Title: Wildfires increasingly threaten oil and gas wells in the western United States with disproportionate impacts on marginalized populations

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Summary

The western United States is home to most of the nation's oil and gas production and, increasingly, wildfires. We examined historical threats of wildfires for oil and gas wells, the extent to which wildfires are projected to threaten wells as climate change progresses, and exposure of human populations to these wells. From 1984–2019, we found that cumulatively 102,882 wells were located in wildfire burn areas, and 348,853 people were exposed (resided ≤ 1 km). During this period, we observed a five-fold increase in the number of wells in wildfire burn areas and a doubling of the population within 1 km of these wells. These trends are projected to increase by late century, likely threatening human health. Approximately 2.9 million people reside within 1 km of wells in areas with high wildfire risk, and Black, Hispanic, and Native American people have disproportionately high exposure to wildfire-threatened wells.

Introduction

The extent and intensity of wildfires have worsened in recent years across the world, including the western United States (U.S.), and are expected to continue worsening as climate change intensifies[1–3]. Substantial areas of the western U.S. have particularly high wildfire risk due to conditions including extreme temperature and drought, which contribute to the aridity of trees and other vegetation that can fuel wildfires[1,3,4]. Since 2014, the U.S. has been the top global producer of crude oil and natural gas[5], with most production concentrated in western states[6,7]. Drilling is ongoing, and the Inflation Reduction Act of 2022 ties renewable energy rights-of-way on federal land to new oil and gas lease auctions[8]. The impact of emerging climate-related hazards, including wildfire, on existing and future infrastructure is of relevance to diverse stakeholders, including nearby residents and land management authorities in tribal, local, state, and federal government.

The recent proliferation of U.S. oil and gas development has coincided with rising wildfire risks, as well as significant population growth in the wildland-urban interface (WUI) with an estimated 350,000 new houses constructed in the WUI each year in the past two decades [2,9]. Between 2010 and 2019, approximately 215,000 new wells were sited in the western U.S., accounting for 12.9% of all wells drilled at any time. However, it is unclear to what extent wildfires threaten oil and gas development, whether and to what degree human populations are at risk of exposure to these wells, and whether climate change and continued development in the WUI will exacerbate these risks. Under typical conditions, engineers carefully manage fire-related hazards in onshore oil and gas fields to avoid placing heat sources near flammable hydrocarbons [10]. Uncontrolled, large-scale wildfires in oil and gas fields can result in explosions, emissions of hazardous air and water pollutants, and physical damage to infrastructure, which still provides a critical source of energy. There is already widespread exposure to oil and gas wells in the U.S., with 17.6 million people (5.4% of the population) residing within 1.6 km (1 mile) of active wells (14). There is even broader exposure to inactive wells[11], a subset of which emit methane and other flammable gases[12–14]. A comprehensive assessment of wildfire risks for oil and gas development in a changing climate is a necessary step in designing interventions to proactively mitigate associated public health hazards.

Wildfires in the WUI have destroyed and damaged residences and public works[15], polluted the air[16], and increased emergency room visits[17]. Wildfires can also trigger secondary infrastructure-related disasters, such as when extreme heat from wildfires results in contamination of drinking water supplies with carcinogenic compounds (e.g., benzene)[18,19]. These sorts of natural hazards that trigger technological accidents are referred to as natechs. Natech events may heighten risks to human health and the environment beyond those associated with natural disasters alone [19–21]. Even in the absence of wildfire or other natech threats, drilling and operating wells has resulted in emissions of air pollutants[22–25] and contamination of ground and surface water[24,26]. There is mounting evidence that living near oil and gas wells is associated with increased risk of adverse cardiovascular, respiratory, perinatal, and mental health outcomes[27–38]. Fires at oil and gas wells, unrelated to wildfire, have presented additional hazards such as high levels of radiant heat, explosions, and emissions of air toxics[39,40].

