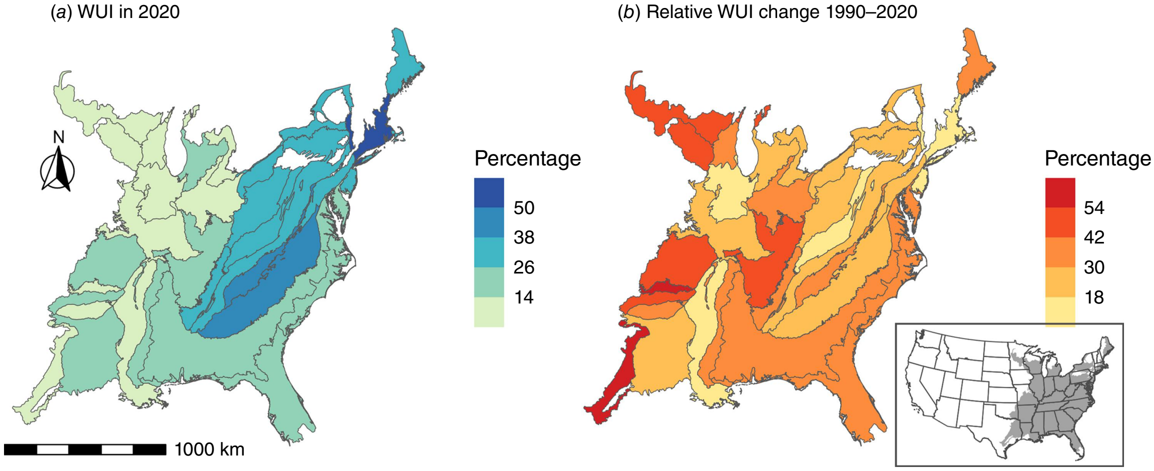

Fig. 1. Maps showing the (*a*) percentage area occupied by the wildland–urban interface (WUI) in 2020; and (*b*) the relative percentage change from 1990 to 2020 ((area 2020 - area 1990) ÷ area 1990) for Level III ecoregions of the eastern United States.

Spatial patterns in WUI large wildfires

To contrast characteristics of WUI versus non-WUI large wildfire regimes across the eastern US, we combined large wildfire perimeters from the MTBS dataset with the WUI geodatabase. We defined a 'WUI wildfire' as one that burns any area of the WUI (interface or intermix). A limitation of this method is the fact that our definition of a WUI large wildfire may favour larger wildfires because larger wildfires could spread into and burn a small portion of the WUI. However, as the WUI is often a source of wildfire ignitions (Syphard and Keeley 2015; Mietkiewicz *et al.* 2020), many of these large wildfires may have begun within the WUI and spread outwards. WUI maps are decadal. Wildfires were categorised as WUI or non-WUI using the WUI map from the year closest to their ignition date. We used the 1990 WUI map for categorising all large wildfires between 1986 and 1995, the 2000 WUI map for all large wildfires between 1996 and 2005, the 2010 WUI map for all large wildfires between 2006 and 2015, and the 2020 WUI map for all large wildfires between 2016 and 2021. We characterised large wildfire regimes within WUI and non-WUI areas by calculating the total number, average size, total area burned and ignition sources of large wildfires inside and outside the WUI for each L3 ecoregion. Average large wildfire size is the mean area burned by a single wildfire within a given ecoregion, measured in hectares. In contrast, the total area burned is the sum of the area burned by all large wildfires within a given ecoregion, measured in hectares (Fig. 2, Table 1).

Temporal patterns in WUI large wildfires

To assess temporal trends in WUI versus non-WUI large wildfire regime characteristics across the eastern US, we examined changes in total number, average size, total area burned within an ecoregion and ignition source of large wildfires inside and outside the WUI for each L3 ecoregion from 1986 to 2021 using the Mann–Kendall Trend Test ($\alpha = 0.05$), which determines the presence, strength and direction of monotonic trends. We only included ecoregions that contained 10 or more WUI ($n = 16$) or 10 or more non-WUI ($n = 15$) large wildfires from 1986 to 2021 because a smaller sample size would be insufficient for statistical analysis (Donovan *et al.* 2023). We used a logistic model ($\alpha = 0.05$) to assess temporal trends in the presence and absence of wildfires inside and outside the WUI. We also examined temporal trends in the probability of human-ignited wildfires inside and outside the WUI using a logistic model ($\alpha = 0.05$). We visualised changes in wildfire seasonality across L3 ecoregions using Gaussian kernel density estimates of fire density for the first and last decades of our study period (Wickham 2016). We only included ecoregions that contained five or more WUI and non-WUI large wildfires per decade, as we deemed that a smaller sample size would be insufficient for visualisation purposes (Donovan *et al.* 2023). Bandwidth was calculated using 'Silverman's rule of thumb' (Silverman 1986).

We used ArcGIS Pro (version 3.1.2) to merge spatial datasets. We used the R statistical environment (R Core Team 2023) in RStudio (RStudio Team 2023) for data visualisation and statistical analysis.

Results

Temporal patterns in the WUI

In 2020, the WUI covered 548,361 km^2, constituting 22% of the eastern US (Supplementary Table S1, Fig. 1). Intermix WUI covered 17% of the area and interface WUI covered 5% (Supplementary Table S1). In 2020, WUI area in the eastern

