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WILDFIRES

The fastest-growing and most destructive fires in the US (2001 to 2020)

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The most destructive and deadly wildfires in US history were also fast. Using satellite data, we analyzed the daily growth rates of more than 60,000 fires from 2001 to 2020 across the contiguous US. Nearly half of the ecoregions experienced destructive fast fires that grew more than 1620 hectares in 1 day. These fires accounted for 78% of structures destroyed and 61% of suppression costs ($18.9 billion). From 2001 to 2020, the average peak daily growth rate for these fires more than doubled (+249% relative to 2001) in the Western US. Nearly 3 million structures were within 4 kilometers of a fast fire during this period across the US. Given recent devastating wildfires, understanding fast fires is crucial for improving firefighting strategies and community preparedness.

Some of the most deadly and destructive wildfires in US history have occurred in recent years, with most having the common characteristic of extremely rapid growth. The 2018 Camp Fire in California burned >21,000 ha the day it started, killing 85 people and destroying >16,000 homes. The 2021 Marshall Fire, the most destructive wildfire in Colorado history, was driven by winds >100 mph; it traveled 3 miles within the hour it started and burned >1000 homes. The 2023 Lahaina Fire in Hawaii killed 101 people and destroyed >2200 structures when a small brush fire escaped containment and burned through the town to the shore in 2 hours. The modern era of megafires is often defined based on wildfire size (*1*), but it should be defined based on how fast fires grow and their consequent societal impacts. Speed fundamentally dictates the deadly and destructive impact of megafires, rendering the prevailing paradigm that defines them by size inadequate. Although big fires change air quality, ecosystems, and carbon dynamics (*2*), fire speed matters more for infrastructure risk and evacuation planning (*3*).

The scientific community has explored trends in extreme fire size (*4*, *5*) and burn severity (*6*) and documented increasing burned areas across the Western US (*7*). Further, we know that fast fires occur when it is hot, dry, and windy, but relatively little research exists about when and why they occur across regional or national scales. Most of the area burned in extremely large events is from the growth on a single day, which is driven by extreme fire weather (*8*). Moreover, the frequency of fast-growing fires is predicted to increase by ~50 to 200% with projected warming (*9*, *10*). Humans also ignite fires in areas closer to structures (*3*) and during times with more extreme fire weather (*11*), both of which result in more destructive fires (*12*). Recent observational evidence is corroborated by empirical models (*13*) that derive relationships to predict fire growth (*14*) and drive landscape fire simulations for individual events (*15*, *16*). Such fire behavior models inform wildfire risk models suggesting that the most deadly and damaging wildfires are also some of the fastest (*17*, *18*). How fast fires burn also affects burn severity, spatial complexity (*19*, *20*), and synchronicity (*21*). However, we do not know the patterns, drivers, and consequences of fast fires on a national scale.

Fire suppression policies, logging, the proliferation of invasive species, climate change, and anthropogenic ignition patterns have fundamentally altered the fire-evolved landscapes of postcolonial America (*22*–*28*). Moreover, the expansion of the urban footprint (*29*) has placed tens of millions of homes squarely into this contemporary fuel matrix, which is called the wildland-urban interface (WUI) (*30*). The rapid expansion of this footprint has occurred largely without regard for wildfire risk, either through building policies or comprehensive community planning (*31*). As a result, nearly 60 million homes in the US were threatened by a wildfire between 1992 and 2015 (*3*), a number that has likely increased substantially in the intervening years due to record fires in California, Oregon, and Colorado. The wildfire risk models currently used at a national scale are based on probability of occurrence and area burned, intensity, or severity (*21*, *32*–*35*) rather than on how fast wildfires could move. This lack of attention to fire growth is a critical risk assessment gap, particularly given the rapid expansion of the WUI into areas with the greatest probability of wildfire (*36*, *37*) and the mechanisms by which most homes burn. We know that the primary mechanism for home ignition is firebrands propelled ahead of the flaming front that land on flammable materials attached to, on, or inside the structure and ultimately consume it (*38*). Firefighters can extinguish these building ignitions during slower fires or when structure ignition is mitigated (*39*), but during fast-moving events, they are often overwhelmed by the higher number of homes catching fire simultaneously and the need to focus on life safety and evacuations, such as during the 2018 Camp Fire (*17*).