Here we examine the past and future hazards of wildfire in areas with oil and gas wells in the western U.S. First, we retrospectively determined to what extent wildfires have already occurred in areas with oil and gas wells and assessed population exposures. We then used data on projected wildfire risks to determine to what extent existing oil and gas wells will be threatened as climate change worsens. Our analysis shows that wildfires have already burned through areas with tens of thousands of oil and gas wells, including wells near residences in what we here refer to as the petro-wildland-urban interface (PWUI), with disproportionate impacts for persistently marginalized groups. This trend has worsened in recent years and will likely continue through the end of the century as climate change progresses.

Results

Methods Summary

Our study had three overarching objectives. First, we examined trends in the number of oil and gas wells located in wildfire burn areas in the western U.S. from 1984–2019. Second, we estimated how many people were exposed to wells located in historical wildfire burn areas and how many people currently reside near wells with high wildfire risk. We also determined whether there are racial/ethnic disparities in exposure to wildfire-threatened wells. Third, we examined trends in the number of wells in areas projected to have high wildfire risk through the end of the century.

We assembled geospatial data on oil and gas wells, historical wildfires, projected wildfire risk, and population density for the 19 states west of the Mississippi River that had at least one oil or gas well. We obtained well data from Enverus, a private data aggregation service, for all active or inactive oil and gas wells. We obtained data on the extent of historical wildfires from two sources: Monitoring Trends in Burn Severity (MTBS) and the National Interagency Fire Center (NIFC). To estimate overall and race/ethnicity-specific populations exposed to wells in wildfire burn areas, we used high-resolution gridded population data from SocScape[41,42]. To determine which areas had high historical or future wildfire risk, we used a dataset with the Keetch-Byram Drought Index (KBDI) calculated for 2017, as well as projected KBDI in mid-century (2046–2054) and late century (2086–2094)[4]. We used two KBDI thresholds to consider historical and future wildfire risk: KBDI $\geq$ 600 indicating high wildfire risk[4]; and KBDI $\geq$ 450 indicating moderately high risk, a more conservative threshold used by some government agencies[43].

We first identified oil and gas wells located within historical wildfire burn areas in the western U.S. for each state and year (Figure 1). Next, we determined how many people were exposed, which we defined as residing within 1 km of these wells. Prior studies have consistently found that residing within 1 km of oil and gas wells is associated with poorer air quality and greater health risks[23,44–48]. To assess temporal trends both for the number of wells in wildfire burn areas and the population exposed to these wells, we fit Poisson regression models with and without adjustment for state. Finally, we assessed how many people reside within 1 km of wells in areas with high historical and projected future wildfire risk. Because past studies indicate racially marginalized people have disproportionately high exposure to oil and gas wells[11,49], we investigated whether there were racial/ethnic disparities in exposure to wildfire-threatened wells. To do so, we estimated group risk ratios (RR), where RR > 1 indicates disproportionately high exposure and RR < 1 indicates disproportionately low exposure.

Historical increases in wildfire-threatened wells and exposed populations

Cumulatively, between 1984 and 2019 wildfires burned areas containing 102,882 oil and gas wells (Figure 2). Most of these wells were in Oklahoma (n = 39,352), Texas (n = 32,426), and California (n = 17,143). Across the study region, the annual mean ± standard deviation (SD) of wells in wildfire burn areas was 2,858 ± 4,012 (median: 779), with a peak of 18,047 in 2011 (Table S1). The number of wells in burn areas increased five-fold over our study period ($p < 0.001$) (Figure 2), from an annual average of 1,065 ± 161 in 1984–1993 to 5,098 ± 1,054 in 2010–2019. We observed significant increasing trends in Oklahoma and Texas, though there were fluctuations throughout the study period (Figure S1). There was not a significant time trend in California, where there were several years with a relatively high number of wells in wildfire burn areas throughout the study period. We identified 3,341 individual wildfires that had at least one well in the burn area. Some wildfires were particularly impactful, including 15 wildfires with over 1,000 wells in the burn area. For example, the 2006 East Amarillo Complex Fire in Texas burned an area containing 3,845 oil and gas wells (Figure 3, Table S2).