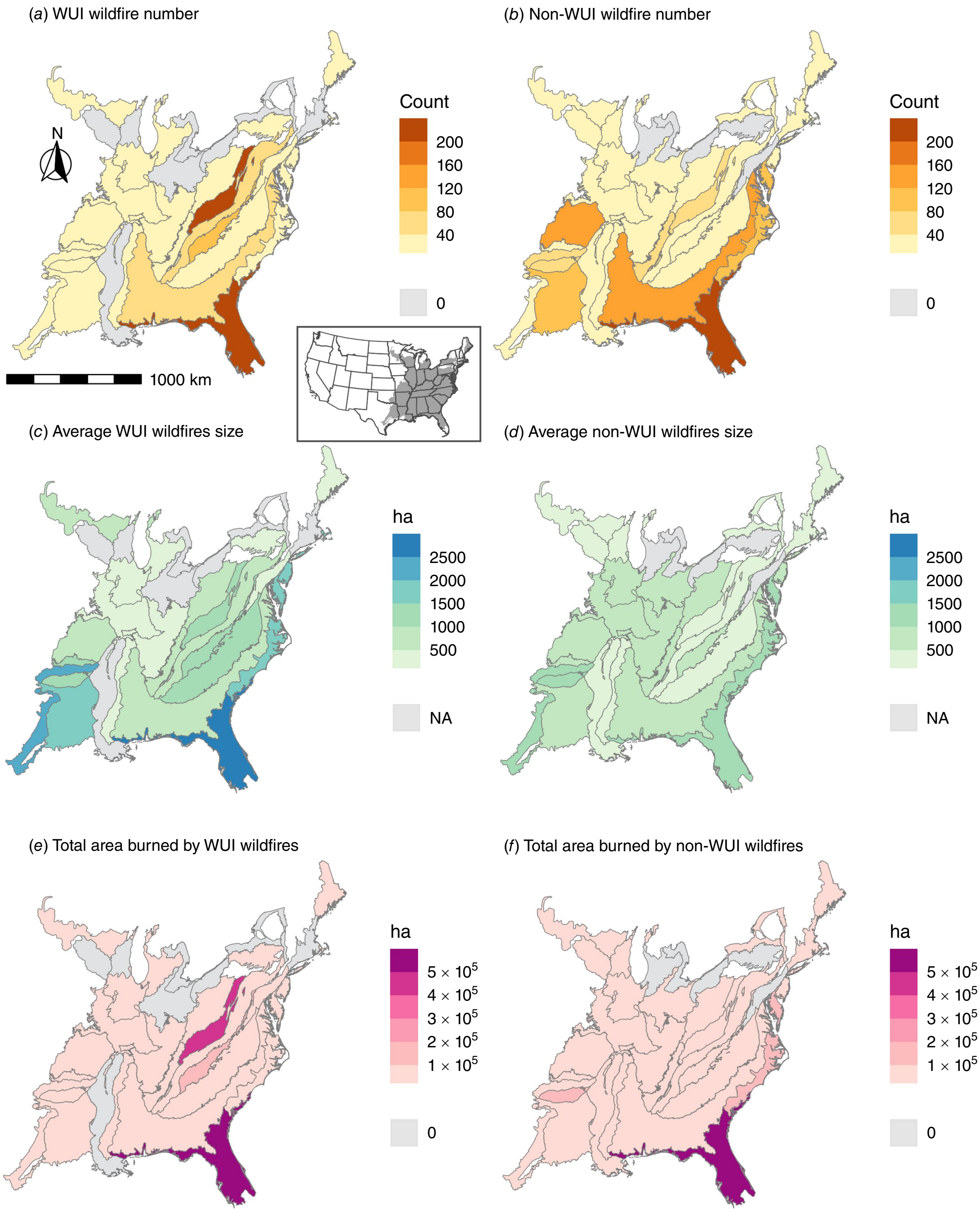

Fig. 2. Maps showing the (*a*–*b*) total number, (*c*–*d*) average size (in ha), and (*e*–*f*) total area burned (in ha) by large wildfires (>200 ha) inside and outside the wildland–urban interface (WUI) across Level III ecoregions of the eastern United States between 1986 and 2021. Darker colours indicate larger values, while lighter colours indicate smaller values. Ecoregions in grey contained no WUI or non-WUI large wildfires during the study period.

US had expanded 29% relative to 1990. Intermix WUI grew 28%, while interface WUI grew 34% (Supplementary Table S1, Fig. 1).

We observed unique patterns in the WUI's geographic distribution and growth across the eastern US. Central and northeastern ecoregions contained the highest proportion of WUI area (Supplementary Table S1, Fig. 1). In 2020, the southwestern ecoregions had experienced the greatest increase in intermix WUI area relative to 1990 (Supplementary Table S1, Fig. 1). Ecoregions in the central and western parts of the eastern US experienced the greatest increase in interface WUI (Supplementary Table S1, Fig. 1).

Table 1. Large wildfire regime characteristics.

Ecoregion	Number of non-WUI wildfires	Number of WUI wildfires	Average non-WUI wildfire size ± s.e. (ha)	Average WUI wildfire size ± s.e. (ha)	Area burned by non-WUI wildfires (ha)	Area burned by WUI wildfires (ha)	Proportion non-WUI wildfires ignited by humans	Proportion WUI wildfires ignited by humans
L1 Eastern Temperate Forests	1308	1080	1003 ± 97	1468 ± 167	1,311,490	1,585,195	0.80	0.91
Acadian Plains and Hills	1	1	285	254	285	254	1.00	1.00
Arkansas Valley	51	23	1500 ± 228	2206 ± 593	76,506	50,737	0.93	1.00
Atlantic Coastal Pine Barrens	24	20	588 ± 101	1685 ± 518	14,124	33,698	0.79	1.00
Blue Ridge	40	89	691 ± 271	1155 ± 169	27,621	102,777	0.62	0.86
Boston Mountains	34	13	878 ± 96	1417 ± 388	29,846	18,420	0.96	1.00
Central Appalachians	69	406	480 ± 40	1202 ± 98	33,134	488,140	1.00	1.00
Central Corn Belt Plains	1	1	648	349	648	349	–	–
Driftless Area	1	0	223	–	223	0	–	–
East Central Texas Plains	4	10	1309 ± 359	2272 ± 1190	5237	22,722	1.00	1.00
Eastern Corn Belt Plains	3	0	637 ± 134	–	1912	0	1.00	–
Eastern Great Lakes Lowlands	1	0	412	–	412	0	–	–
Interior Plateau	7	5	577 ± 222	347 ± 69	4039	1736	0.60	1.00
Interior River Valleys and Hills	2	2	525 ± 105	433 ± 174	1050	866	1.00	1.00
Middle Atlantic Coastal Plain	88	40	1338 ± 308	1554 ± 788	117,709	62,180	0.85	0.84
Mississippi Alluvial Plain	3	0	396 ± 69	–	1187	0	0.00	–
Mississippi Valley Loess Plains	7	7	335 ± 48	333 ± 40	2343	2329	1.00	1.00

(*Continued on next page*)

Table 1. (*Continued*)

Ecoregion	Number of non-WUI wildfires	Number of WUI wildfires	Average non-WUI wildfire size ± s.e. (ha)	Average WUI wildfire size ± s.e. (ha)	Area burned by non-WUI wildfires (ha)	Area burned by WUI wildfires (ha)	Proportion non-WUI wildfires ignited by humans	Proportion WUI wildfires ignited by humans
North Central Hardwood Forests	18	6	380 ± 45	774 ± 188	6837	4642	1.00	1.00
Northeastern Coastal Zone	1	0	308	–	308	0	1.00	–
Northern Allegheny Plateau	0	1	–	382	0	382	–	1.00
Northern Piedmont	0	2	–	292 ± 37	0	584	–	1.00
Ouachita Mountains	72	17	1475 ± 169	1177 ± 218	106,188	20,005	0.86	0.79
Ozark Highlands	126	39	631 ± 67	707 ± 122	79,508	27,561	0.97	1.00
Piedmont	23	20	385 ± 50	1080 ± 315	8866	21,590	0.93	0.80
Ridge and Valley	38	57	434 ± 34	917 ± 145	16,474	52,268	0.88	0.93
South Central Plains	83	40	751 ± 99	1787 ± 465	62,357	71,495	0.82	0.79
Southeastern Plains	160	65	617 ± 47	534 ± 46	98,776	34,711	0.94	0.95
Southeastern Wisconsin Till Plains	2	0	354 ± 26	–	709	0	1.00	–
Southern Coastal Plain	442	214	1413 ± 271	2741 ± 788	624,362	586,560	0.59	0.76
Southern Michigan/Northern Indiana Drift Plains	0	2	–	392 ± 44	0	785	–	–
Southwestern Appalachians	49	38	541 ± 51	694 ± 100	26,519	26,365	1.00	1.00
Western Allegheny Plateau	4	22	559 ± 195	944 ± 207	2237	20,769	1.00	1.00

Characteristics of large (>200 ha) wildfires inside and outside the wildland–urban interface (WUI) across Level III ecoregions of the eastern United States between 1986 and 2021, including total number, average size (±s.e.) (in ha), total area burned (in ha) (*n* = 2388), and proportion of wildfires ignited by humans (*n* = 1749). Dashes (–) represent the absence of a large wildfire for a given ecoregion.