Our lack of understanding is linked to our lack of national data on fire growth rates (FGRs) across events. Recent data on individual fire events and how they progressed, coupled with fine-grained settlement data, enable us to explore how fast fires move at a national scale and how that affects residential exposure. We developed a Fire Event Delineation (FIRED) perimeter dataset for >60,000 fire events (*40*). This dataset is derived from daily burn date estimations from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) Burned Area Product (*41*), enabling calculation and investigation of daily FGR. FGR derived from satellite-detected burned area on a daily basis is different from, but related to, how fast a burning fireline moves on the ground. Settlement data have also become available to measure trends of development over long time periods at fine resolution (*29*). The Historical Settlement Data Compilation of the US (HISDAC-US) (*42*, *43*), which is derived from >200 million property and housing records, allows us to estimate nearby exposure to wildfires (up to 4 km away). Government records during suppression activities (ICS-209-PLUS) enable us to further explore the societal consequences of wildfires by providing documentation on how many structures were damaged or destroyed on a daily basis during fire events (*25*, *44*). The aggregation of ICS-209 reports provides the best available information on the high costs of US wildfires at a national scale. The combination of these latter two datasets, HISDAC-US on the spatiotemporal distribution of residential structures and the ICS-209-PLUS on actual structure loss, allows us to explore both potential exposure and documented impact.

Given the critical need to understand fast-moving wildfires and the tens of millions of homes that stand in their paths, we analyzed fires in the context of their speed and damage to homes. We documented the fastest-growing fires in the US from 2001 to 2020, exploring the maximum single-day FGR across an event,

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hereafter referred to as "maximum FGR." We then related maximum FGR with structure loss (i.e., damaged or destroyed) to provide a societally relevant threshold for defining fast fires (maximum FGR > 1620 ha/day). Finally, we explored the trends in maximum FGR and how many total structures, specifically residences, were exposed to fast fires over the past two decades.

FGRs in the contiguous US

FGRs were highly variable across all events (N = 60,012), with fires growing at an average rate of 255 ha/day. Maximum FGR ranged from 21 to 214,200 ha/day, often multiple orders of magnitude greater than the mean FGR across the entire event (table S1). Burned area on the day of maximum FGR accounted for more than one-third (38%) of the area burned across the US (table S2), and >70% for some land cover types in certain ecoregions (e.g., shrublands in the Great Plains; table S2). The maximum FGR is very strongly associated with final fire size across land cover types (fig. S1), with the log-log relationship suggesting that it follows a power law distribution (adjusted R^2 = 0.97). The importance of this is that extreme fire weather on individual days is driving fire growth and has consequences for suppression efforts (*45*). Further, >90% of events last no longer than 20 days (fig. S2A), and 83% of events reach their maximum growth rate within 5 days across all ecoregions (fig. S2B). In addition, there are distinct temporal and spatial characteristics across different vegetation types (e.g., grassland fires burn large areas within a few days, whereas broadleaf forests sustain fire growth for longer periods of time; fig. S3). Many modeling efforts at regional to national scales model fire activity at monthly to yearly timescales (*4*, *46*). Our results highlight the need for regional models of fire behavior that use predictors at daily to hourly timescales rather than burned area estimations based on topography and spatiotemporally coarse climate data. This is particularly important in the context of modeling the occurrence of extreme meteorological events and their ability to drive rapid fire growth (*20*). Such models exist (*13*–*15*) and are being further advanced (*33*), but it remains to be tested whether they can replicate the remotely sensed spread rates in extreme events such as those discussed here. We also found that mean and maximum FGRs

Table 1. Top 20 fastest-growing fires across the CONUS from 2001 to 2020. Summary statistics describe the top 20 fastest fires from FIRED linked to their associated incident command system summary report (*44*). The top 20 fastest fires accrued an estimated $398 million in suppression costs alone, exposed 264,338 properties (within 4 km of a fire perimeter), and destroyed >9000 structures. Of the 20 fastest fires, 16 occurred primarily in grassland vegetation types (>50% grassland in burned area).