Projected growth in extent of wildfire threats for wells

In 2017, 118,409 oil and gas wells were in high (KDBI ≥ 600) wildfire risk areas (Figure 2), of which 103,878 (87.7%) were in California and 9,753 (8.2%) in Texas (Table 1). By late century (2086–94), we project that 205,670 wells will be in high wildfire risk areas, an increase of 73.7% from 2017, of which over half (n = 109,801, 53.3%) are in California and 76,320 (37.2%) are in Texas (Figure 4). Wildfire threats for wells were consistently high in southern California counties such as Los Angeles, whereas there were substantial increases in the number of wildfire-threatened wells in other regions (Table S3). For example, currently there are no wells in Uintah County, Utah, in areas with KBDI ≥ 600, but we estimate that by late century there will be 12,790 wells in areas with KBDI ≥ 600. In Dimmit County, Texas, we estimate a seven-fold increase in wildfire-threatened wells, from 631 wells in 2017 to 4,784 in 2086–2094. We estimated that 25,828 of the 166,106 (15.5%) wells on federal land will be in areas with high wildfire risk by late century (2086–2094), a 29.8% increase from historical (2017) risks (Table S4).

When we considered areas with moderately high wildfire risk (KBDI ≥ 450), we identified 551,676 wells historically threatened (2017), increasing by 116.3% to 1,193,386 wells by late century (Table 1). Most of these wells are in Texas, Oklahoma, California, and Louisiana. Again, the threats were consistently high in counties in southern California, and there were also substantial increases in the number of wildfire-threatened wells in other regions. For example, we observed a 252% increase in wildfire-threatened wells in Eddy County, New Mexico (7,808 wells in 2017 to 27,509 in 2086–2094) and a 1,351% increase in Lea County, New Mexico (1,879 wells in 2017 to 27,269 in 2086–2094) (Table S5). By late century, 90,737 (54.6%) of wells on federal land are projected to be in areas with KBDI ≥ 450, an 82.8% increase from 2017 (Table S6).

Populations increasingly exposed to wildfire-threatened wells

Between 1984 and 2019, cumulatively 348,853 people resided within 1 km of oil and gas wells located in wildfire burn areas (Table S7). Most exposed people lived in California (n = 252,644, 72.4%), Oklahoma (n = 60,542, 17.4%), and Texas (n = 22,734, 6.5%) (Table S7). Across all 19 states from 1984–2019, the annual average count of people living near wells in burn areas was 9,690 ± 10,507 (median: 8,521), peaking at 51,352 in 2008 (Figure 2). The annual average count of people exposed to wells in wildfire burn areas increased from 6,927 ± 1,483 in 1984–1993 to 13,380 ± 3,440 in 2010–2019. Oklahoma, Kansas, California, and Texas saw the steepest increases in the number of people exposed to wells in burn areas (Figure S2). Over the course of the study period, we did not observe any substantial trends with respect to well or population density in the PWUI (Figure S3).

We estimated that 10,618,601 people live within 1 km of wells with moderately high wildfire risk areas (KBDI ≥ 450 in 2017, Table S8), with disproportionately high exposure among Asian, Black, and Hispanic people (Figure 5, Table S9). In Arkansas, Colorado, Louisiana, New Mexico, Oklahoma, and Utah, American Indian/Alaska Native people had disproportionately high exposure. In Utah, the representation of Native American/Alaska Native people residing within 1 km of wildfire-threatened wells was approximately 22 times the representation of this group across the state, the widest disparity we observed. Of the 31,400 wells in Utah, 22,599 (72.0%) are in the Uintah and Ouray Reservation of the Ute Tribe and 1,091 (3.5%) are in the Navajo Nation. When we used a more stringent threshold for historically high wildfire risk (KBDI ≥ 600), we estimated that 2,915,457 people live ≤ 1 km of wildfire-threatened wells, with 2,597,330 in California and 303,569 in Texas (Table S8). In both states, Hispanic people disproportionately lived near wells in high wildfire risk areas, with RRs of 1.23 for Hispanic people in California and 2.27 in Texas (Table S10). All other racial/ethnic groups had disproportionately low exposure in these two states (Figure 5). Aggregated across all states, Hispanic and non-Hispanic Asian people were also more likely to live near wells in high wildfire risk areas (Table S10).