Spatial patterns in WUI large wildfires

Forty-five percent of the 2388 wildfires that burned in the eastern US burned in the WUI, more than would be expected based on WUI land area (Table 1). WUI large wildfires made up the majority of the area burned in the eastern US, accounting for 55% of the area burned (1.6 million ha) (Table 1). Large wildfires that burned in the WUI were, on average, also 46% larger than those outside the WUI (Table 1). WUI large wildfires were 1468 ± 167 s.e. ha, whereas non-WUI large wildfires were 1003 ± 97 s.e. ha (Table 1).

WUI large wildfires were more often ignited by humans than non-WUI large wildfires. Human ignitions were responsible for 91% of WUI large wildfires, compared with 80% of non-WUI large wildfires (Table 1). 'Arson and incendiarism' was the most common cause of WUI large wildfires (52%), and 'debris and open burning' was the next most common cause (18%) (Supplementary Fig. S9).

The Central Appalachians ecoregion contained the greatest number of large wildfires inside the WUI. In contrast, the Southern Coastal Plain ecoregion had the greatest number of large wildfires outside the WUI (Table 1, Fig. 2). WUI and non-WUI large wildfires burned the greatest total area within the Southern Coastal Plain (569,212 and 594,588 ha, respectively) (Table 1, Fig. 2). All WUI and non-WUI large wildfires in the Central Appalachians were human-caused, whereas in the Southern Coastal Plain, only 59% of non-WUI large wildfires and 76% of WUI large wildfires were human-caused (Table 1, Fig. 2). Southwestern and southeastern ecoregions had the greatest average size for WUI large wildfires, ranging from 2206 to 2741 ha (Arkansas Valley and Southern Coastal Plain, respectively) (Table 1).

Temporal patterns in WUI large wildfires

At the L1 ecoregion scale, both the number and the total area burned by large wildfires outside the WUI increased, though only trends in large wildfire number were statistically significant (Table 2). In contrast, there was a slight, non-significant negative trend in WUI large wildfire number and total area burned (Table 2). At the L3 ecoregion scale, increasing trends in large wildfires in the WUI were generally weaker than those occurring outside the WUI (Table 2). For example, 75% (12 of 16) of ecoregions analysed showed increasing trends in the number and total area burned by large wildfires inside the WUI; however, these trends were fairly weak, with only 13% (2 of 16) of ecoregions showing statistical significance in large wildfire number and 6% (1 of 16) in total area burned (Table 2, Fig. 3). However, 87% (13 of 15) of ecoregions analysed showed increasing trends in the number of large wildfires outside the WUI, with 33% (5 of 15) being statistically significant (Table 2, Fig. 3). Additionally, 73% (11 of 15) showed increases in total area burned by large wildfires outside the WUI, with 27% (4 of 15) showing statistical significance (Table 2, Fig. 3). Southwestern ecoregions such as the Ouachita Mountains and Arkansas Valley had very consistent increasing trends in the number and total area burned by both WUI and non-WUI large wildfires (Table 2, Fig. 3).

The eastern US as a whole did not experience any substantial changes in the average size of large wildfires inside the WUI. At the L3 ecoregion scale, 50% of ecoregions showed slight declining trends in the average size of large wildfires inside the WUI, with only 6% (1 of 16; Southwestern Appalachians) being statistically significant (Table 2, Fig. 3). Large wildfires outside the WUI also showed weak declining trends; 60% of ecoregions showed slight declining trends in the average size of large wildfires outside the WUI, with 7% being statistically significant (1 of 15; Table 2, Fig. 3). The Ozark Highlands showed a strong increasing trend in the average size of large wildfires outside the WUI, whereas central ecoregions, such as the Central Appalachians and Piedmont as well as the Atlantic Coastal Pine Barrens, showed strong decreasing trends in the average size of large wildfires (Table 2, Fig. 3).

Across the eastern US, WUI and non-WUI large wildfires occurred every year between 1986 and 2021. At the L3 ecoregion scale, most ecoregions showed signals of increases in the annual probability of occurrence for both WUI and non-WUI large wildfires (Table 2). Southwestern ecoregions, such as the Arkansas Valley and Ouachita Mountains, showed some of the greatest increases in the annual probability of a WUI and non-WUI large wildfire occurring over time (Table 2). Not all ecoregions experienced increases in the annual probability of large wildfire occurrence. For instance, the North Central Hardwood Forests ecoregion showed a significant decline in the annual probability of occurrence of large wildfires outside the WUI. The Southern Coastal Plain experienced non-WUI large wildfires every year of our study period.

The eastern US also experienced changes in the seasonality of WUI and non-WUI large wildfires. During the first decade of our assessment (1986–1995), WUI large wildfires occurred predominantly during the fall (autumn). By the last decade of our assessment, WUI large wildfires were more equally distributed between spring and fall (2012–2021) (Fig. 4*a*). This pattern contrasts with non-WUI large wildfire seasonality, which remained fairly consistent across the first and last decades of our assessment. At the L3 ecoregion scale, WUI and non-WUI large wildfires became more common during the spring in the Ridge and Valley ecoregion (Fig. 4*b*). In the Southeastern Plains ecoregion, large wildfires outside the WUI became less common during the fall, whereas WUI large wildfires became less common during the summer (Fig. 4*b*). In the Southern Coastal Plain, WUI large wildfires became slightly more common during early fall, whereas in the Central Appalachian ecoregion, WUI large wildfires became slightly more common during spring (Fig. 4*b*).

Table 2. Changes in large wildfire regime characteristics.

Ecoregion	WUI status	Number		Average size (ha)		Area burned (ha)		Annual probability of occurrence				Probability of human ignition			
		T	*P*	*T*	*P*	*T*	*P*	Odds ratio	2.5%	97.5%	*P*	Odds ratio	2.5%	97.5%	*P*
L1 Eastern Temperate Forests (eastern US)	WUI	−0.04	0.75	0.00	1.00	−0.05	0.65	–	–	–	–	1.02	0.98	1.07	0.25
	Non-WUI	0.29	0.01	0.03	0.80	0.21	0.08	–	–	–	–	1.00	0.98	1.03	0.89
Arkansas Valley	WUI	0.27	0.05	−0.15	0.50	0.23	0.08	1.08	1.01	1.18	0.04	–	–	–	–
	Non-WUI	0.42	<0.01	−0.11	0.54	0.33	<0.01	1.12	1.04	1.23	<0.01	–	–	–	–
Atlantic Coastal Pine Barrens	WUI	0.08	0.58	−0.07	0.77	0.07	0.57	1.02	0.96	1.09	0.49	–	–	–	–
	Non-WUI	0.02	0.88	−0.34	0.10	−0.03	0.83	1.01	0.94	1.07	0.84	–	–	–	–
Blue Ridge	WUI	0.08	0.54	−0.03	0.87	0.07	0.59	1.02	0.96	1.09	0.52	1.04	0.93	1.15	0.49
	Non-WUI	−0.14	0.30	0.04	0.81	−0.05	0.68	0.98	0.92	1.05	0.57	0.94	0.82	1.07	0.37
Boston Mountains	WUI	0.04	0.79	0.36	0.27	0.04	0.78	1.00	0.93	1.08	0.97	–	–	–	–
	Non-WUI	0.18	0.18	0.25	0.17	0.17	0.18	1.02	0.96	1.09	0.45	–	–	–	–
Central Appalachians	WUI	−0.08	0.53	−0.10	0.49	−0.08	0.53	1.03	0.96	1.11	0.46	–	–	–	–
	Non-WUI	0.01	0.92	−0.39	0.02	−0.04	0.76	1.03	0.97	1.10	0.37	–	–	–	–
East Central Texas Plains	WUI	0.16	0.25	0.40	0.46	0.17	0.22	1.06	0.96	1.18	0.27	–	–	–	–
	Non-WUI	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Middle Atlantic Coastal Plain	WUI	−0.18	0.17	0.01	1.00	−0.15	0.24	0.96	0.89	1.02	0.18	0.90	0.68	1.15	0.38
	Non-WUI	0.07	0.61	0.03	0.82	0.04	0.76	0.98	0.87	1.11	0.79	1.08	0.99	1.20	0.08
North Central Hardwood Forests	WUI	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Non-WUI	−0.33	0.02	−0.13	0.64	−0.31	0.02	0.92	0.84	0.99	0.04	–	–	–	–
Ouachita Mountains	WUI	0.40	<0.01	0.07	0.86	0.38	<0.01	1.14	1.05	1.29	0.01	1.98	1.10	6.16	0.08