Incident name	Year	State(s)	Fire size (ha)	Maximum fire growth (ha/day)	Duration (days)	Cost (US dollars)	Properties exposed (*n*)	Structures destroyed (*n*)	Total aerial units (*n*)	Total personnel (*n*)	Dominant vegetation
NW Oklahoma Complex	2017	OK, KS	315,369	214,208	16	3,200,000	1647	151	2	955	Grasslands
Long Draw	2012	OR	225,664	129,911	14	4,360,000	2	0	49	4237	Grasslands
Cold Springs Complex	2020	WA	218,969	102,199	33	11,459,351	4907	288	34	4327	Grasslands
Perryton	2017	TX	128,753	100,911	14	NR	97	11	3	235	Grasslands
Anderson Creek	2016	OK, KS	148,819	81,420	19	1,750,000	1098	54	20	1183	Grasslands
Murphy Complex	2007	ID	263,862	70,150	30	13,000,000	21	3	56	10,443	Grasslands
East Amarillo Complex	2006	TX	367,149	60,770	23	NR	4821	89	6	702	Grasslands
Martin	2018	NV	176,269	59,246	20	8,500,000	0	1	97	2332	Grasslands
Milford Flat	2007	UT	146,922	58,258	16	5,050,000	112	2	25	4421	Grasslands
Glass	2008	TX	88,851	57,979	5	NR	1	0	8	56	Grasslands
Buzzard Complex	2014	OR	160,153	50,252	14	11,062,411	42	4	96	5265	Grasslands
August Complex	2020	CA	417,898	46,629	68	115,511,218	196	446	1153	63,814	Evergreen needle-leaf forests
Kinyon Road	2012	ID	85,338	47,461	12	1,625,000	57	0	18	1361	Grasslands
Soda	2015	ID	115,482	46,474	9	6,250,000	662	1	69	1706	Grasslands
Rhea	2018	OK	115,820	44,499	26	3,707,498	1669	32	62	941	Grasslands
North Complex	2020	CA	129,069	42,438	52	112,711,950	4607	2342	802	63,229	Evergreen needle-leaf forests
Cedar	2003	CA	110,579	41,408	18	32,616,213	132,444	2820	626	74,404	Closed shrublands
Cooper Mountain Ranch	2011	TX	65,812	39,969	13	1,194,159	740	0	8	854	Grasslands
LNU Lightning Complex	2020	CA	146,990	39,132	22	94,646,381	34,344	1479	354	36,601	Grasslands
Witch-Poomacha	2007	CA	80,124	38,639	19	18,000,000	76,871	1680	2	46,819	Closed shrublands

NR, not recorded.

vary by land cover and ecoregion, with the fastest-growing fires typically in the grasslands and savannas of arid ecoregions (table S3). The 10 fastest fires were in grassland-dominated vegetation, which highlights the role of fine, flashy fuels and low wind friction (Table 1 and table S4). The three wildfires highlighted in Fig. 1 show how fast fires can grow within the first few days.