Discussion

From 1984 to 2019, we observed a five-fold increase in the number of oil and gas wells in wildfire burn areas, with varying temporal trends by state. As climate change worsens, we project that by the end of the century the number of wells in high wildfire risk areas will increase to over 200,000, a 53.9% increase from the present day. Furthermore, we project that approximately 1 million additional wells will be in areas with moderately high risk of wildfire by late century, over twice the number of wells historically threatened by wildfire. Approximately 350,000 people have already been exposed to wells in historical wildfire burn areas. Increases in population exposures appear to be driven by increases in wildfire size and frequency, as the density of wells and residents in the PWUI has not changed substantially over the past forty years. As wildfire risk expands to new locations in the coming decades, wildfires in urban or peri-urban oil fields could pose a hazard for many more PWUI residents. Indeed, we estimated that approximately 2.9 million people in the study region live within 1 km of wells in areas with high historical wildfire risk, and approximately 10.6 million people live near wells with moderately high wildfire risk. The greatest concentrations of populations living near wildfire-threatened wells, both in historical and projected future assessments, were in California and Texas. The public health implications of population exposures to wildfire-damaged wells remain unclear, and further work is needed to determine the extent to which wildfires physically damage oil and gas infrastructure, identify effective hazard mitigation processes, and elucidate potential acute and chronic human health effects.

There are already well-known hazards associated with fires (unrelated to wildfire) in areas with both active and inactive wells, particularly in densely populated areas. Petroleum engineers typically manage fire-related hazards by locating fired process equipment away from flammable hydrocarbons[10]. Blowout and ignition near gas wells have resulted in radiant heat strong enough to cause second-degree burns within several hundred feet of wells[39]. These hazards may be exacerbated by the broad scale and uncontrolled nature of wildfires, some of which have encompassed thousands of wells at a time, and which can complicate wildfire emergency response efforts and increase the costs of wildfire suppression. Wildfire damage to oil and gas wells may also increase emissions of pollutants from the wells, with implications for sensitive cultural sites, the health of humans and non-human animals, and ecosystem functioning.

We found that Asian, Black, Hispanic, and Native American people had disproportionately high exposure to wells at risk of wildfire. Prior research has already identified environmental justice concerns related to oil and gas wells and, separately, wildfires. Studies of California, Texas, and Colorado have found that racially and socioeconomically marginalized people are more likely to live near oil and gas development compared to their white and more privileged counterparts[11,49–52]. One prior study has investigated climate-related risks and population exposures to hazardous facilities including oil and gas wells, finding that racially and socioeconomically marginalized people had disproportionately high exposure to hazardous sites threatened by sea level rise in California[53]. There is some evidence that Native American, Black, and Hispanic/Latinx people are more likely to live in communities that have less capacity to adapt to wildfire, though Black and Hispanic/Latinx people are less likely to live in areas with wildfire risk overall[54]. A 2021 study found that Indigenous people in North America are more likely to live in wildfire-prone areas due to forced migration and land dispossession [55]. Racially and socioeconomically marginalized communities may experience disproportionate wildfire impacts due to structural factors that reduce their capacity to undertake wildfire mitigation measures, such as hazardous fuels reductions[56]. Additionally, a 2024 study found that Native American and, to a lesser extent, multiracial California residents had disproportionately high exposure to wildfire fine particulate matter ($PM_{2.5}$)[57]. Increasing emissions of wildfire $PM_{2.5}$ may exacerbate existing racial/ethnic disparities in air pollutant exposures.

To our knowledge, this is the first study to investigate historical and projected future wildfire threats to oil and gas infrastructure across the U.S. Notably, a 2018 report from FracTracker Alliance found that approximately 10,000 wells in 160 California oil fields were impacted by wildfire between 1998 and 2018, which highlighted the need for further research as undertaken here[58]. In the current study, we leveraged 36 years of historical observations and climate projections spanning a century, the widest available timespan for which reliable wildfire data were available nationwide.