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Table 2. (*Continued*)

Ecoregion	WUI status	Number		Average size (ha)		Area burned (ha)		Annual probability of occurrence				Probability of human ignition			
		T	*P*	*T*	*P*	*T*	*P*	Odds ratio	2.5%	97.5%	*P*	Odds ratio	2.5%	97.5%	*P*
	Non-WUI	0.39	<0.01	–0.03	0.88	0.37	<0.01	1.12	1.04	1.24	<0.01	1.05	0.92	1.21	0.44
Ozark Highlands	WUI	–0.14	0.30	0.21	0.18	–0.06	0.62	0.96	0.90	1.02	0.23	–	–	–	–
	Non-WUI	0.24	0.05	0.28	0.03	0.31	<0.01	1.15	1.02	1.36	0.05	–	–	–	–
Piedmont	WUI	0.20	0.15	0.13	0.58	0.19	0.14	1.04	0.98	1.12	0.21	–	–	–	–
	Non-WUI	0.17	0.20	–0.36	0.10	0.12	0.36	1.03	0.97	1.11	0.36	–	–	–	–
Ridge and Valley	WUI	0.09	0.48	0.16	0.29	0.10	0.43	1.02	0.95	1.09	0.59	–	–	–	–
	Non-WUI	0.22	0.10	–0.05	0.77	0.18	0.14	1.06	0.99	1.14	0.10	–	–	–	–
South Central Plains	WUI	0.20	0.14	–0.07	0.77	0.18	0.16	1.05	0.99	1.14	0.12	1.07	0.92	1.26	0.35
	Non-WUI	0.18	0.15	0.01	0.96	0.16	0.19	1.06	0.99	1.15	0.11	0.99	0.89	1.08	0.78
Southeastern Plains	WUI	0.07	0.61	0.11	0.47	0.07	0.56	1.00	0.93	1.07	0.99	–	–	–	–
	Non-WUI	0.36	<0.01	–0.07	0.59	0.25	0.04	1.26	1.04	1.83	0.09	–	–	–	–
Southern Coastal Plain	WUI	0.13	0.28	–0.00	0.99	0.11	0.37	1.18	0.98	1.68	0.18	1.01	0.95	1.06	0.83
	Non-WUI	0.26	0.03	0.05	0.67	0.16	0.19	–	–	–	–	1.00	0.96	1.03	0.84
Southwestern Appalachians	WUI	0.04	0.79	–0.52	0.02	0.01	0.94	1.01	0.95	1.08	0.71	–	–	–	–
	Non-WUI	0.07	0.61	–0.18	0.29	0.06	0.65	1.02	0.96	1.09	0.47	–	–	–	–
Western Allegheny Plateau	WUI	–0.18	0.19	–0.20	0.47	–0.17	0.20	0.96	0.89	1.04	0.34	–	–	–	–
	non-WUI	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Changes in regime characteristics for large (>200 ha) wildfires inside and outside the wildland–urban interface (WUI) across Level III ecoregions of the eastern United States from 1986 to 2021. The number, average size (in ha) and total area burned (in ha) were assessed using the Mann–Kendall Trend Test. The annual probability of large wildfire occurrence and the probability of human ignition were also evaluated using a binomial generalised linear model. We only included ecoregions containing 10 or more WUI or non-WUI large wildfires during the study period for these assessments. Dashes (–) indicate insufficient data for analysis.