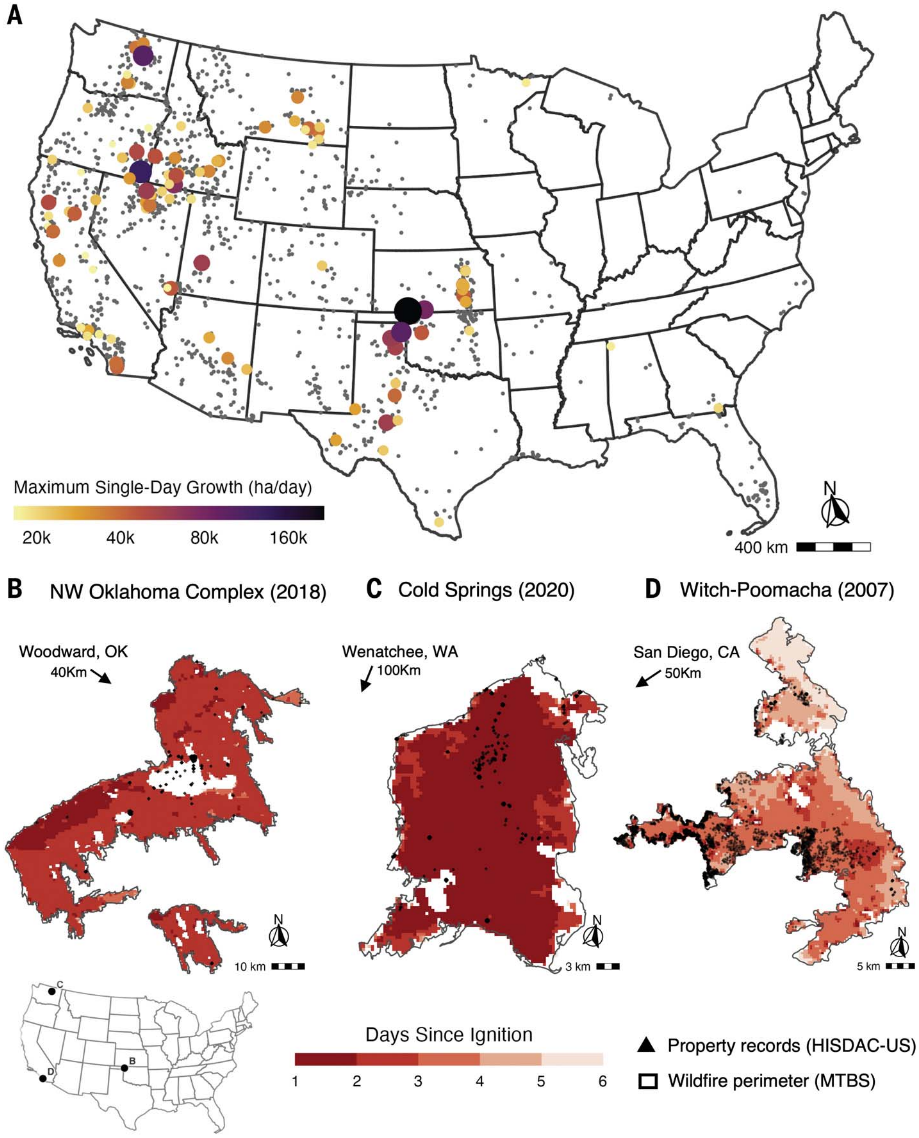

Fig. 1. Fast fires in the US. (**A**) Locations of all recorded fast fires from 2001 to 2020 (maximum FGR >1620 ha, *N* = 1616, in gray) in the CONUS with the top 100 fastest fires scaled in color and size by their maximum single-day fire growth rate in hectares/day. The fastest fires occurred primarily in the Western US and in the Southeastern Plains (Texas and Oklahoma), but across a wide range of ecoregions and fuel types. (**B** to **D**) Three examples of the fastest fires on record highlighting the daily burned area from the MODIS Burned Area Product (MCD64A1), fire perimeters from the Monitoring Trends in Burn Severity (MTBS), and approximate locations of properties within the burned area from the BUPR obtained from the HISDAC-US database. (B) The Northwest Oklahoma Complex Fire in 2018 is the fastest recorded fire in the database, with a single-day maximum growth of 214,208 ha/day, burning in grasslands. (C) The Cold Springs Fire in 2020 was part of the destructive Labor Day fires, which burned in high winds and, together with the Pearl Hill and Whitney fires, burned >165,000 ha in a matter of days. The Cold Springs Fire was the largest of the three and burned almost entirely in a single day (102,198 ha/day). (D) The Witch and Poomacha fires in 2003 burned just outside of San Diego, CA, directly exposing >8000 properties within days (with >76,000 properties within 4 km of the burned area) and destroying 1680 structures, making it one of the most destructive fast fires in the database.

Fast fires are also the most destructive and deadly ones

Although there has been substantial focus on megafires defined primarily by their size (*47*), we delineate a critical physical metric that links directly with impact: maximum daily FGR. Treating wildfires as social-environmental extremes (*48*) and defining a subset of events based on both their physical behavior and destructive impact advances our understanding and ability to prepare for such events (*49*). Fires growing faster than 1620 ha on any single day damage or destroy a large number of structures (Fig. 2). Regression tree analysis (residual mean deviance = 2.39) indicates that one of the best predictors of whether a large number of structures were damaged or destroyed across the entire event is whether the maximum FGR exceeded this threshold of 1620 ha (see the supplementary materials and methods). There is an association between the day of maximum daily growth and the day that structures were reported as being affected (fig. S4). This speed corresponds to the 97th percentile of maximum daily fire growth registered between 2001 and 2020, representing 1616 events out of 60,012 total events and 60.1% of the burned area in the FIRED record. Therefore, we define fast fires as events that grow >1620 ha on a single day (i.e., maximum FGR > 1620 ha/day). These fast fires represent only 2.7% of all events, yet they account for 89% of the total structures damaged or destroyed. It is important to note that this is a nationwide threshold based on fires that had any structure loss at all. Of the fires that damaged or destroyed >100 structures (*N* = 71), their average maximum daily growth was 8569 ha/day (median = 4916 ha/day). Moreover, there are important differences across states (table S5). For example, California has by far the highest structure loss compared with other states (*N* = 66,715 structures damaged or destroyed) and exhibits a fast fire threshold of 2870 ha/day.

Our results document that 58 of the 85 level 3 ecoregions in the contiguous US (CONUS) experienced more than one fast fire between 2001 and 2020 (fig. S5), representing an area of ~3,780,000 km^2 or 49% of CONUS land area. According to the ICS-209-PLUS fire suppression records (2001 to 2020) (*44*), fast fires threatened 1,780,476 structures (67% of total threatened) and resulted in $18.9 billion of suppression expenditures (61% of total). Moreover, 80,700 structures were destroyed (78% of total destroyed), and 57,883 were damaged (82% of total damaged) across this time period during fast fire events. This subset of fires represents a devastating impact to society, accounting for 337 fatalities (66% of total) and 5623 injuries (43% of total).