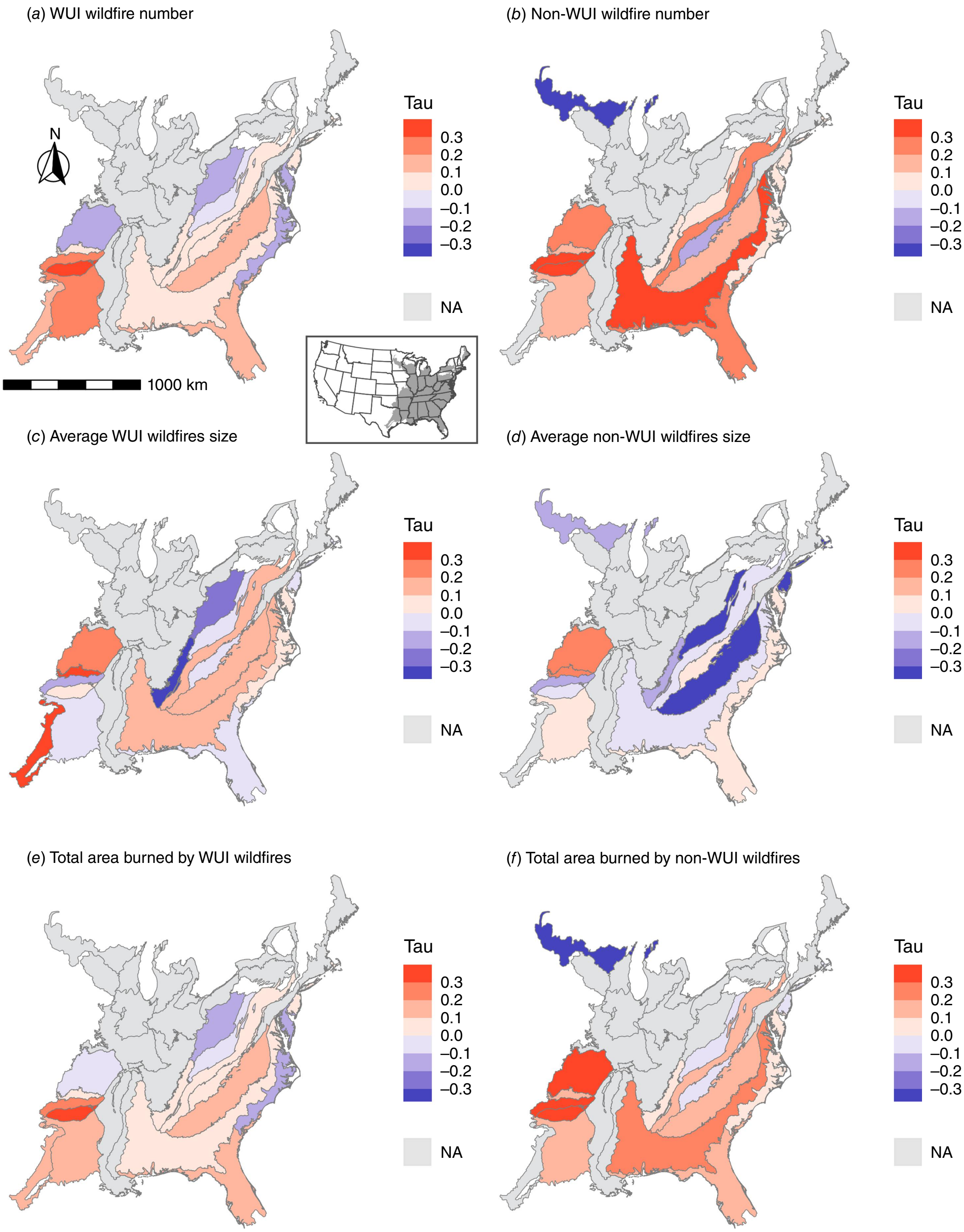

Fig. 3. Maps showing Mann–Kendall tau values for annual changes in the (*a–b*) number, (*c–d*) average size (in ha), and (*e–f*) total area burned (in ha) by large wildfires (>200 ha) inside and outside the WUI. Darker red colours represent ecoregions with more consistent positive trends over time, whereas darker blue colours represent ecoregions with more consistent negative trends over time. Grey represents ecoregions excluded from analysis owing to insufficient wildfire numbers over the study period.

Across the eastern US, the odds of a large wildfire being human-ignited increased both inside and outside the WUI; however, neither was statistically significant (Table 2). At the L3 ecoregion scale, the odds of a large wildfire being human-ignited increased through time in the Ouachita Mountains ecoregion inside the WUI, whereas the Middle

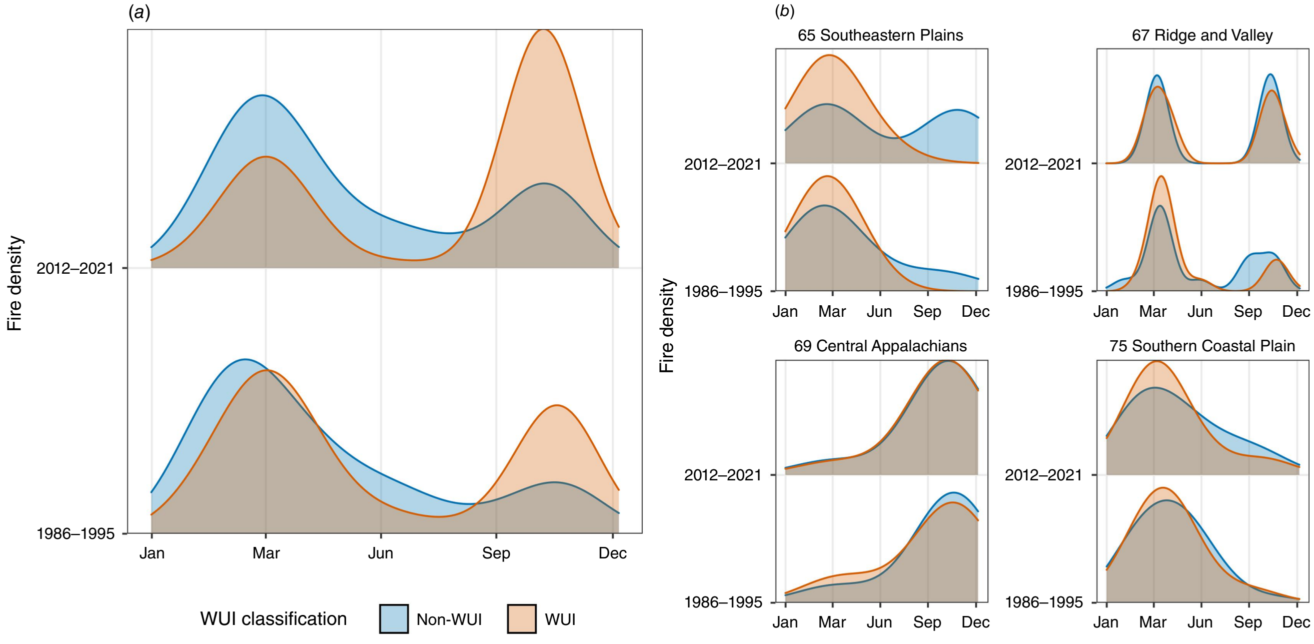

Fig. 4. Gaussian kernel density estimates for large (>200 ha) wildfire seasonality inside and outside the wildland–urban interface (WUI) of the (*a*) Level 1 Eastern Temperate Forests ecoregion (the eastern US), and (*b*) Level III ecoregions. Only ecoregions that contained five or more WUI and non-WUI large wildfires within the first and last decades of our assessment were used to create density estimates because a smaller sample size would be insufficient for proper visualisation. Bandwidth was determined using 'Silverman's Rule of Thumb' (Silverman 1986).

Atlantic Coastal Plain showed an increasing trend in the odds of human-ignited large wildfires outside the WUI. That said, neither ecoregion trend was statistically significant (Table 2).

Discussion

Large wildfire regime characteristics in the eastern US displayed unique dynamics in the WUI compared with non-WUI wildfires. Although the WUI covers 22% of the area in the eastern US, 45% of large wildfires burned there, indicating that the WUI disproportionately affects wildfire risk in the eastern US. Southwestern ecoregions of the eastern US experienced rapid WUI growth, which coincided with the strongest signals of increasing wildfire both inside and outside the WUI. WUI wildfires are increasing in certain ecoregions; however, increasing trends were more substantial and abundant outside the WUI, suggesting that non-WUI wildfires are likely the primary driver of increasing large wildfire trends documented across the eastern US (Donovan *et al.* 2023). Furthermore, we found that northern ecoregions experienced very few large wildfires, despite having a high proportion of WUI. These findings suggest that increasing large wildfire trends in the eastern US are primarily driven by large wildfires outside the WUI.

The disparity in shifting wildfire regime characteristics within and outside the WUI is likely linked to a host of social-ecological factors. Numerous studies have demonstrated links between increasing wildfire and shifting climate and vegetation dynamics (Weltzin and McPherson 2003; Donovan *et al.* 2020; Brown *et al.* 2021). The southeast is experiencing increasingly drier and warmer climatic conditions, which likely plays an important role in increasing large wildfire occurrence across the region (Fill *et al.* 2019; Kupfer *et al.* 2020). However, factors that function at smaller scales, such as fuel dynamics, ignitions and suppression potential are more likely to be influencing differences in wildfire regime characteristics inside and outside the WUI. For example, the WUI is more likely to have higher-density forests (Sonti *et al.* 2022), more invasive species (Gavier-Pizarro *et al.* 2010) and a greater number of ignition sources (Calviño-Cancela *et al.* 2016; Syphard *et al.* 2017), all of which have the potential to increase wildfire risk. We correspondingly found that wildfires occur disproportionately more in the WUI. Interestingly, however, increases in large wildfires are largely occurring outside the WUI. Although decades of fire suppression are likely leading to more large wildfires outside the WUI owing to increased fuel loads (Kreider *et al.* 2024) combined with changing climate (Brown *et al.* 2021), within the WUI, these same drivers may be largely mitigated by timely and effective firefighting (e.g. Calkin *et al.* 2014; Swimley 2021; Daniels *et al.* 2024; Kreider *et al.* 2024). Suppression resources are often directed toward larger wildfires that burn in areas with higher housing density, thereby minimising economic loss (Swimley 2021). However, this may leave areas of low housing density without firefighting resources, allowing fires to grow larger and burn for longer. Furthermore, higher levels of fragmentation in the WUI, particularly as it becomes more densely populated (Radeloff *et al.* 2018), may inherently drive smaller wildfires, meaning that increases in their occurrence were not captured in this study (Kreider *et al.* 2024). Although our findings may suggest that suppression efforts have been fairly effective at preventing increases in large wildfire risk to people and structures in many areas in the eastern US, the slight increases in WUI large wildfires in the majority of ecoregions analysed may be a potential early warning for future increases in WUI wildfires if current socio-ecological trajectories continue.

Although the northeastern US has a high proportion of WUI area, it experienced relatively few large wildfires compared with southern ecoregions. This difference in the occurrence of large wildfires may be due, in part, to a high degree of fragmentation in the north (e.g. Wickham *et al.* 2008; Riitters *et al.* 2012; Hanberry 2020; Carlson *et al.* 2021). Although these regions contain a high proportion of WUI area, they also contain dense urban areas and croplands, which have been shown to limit the occurrence of large wildfires owing to insufficient fuel and fuel connectivity (Hanberry 2020) to generate wildfires greater than 200 ha (the threshold for inclusion in our analysis). Prior research has suggested that fragmented landscapes in the northeastern US hamper wildfire spread, driving numerous small wildfires not captured in our study (Carlson *et al.* 2021). Further research could examine the overall trends of small wildfires to determine if shifts in large wildfire occurrence are happening in smaller wildfires in northern regions. Northern regions of our study area have also experienced wetter conditions that may be increasing fuel moisture and thereby reducing wildfire risk (Thibeault and Seth 2014; Vaittinada Ayar and Mailhot 2021). Furthermore, the north has experienced substantial 'mesophication', in which tree species experience a compositional change toward shade tolerance following fire exclusion, creating conditions that further preclude fire from the system (Nowacki and Abrams 2008; Donovan *et al.* 2023). Nonetheless, climate change is predicted to increase the risk of wildfires across the eastern US (Bedel *et al.* 2013; Swanston *et al.* 2018; Fill *et al.* 2019), making preemptive and adaptive management imperative.

Increased wildfire risk in ecoregions that experienced significant increases in large wildfire within the WUI may be driven by changing land use and WUI expansion. We observed the greatest increases in WUI area in southwestern ecoregions, which also experienced the most consistent increases in wildfire activity. This may be due to heightened ignition potential, the spread of exotic and woody species, and an increase in the presence of flammable materials associated with WUI growth (Fernandez-Pello 2017; Donovan *et al.* 2020; Mietkiewicz *et al.* 2020; Hanberry 2022). For instance, the Ouachita Mountains of Arkansas experienced an increase in the odds of human-ignited large wildfires in the WUI, suggesting that additional ignition sources associated with WUI expansion may be a driving factor for increased WUI wildfire activity. Although WUI growth may be heightening wildfire risk in southwestern ecoregions, this area also experienced changing land use associated with timber harvesting (Drummond *et al.* 2020). Timber operation can increase wildfire activity through ignition from machinery and increased dry fuels from slash piles (Stone *et al.* 2004; Sjöström *et al.* 2019). Timber harvesting has been shown to promote the invasion of exotic species such as cogongrass (*Imperata cylindrica*), thereby substantially altering the fuelbed (Burrell *et al.* 2015; McGranahan and Wonkka 2022). This alteration can heighten fire intensity by increasing fuel loading and continuity, and promote more rapid and expansive fire spread in logged areas (Tomat-Kelly *et al.* 2021). With the number of large wildfires projected to continue to increase under future climate (Senande-Rivera *et al.* 2022) and the continuing expansion of the WUI, suppression capacity is likely to be spread increasingly thinly in the eastern US. Proactive fuels management, especially in and around communities in the WUI, will be important, particularly in regions showing signals of increasing large wildfire activity in the WUI. Our study highlights the importance of the WUI in influencing large wildfire regimes, and provides a starting point for more region-specific analyses of drivers of changing large wildfire dynamics inside and outside the WUI.

Supplementary material

Supplementary material is available online.

References

Abatzoglou JT, Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* **113**, 11770–11775. doi:10.1073/pnas.1607171113

Alston KP, Richardson DM (2006) The roles of habitat features, disturbance, and distance from putative source populations in structuring alien plant invasions at the urban/wildland interface on the Cape Peninsula, South Africa. *Biological Conservation* **132**, 183–198. doi:10.1016/j.biocon.2006.03.023

Balch JK, Bradley BA, Abatzoglou JT, Nagy RC, Fusco EJ, Mahood AL (2017) Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* **114**, 2946–2951. doi:10.1073/pnas.1617394114

Bedel AP, Mote TL, Goodrick SL (2013) Climate change and associated fire potential for the south-eastern United States in the 21st century. *International Journal of Wildland Fire* **22**, 1034–1043. doi:10.1071/WF13018

Brown EK, Wang J, Feng Y (2021) US wildfire potential: a historical view and future projection using high-resolution climate data. *Environmental Research Letters* **16**, 034060. doi:10.1088/1748-9326/aba868

Bryce SA, Omernik JM, Larsen DP (1999) Environmental review: ecoregions: a geographic framework to guide risk characterization and ecosystem management. *Environmental Practice* **1**, 141–155. doi:10.1017/S1466046600000582

Burrell AM, Pepper AE, Hodnett G, Goolsby JA, Overholt WA, Racelis AE, Diaz R, Klein PE (2015) Exploring origins, invasion history and genetic diversity of *Imperata cylindrica* (L.) P. Beauv. (cogongrass) in the United States using genotyping by sequencing. *Molecular Ecology* **24**, 2177–2193. doi:10.1111/mec.13167

Butsic V, Kelly M, Moritz MA (2015) Land use and wildfire: a review of local interactions and teleconnections. *Land* **4**, 140–156. doi:10.3390/land4010140

Calkin DE, Cohen JD, Finney MA, Thompson MP (2014) How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences* **111**, 746–751. doi:10.1073/pnas.1315088111

Calviño-Cancela M, Chas-Amil ML, García-Martínez ED, Touza J (2016) Wildfire risk associated with different vegetation types within and outside wildland–urban interfaces. *Forest Ecology and Management* **372**, 1–9. doi:10.1016/j.foreco.2016.04.002

Carlson AR, Sebasky ME, Peters MP, Radeloff VC, Carlson AR, Sebasky ME, Peters MP, Radeloff VC (2021) The importance of small fires for wildfire hazard in urbanised landscapes of the northeastern US. *International Journal of Wildland Fire* **30**, 307–321. doi:10.1071/WF20186