From 2001 to 2020, fast fires grew even faster across much of the Western US

For all fires, mean FGR significantly increased in 38 and maximum FGR significantly increased in 20 of the 84 level III ecoregions (mainly in the Western US). Mean FGR significantly decreased in 16 and maximum FGR significantly

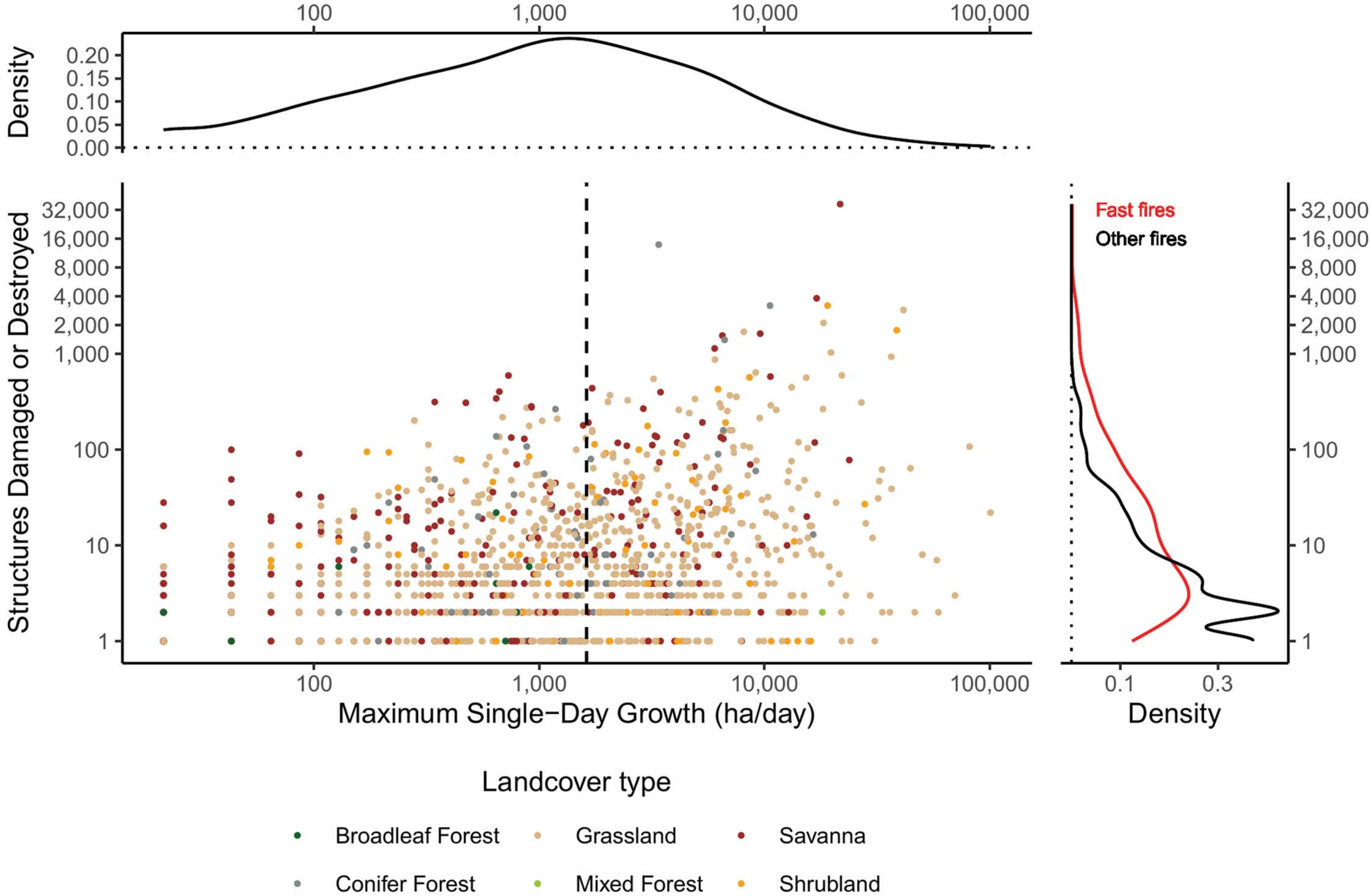

Fig. 2. Defining fast fires as a function of social-economic impacts. Scatterplot of log-transformed maximum FGR and log-transformed number of structures destroyed, with marginal probability density distributions. The dashed line shows the lower bound of growth of fast fires (1620 ha/day or above) that were also the most destructive ones. Note that the axes are in log scale and that only fast fires destroyed >600 structures.