Daniels MC, Braziunas KH, Turner MG, Ma T-F, Short KC, Rissman AR (2024) Multiple social and environmental factors affect wildland fire response of full or less-than-full suppression. *Journal of Environmental Management* **351**, 119731. doi:10.1016/j.jenvman.2023.119731

Donovan VM, Crandall R, Fill J, Wonkka CL (2023) Increasing large wildfire in the eastern United States. *Geophysical Research Letters* **50**, e2023GL107051. doi:10.1029/2023GL107051

Donovan VM, Wonkka CL, Wedin DA, Twidwell D (2020) Land-use type as a driver of large wildfire occurrence in the US Great Plains. *Remote Sensing* **12**, 1869. doi:10.3390/rs12111869

Drummond MA, Stier MP, McBeth JL, Auch RF, Taylor JL, Riegle JL (2020) Causes of land change in the US Interior Highlands, 2001–2011. US Geological Survey, 1127. doi:10.3133/ds1127

Eidenshink J, Schwind B, Brewer K, Zhu Z-L, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. *Fire Ecology* **3**, 3–21. doi:10.4996/fireecology.0301003

EPA (2013) Level III Ecoregions of the Conterminous United States. Available at https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states

Federal Emergency Management Agency (FEMA) (2021) Analysis of NFIRS incidents in the wildland urban interface. Available at https://www.usfa.fema.gov/wui/data/wildfire-report-series/nfirs-wui-incidents-california.html

Fernandez-Pello AC (2017) Wildland fire spot ignition by sparks and firebrands. *Fire Safety Journal* **91**, 2–10. doi:10.1016/j.firesaf.2017.04.040

Fill JM, Davis CN, Crandall RM (2019) Climate change lengthens southeastern USA lightning-ignited fire seasons. *Global Change Biology* **25**, 3562–3569. doi:10.1111/gcb.14727

FMB (2019) Federal wildland fire policy terms and definitions. Available at https://www.nwcg.gov/sites/default/files/docs/eb-fmb-m-19-004a.pdf

Gavier-Pizarro GI, Radeloff VC, Stewart SI, Huebner CD, Keuler NS (2010) Housing is positively associated with invasive exotic plant species richness in New England, USA. *Ecological Applications* **20**, 1913–1925. doi:10.1890/09-2168.1

Gehlhausen SM, Schwartz MW, Augspurger CK (2000) Vegetation and microclimatic edge effects in two mixed-mesophytic forest fragments. *Plant Ecology* **147**, 21–35. doi:10.1023/A:1009846507652

Gilliam FS (2016) Forest ecosystems of temperate climatic regions: from ancient use to climate change. *New Phytologist* **212**, 871–887. doi:10.1111/nph.14255

Hanberry BB (2020) Classifying large wildfires in the United States by land cover. *Remote Sensing* **12**, 2966. doi:10.3390/rs12182966

Hanberry BB (2022) Confronting the issue of invasive native tree species due to land use change in the eastern United States. *Land* **11**, 161. doi:10.3390/land11020161

Haynes K, Short K, Xanthopoulos G, Viegas D, Ribeiro LM, Blanchi R (2020) Wildfires and WUI fire fatalities. In 'Encyclopedia of wildfires and wildland–urban interface (WUI) fires'. (Ed. SL Manzello) pp. 1–16. (Springer International Publishing: Cham, Switzerland) doi:10.1007/978-3-319-51727-8_92-1

Iglesias V, Balch JK, Travis WR (2022) US fires became larger, more frequent, and more widespread in the 2000s. *Science Advances* **8**, eabc0020. doi:10.1126/sciadv.abc0020

Johnston L, Blanchi R, Jappiot M (2019) Wildland–urban interface. In 'Encyclopedia of wildfires and wildland-urban interface (WUI) fires'. (Ed. SL Manzello) pp. 1–13. (Springer International Publishing: Cham, Switzerland) doi:10.1007/978-3-319-51727-8_130-1

Krannich RS, Luloff AE, Field DR (2011) Putting rural community change in perspective. In 'People, places and landscapes: social change in high amenity rural areas'. Landscape Series. (Eds RS Krannich, AE Luloff, DR Field) pp. 9–25. (Springer Netherlands: Dordrecht) doi:10.1007/978-94-007-1263-8_2

Kreider MR, Higuera PE, Parks SA, Rice WL, White N, Larson AJ (2024) Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. *Nature Communications* **15**, 2412. doi:10.1038/s41467-024-46702-0

Kupfer JA, Terando AJ, Gao P, Teske C, Hiers JK (2020) Climate change projected to reduce prescribed burning opportunities in the south-eastern United States. *International Journal of Wildland Fire* **29**, 764–778. doi:10.1071/WF19198

Mandle L, Bufford JL, Schmidt IB, Daehler CC (2011) Woody exotic plant invasions and fire: reciprocal impacts and consequences for native ecosystems. *Biological Invasions* **13**, 1815–1827. doi:10.1007/s10530-011-0001-3

Matilainen A, Pohja-Mykrä M, Lähdesmäki M, Kurki S (2017) "I feel it is mine!" – Psychological ownership in relation to natural resources. *Journal of Environmental Psychology* **51**, 31–45. doi:10.1016/j.jenvp.2017.03.002

McGranahan DA, Wonkka CL (2022) Fuel properties of effective green-strips in simulated cheatgrass fires. *Environmental Management* **70**, 319–328. doi:10.1007/s00267-022-01659-y

Mietkiewicz N, Balch JK, Schoennagel T, Leyk S, St. Denis LA, Bradley BA (2020) In the line of fire: consequences of human-ignited wildfires to homes in the US (1992–2015). *Fire* **3**, 50. doi:10.3390/fire3030050

Modaresi Rad A, Abatzoglou JT, Kreitler J, Alizadeh MR, AghaKouchak A, Hudyma N, Nauslar NJ, Sadegh M (2023) Human and infra-structure exposure to large wildfires in the United States. *Nature Sustainability* **6**, 1343–1351. doi:10.1038/s41893-023-01163-z

MTBS (2023) Burned areas boundaries dataset. Available at https://www.mtbs.gov/direct-download.