decreased in nine of the ecoregions (mainly in the Northeast; Fig. 3 and fig. S6). Most of California's ecoregions, along with coastal Oregon and Washington state, exhibited an increase in FGR over this period. Most pronounced were the increases in event-level spread and daily growth rates in mediterranean California, with an increase of 300 ha/day in maximum daily growth in Southern California mountains (Theil-Sen coefficient = 15.0 ha/day/year; table S6). Across ecoregions in the state of California, the average maximum FGR increased by 4.2 ha/day/year (±0.4 SE), or ~80 ha/day across the 20-year record (table S7). The Snake River Plain and Columbia Plateau of the North American desert ecoregion also saw a substantial increase of >278 ha/day in maximum daily growth (Theil-Sen coefficient = 13.9 ha/day/year; table S6). Across ecoregions in 11 Western states, the mean of the maximum FGR increased by 2.1 ha/day/year (±0.1 SE), or ~40 ha/day across the 20-year record (table S7). On the basis of these trends, fires grew 249% faster (based on maximum daily FGR) across the Western US by the end of the 20-year record (table S8). In California, fires grew 398% faster

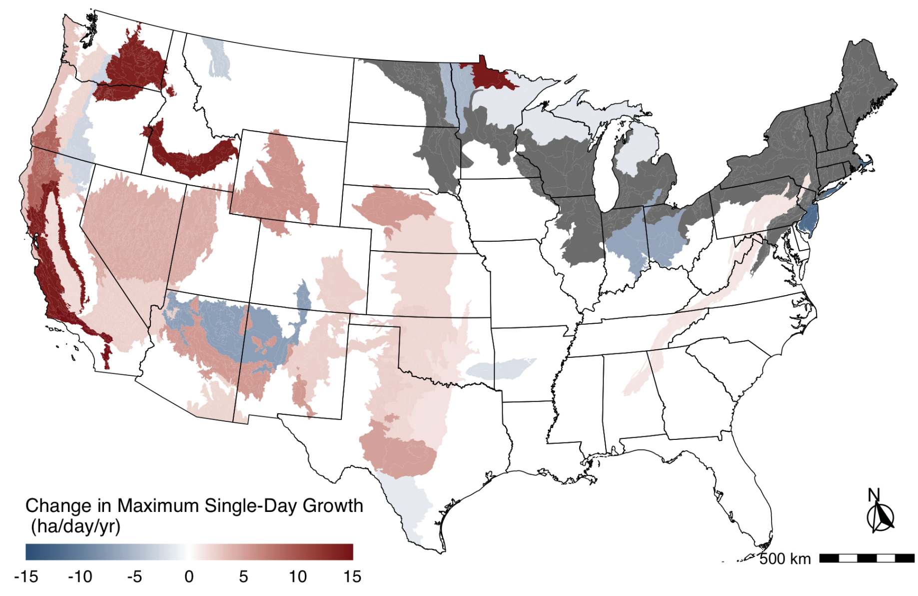

Fig. 3. Temporal trends in maximum annual fire growth on a given day for events longer than 4 days per Environmental Protection Agency (EPA) ecoregion level IV from 2001 to 2020. Statistically significant positive and negative regression coefficients ($P < 0.05$) are depicted in warm and cold colors, respectively. Regression coefficients that were not statistically significant from zero (i.e., no significant trend) are shown in white. Ecoregions without sufficient data for the analysis are indicated in gray.

(based on maximum FGR) by the end of the 20-year record (table S8). (These percentage increases in California and the Western US represent the mean of the maximum FGR in 2020 as a percentage of mean maximum FGR in 2001; see the materials and methods.) Across the Western US, this trend in growth has been accompanied by an increase in annual burned area near built-up areas (i.e., those <1 km from a residential structure) of 323% since 2001 (fig. S7).

Using the HISDAC-US Historical Built-up Property Records (BUPR) (*43*), we estimated that 184,917 properties were exposed directly to fast fires (e.g., within the fire perimeter), 722,017 structures were within 1 km of fast fire perimeters, and 2,948,501 structures were within 4 km of fast fire perimeters (Fig. 4 and fig. S8). Firebrands have ignited WUI materials several kilometers from the main fire (*39*), thus putting structures within this proximity at some risk of loss.

Conclusions: Fire speed matters

Wildfire events should be defined based on their speed, not just their size. Here, we provide a first look at understanding national patterns and trends (2001 to 2020) in FGR using a satellite-derived metric (*50*). There are two major implications of our work: (i) we define what constitutes "fast fires" and (ii) we demonstrate that fires are getting faster, particularly in the Western US.