Murcia C (1995) Edge effects in fragmented forests: implications for conservation. *Trends in Ecology & Evolution* **10**, 58–62. doi:10.1016/S0169-5347(00)88977-6

Nagy RC, Fusco E, Bradley B, Abatzoglou JT, Balch J (2018) Human-related ignitions increase the number of large wildfires across US Ecoregions. *Fire* **1**, 4. doi:10.3390/fire1010004

Nowacki GJ, Abrams MD (2008) The demise of fire and "mesophication" of forests in the eastern United States. *BioScience* **58**, 123–138. doi:10.1641/B580207

Omernik JM, Griffith GE (2014) Ecoregions of the conterminous United States: evolution of a hierarchical spatial framework. *Environmental Management* **54**, 1249–1266. doi:10.1007/s00267-014-0364-1

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) The wildland–urban interface in the United States. *Ecological Applications* **15**, 799–805. doi:10.1890/04-1413

Radeloff VC, Helmers DP, Kramer HA, Mockrin MH, Alexandre PM, Bar-Massada A, Butsic V, Hawbaker TJ, Martinuzzi S, Syphard AD, Stewart SI (2018) Rapid growth of the US wildland–urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences* **115**, 3314–3319. doi:10.1073/pnas.1718850115

Radeloff VC, Helmers DP, Mockrin MH, Carlson AR, Hawbaker TJ, Martinuzzi S (2023*a*) The 1990-2020 wildland–urban interface of the conterminous United States – geospatial data. 4th edn. (Fort Collins, CO: Forest Service Research Data Archive) doi:10.2737/RDS-2015-0012-4

Radeloff VC, Mockrin MH, Helmers D, Carlson A, Hawbaker TJ, Martinuzzi S, Schug F, Alexandre PM, Kramer HA, Pidgeon AM (2023*b*) Rising wildfire risk to houses in the United States, especially in grasslands and shrublands. *Science* **382**, 702–707. doi:10.1126/science.ade9223

Ranney JW (1977) 'Forest Island edges: their structure, development, and importance to regional forest ecosystem dynamics.' EDFB/IBP-77/1. (Oak Ridge National Lab. (ORNL), Oak Ridge: TN (United States)). doi:10.2172/7278093

R Core Team (2023) R: a language and environment for statistical computing. Available at https://www.r-project.org/

Riitters KH, Coulston JW, Wickham JD (2012) Fragmentation of forest communities in the eastern United States. *Forest Ecology and Management* **263**, 85–93. doi:10.1016/j.foreco.2011.09.022
RStudio Team (2023) RStudio: integrated development environment for R. Available at http://www.rstudio.com/
Sanczuk P, De Pauw K, De Lombaerde E, Luoto M, Meeussen C, Govaert S, Vanneste T, Depauw L, Brunet J, Cousins SAO, Gasperini C, Hedwall P-O, Iacopetti G, Lenoir J, Plue J, Selvi F, Spicher F, Uria-Diez J, Verheyen K, Vangansbeke P, De Frenne P (2023) Microclimate and forest density drive plant population dynamics under climate change. *Nature Climate Change* **13**, 840–847. doi:10.1038/s41558-023-01744-y
Senande-Rivera M, Insua-Costa D, Miguez-Macho G (2022) Spatial and temporal expansion of global wildland fire activity in response to climate change. *Nature Communications* **13**, 1208. doi:10.1038/s41467-022-28835-2
Short KC (2022) Spatial wildfire occurrence data for the United States, 1992-2020 [FPA_FOD_20221014] 6th edn. (Fort Collins, CO: Forest Service Research Data Archive) doi:10.2737/RDS-2013-0009.6
Silverman BW (1986) 'Density estimation for statistics and data analysis.' (Routledge: New York, NY, USA) doi:10.1201/9781315140919
Sjöström J, Plathner FV, Granström A (2019) Wildfire ignition from forestry machines in boreal Sweden. *International Journal of Wildland Fire* **28**, 666–677. doi:10.1071/WF18229
Sonti NF, Riemann R, Mockrin MH, Domke GM (2022) Expanding wildland–urban interface alters forest structure and landscape context in the northern United States. *Environmental Research Letters* **18**, 014010. doi:10.1088/1748-9326/aca77b
Stone C, Hudak A, Morgan P (2004) Forest harvest can increase subsequent forest fire severity. (USDA Forest Service/UNL Faculty Publications) Available at https://digitalcommons.unl.edu/usdafsfacpub/199
Swanston C, Brandt LA, Janowiak MK, Handler SD, Butler-Leopold P, Iverson L, Thompson III FR, Ontl TA, Shannon PD (2018) Vulnerability of forests of the Midwest and Northeast United States to climate change. *Climatic Change* **146**, 103–116. doi:10.1007/s10584-017-2065-2
Swimley K (2021) The influence of wildland urban interface areas on resource assignments to large wildland fires. Graduate Student Theses, Dissertations, & Professional Papers. 11802. University of Montana, ScholarWorks, Missoula, MT. Available at https://scholarworks.umt.edu/etd/11802
Syphard AD, Keeley JE (2015) Location, timing and extent of wildfire vary by cause of ignition. *International Journal of Wildland Fire* **24**, 37–47. doi:10.1071/WF14024
Syphard AD, Keeley JE, Pfaff AH, 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. doi:10.1073/pnas.1713885114
Theobald DM (2005) Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology and Society* **10**, 34. Available athttps://www.jstor.org/stable/26267722.
Theobald DM, Romme WH (2007) Expansion of the US wildland–urban interface. *Landscape and Urban Planning* **83**, 340–354. doi:10.1016/j.landurbplan.2007.06.002
Thibeault JM, Seth A (2014) Changing climate extremes in the Northeast United States: observations and projections from CMIP5. *Climatic Change* **127**, 273–287. doi:10.1007/s10584-014-1257-2
Toman E, Stidham M, Shindler B, McCaffrey S, Toman E, Stidham M, Shindler B, McCaffrey S (2011) Reducing fuels in the wildland–urban interface: community perceptions of agency fuels treatments. *International Journal of Wildland Fire* **20**, 340–349. doi:10.1071/WF10042
Tomat-Kelly G, Dillon WW, Flory SL (2021) Invasive grass fuel loads suppress native species by increasing fire intensity and soil heating. *Journal of Applied Ecology* **58**, 2220–2230. doi:10.1111/1365-2664.13881
USDA, USDI (2001) Urban wildland interface communities within the vicinity of Federal lands that are at high risk from wildfire. Notices. *Federal Register* **66**, 705–1011.
Vaittinada Ayar P, Mailhot A (2021) Evolution of dry and wet spells under climate change over north-eastern North America. *Journal of Geophysical Research: Atmospheres* **126**, e2020JD033740. doi:10.1029/2020JD033740
Weltzin JF, McPherson GR (2003) 'Changing precipitation regimes and terrestrial ecosystems: a North American perspective.' (University of Arizona Press: AZ, USA)
Wickham H (2016) 'ggplot2: elegant graphics for data analysis.' (Springer) doi:10.1007/978-3-319-24277-4
Wickham JD, Riitters KH, Wade TG, Homer C (2008) Temporal change in fragmentation of continental US forests. *Landscape Ecology* **23**, 891–898. doi:10.1007/s10980-008-9258-z
Woodbridge M, Keyser T, Oswalt C (2022) Stand and environmental conditions drive functional shifts associated with mesophication in eastern US forests. *Frontiers in Forests and Global Change* **5**, doi:10.3389/ffgc.2022.991934

Data availability. Wildfire data were obtained from the Monitoring Trends in Burn Severity database (MTBS 2023) and are available at https://www.mtbs.gov/direct-download. Wildland–urban interface data were obtained from the USDA's wildland–urban interface geospatial data (Radeloff *et al.* 2023*a*) and are available at doi:10.2737/RDS-2015-0012-4. Ecoregion boundaries were obtained from the Environmental Protection Agency (EPA 2013) and are available at https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states. Wildfire ignition data were obtained from the USDA's Fire Occurrence Database (Short 2022) and are available at doi:10.2737/RDS-2013-0009.6. The code used to analyse these data can be found at the following GitHub repository: https://github.com/noahweidig/wui_wildfires.

Conflicts of interest. The authors declare no conflicts of interest.

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