Herein, we delineate a new class of the fastest-growing and most destructive fires, or fast fires. This class is akin to "mega-fires" but is defined based on a maximum daily growth rate of >1620 ha/day, where we document most of the structures destroyed (78%) and suppression costs (61%). A major advance is that this class of fast fires is defined by both the physical behavior and societal impact, representing coupled social-environmental extremes (*48*). We also demonstrate that there is a strong relationship between growth rate and burned area (fig. S1); growth is the fundamental mechanism driving final event size. Current national fire risk models and planning efforts tend to focus on fire probability, intensity, or area burned (*50*) rather than on fire speed and consequent settlement exposure or potential damage. Fast fires matter for life safety and structure impacts; large fires matter more for ecosystems and they generate substantial smoke. The speed of a fire determines (i) whether firefighters are more focused on evacuation than home protection (*17*) and (ii) how effectively they can extinguish burning firebrands and new ignitions on structures before the home becomes fully involved (*38*, *39*). Additionally, we quantify that the fastest-growing fires are in grassland systems, where more homes have been destroyed relative to forest wildfires (*51*), highlighting the need to rethink grassland fire management strategies.

We also document that fires are growing significantly faster across nearly half of the CONUS land area and 2.5 times faster across the Western US in just 20 years. Increasing speed will challenge emergency response, evacuation plans, and community preparedness (*52*). Incident command reports indicate that at least 925 emergency evacuation orders affected >1.5 million households between 2001 and 2020 (*44*), and approximately half of these were within 1 km of a fast fire (Fig. 4). Wildfire-related emergency evacuation success will be influenced by the density of human settlements, road access (*53*), and efficient use of early warning systems and information delivery to affected communities (*54*), all of which will be compromised by faster-moving fires. With maximum daily growth occurring within the first 5 days after ignition for 83% of all events (fig. S2B), we also need to focus on proactive measures

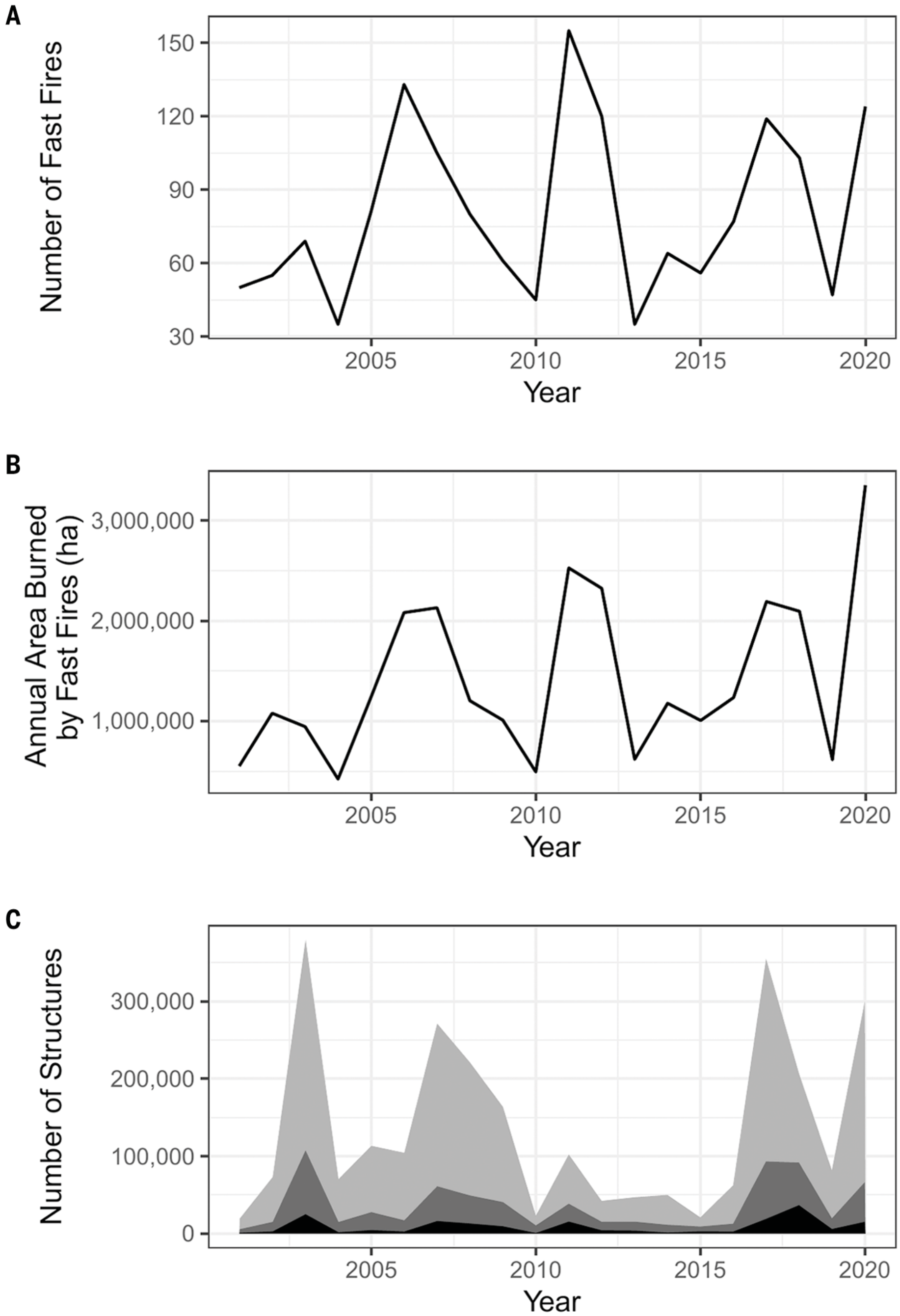

Fig. 4. Exposure to fast fires (>1620 ha/day) from 2001 to 2020. (**A**) Number of fast fires per year. (**B**) Annual area affected by fast fires. (**C**) Trends in the number of structures (based on the BUPR dataset) within the perimeters of fast fires (black), within 1 km of the perimeters of fast fires (dark gray), and within 4 km of the perimeters of fast fires (light gray).

that slow fires down or promote fire resilience of the built environment. We need to implement building codes that incentivize the use of fire-resistant materials (*55*), harden existing homes and remove flammable materials adjacent to structures (*56*), and preemptively plan for evacuation. Fuel mitigation efforts that will slow fires down include, for example, strategic wildland fuel breaks in the expected path of a fire and rethinking the constellation of proximate, flammable homes in new developments. Future research efforts will help us better understand the hourly progression of blow-ups from higher-resolution satellite sensors and how effective fire suppression teams may already be at slowing wildfires.

Fires may be growing faster due to warming trends, vegetation transitions to more flammable fuels, or the co-occurrence of high winds with increasing human-related ignitions. Climate-driven increases in burned area has been well documented in the US (*57*), as well as an observed tripling of fire frequency in the 2000s relative to the prior two decades (*21*). Many fast fires occur during downslope wind events coincident with anomalously dry autumn conditions, which increased both in frequency (25%) and in the area they burned (140%) from 1992 to 2020 (*58*). Juang *et al.* found that the increase in Western US forest fire area since the mid-1980s was driven almost exclusively by increasing sizes of the largest fires (*59*). The mechanism is a function of geometric growth: Larger fires tend to grow faster than smaller fires because longer firelines have greater potential for spread. It is also known that invasive grasses can drive increases in size (*23*), occurrence, and frequency (*24*). Because grass-fueled fires are some of the fastest (table S3), it may then follow that where vegetation transitions have occurred, for example, from forest or shrubland to invasive grassland (*60*), fire speed may have also increased. Further, we know that there is a relationship between human ignitions and higher winds (*11*, *61*), because lightning generally does not occur under high-wind conditions due to the constraints surrounding their associated storms (*61*). Across the US, there has been a steady increase (9%) in the percentage of wildfires started by humans since 1992 (*62*). It has yet to be tested whether the co-occurrence of windy conditions and human-related ignitions, such as downed power lines, is increasing. People start nearly all the wildfires that threaten our homes (*3*), making understanding of the ignition, climatic, and fuel drivers of fast fires an important area of future work.

The number of fast fire events that have destroyed >1000 homes in just the past 5 years is alarming (*63*) and may foreshadow what is coming in years ahead. Fast fires overall accounted for 88% of residential structures destroyed in the US from 2001 to 2020. With warming temperatures increasing the likelihood of wildfires across the US (*64*), we would expect to see more fast fire events in the future. Devastating and fast-moving wildfires, such as the Camp Wildfire in California, the Marshall Wildfire in Colorado, and the Lahaina Wildfire in Hawaii, show that it is critical that we plan for the increasing pace of fires.

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used in this analysis are publicly available. All code necessary to reproduce this analysis is available at https://github.com/viriglesias/fast-fires. The workflow to derive the linked ICS-209+ and FIRED product per (*44*) is available at https://github.com/maxwellCcook/ics209-plus-fired/blob/main/code/R/ics-fired.Rmd. The all-hazards dataset mined from the US National Incident Management System is hosted on Figshare (*65*). Fire Events Delineation (FIRED) CONUS-AK 2001-2022 data are available at https://scholar.colorado.edu/concern/datasets/d504rm74m and latest (version 2) are available at https://scholar.colorado.edu/concern/datasets/fx719p11c. The Historical Settlement Data Compilation of the US (HISDAC-US) data are available at: https://dataverse.harvard.edu/dataverse/hisdacus. US Environmental Protection Agency ecoregions are listed at https://www.epa.gov/eco-research/ecoregions. The Monitoring Trends in Burn Severity (MTBS) website is at https://www.mtbs.gov/.

SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
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