There are several limitations to our study. The KBDI only indirectly accounts for fuel availability, which is a potential concern given the wide range of ecosystem types across the western U.S. and consequent differences in wildfire risk. Other strengths of KBDI offset this potential limitation. KBDI uses cumulative precipitation as a proxy for vegetation, assuming that annual rainfall is associated with vegetation growth and, consequently, more fuel available to burn. Other fire danger indices have been developed to predict wildfire potential. Prior research has evaluated eight fire danger indices by calculating the correlations between the indices and burned area, finding moderate-to-strong correlation between KBDI and fire burned area over the western U.S.[4,59,60]. A 2023 study by Yu et al. found that the correlation between four fire danger indices (FDI) and wildfire size was lower at daily and grid cell levels than at annual and regional scales, the latter of which was comparable to KBDI[61]. Furthermore, daily minimum relative humidity was the most important parameter for assessing fire danger among these four FDIs and was particularly associated with high fire danger potential[61]. These findings indicate that KBDI, despite its simplicity, is an effective method to determine fire risk potential across most of the U.S. Our projections of future wildfire hazards in the PWUI were based on current population and demographic data, and we did not model future demographic shifts. However, if the trends of recent decades continue[2,9], we can expect the number of people living within the PWUI to grow. There is, however, potential for wildfire-driven displacement or managed retreat from the WUI in the coming decades[62], but it is outside the scope of the current study to project such shifts. Finally, we assessed wildfire threats for wells drilled before 2020, and thus, our estimates of the number of wells threatened by wildfire and the populations likely affected are conservative. New wells are drilled yearly, and future studies could update our work to incorporate them.

Future research, including air quality modeling, could better characterize the exposure and health implications of wildfires that burn oil and gas wells, understand how wildfires in oil and gas fields affect non-human animals and disrupt ecosystem functioning, and assess to what extent wildfire-related shocks disrupt oil and gas production. As government agencies concurrently undertake efforts to retire existing wells and permit new wells, decision-makers and regulatory scientists should consider population risks associated with wildfires. This is particularly important in those states where we observed the greatest historical and projected future risks of wildfire overlap with wells and human populations. Interventions could include limiting or eliminating drilling in high wildfire risk areas, creating setbacks between wells and sensitive receptors (e.g., residences, schools, medical facilities), and utilizing technological controls, including proper well plugging and monitoring for leaks of flammable gases[63]. Evacuation has already been necessary in cases where industrial fires have occurred at oil and gas wells[39], and the broad scale of wildfires could complicate disaster response efforts.

Conclusions

We found that from 1984–2019, the number of wells in wildfire burn areas increased five-fold, with wildfire threats projected to worsen by the end of the century. The intersection of wildfires in areas with oil and gas wells represents a pernicious feedback loop. The production and consumption of fossil fuels is the primary driver of climate change[64], with associated rising global temperatures increasing the frequency and intensity of wildfires[1–3]. Greenhouse gas emissions from major carbon producers are be responsible for an estimated 37% of the area burned by wildfires in the western U.S. and southern Canada[65]. Wildfire damage to oil and gas infrastructure may contribute, in turn, to fugitive greenhouse gas emissions, further exacerbating climate change. Given ongoing oil and gas leasing and population growth in the wildland-urban interface[9], public health hazards associated with wildfire-damaged wells are becoming increasingly likely as climate change worsens. Future climate and energy policy—at local, state, and federal levels—should account for co-occurrent risks to human health.

Experimental Procedures

Resource availability
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Materials availability: This study did not generate new unique materials
Data and code availability: All original code has been deposited at Zenodo at https://doi.org/10.5281/zenodo.10930755 and is publicly available as of the date of publication. Data on wildfire locations and extent are available from Monitoring Trends in Burn Severity (MTBS) and the National Interagency Fire Center (NIFC). The gridded population data are available from SocScape[41,42]. Processed data that we generated for the current study are available on Dryad at https://doi.org/10.6078/D1K12N. Several datasets we utilized are not publicly available but may be available upon request for research purposes, including data from Enverus DrillingInfo and the gridded historical and projected future KBDI estimates from Brown et al. (2021).

Study region

The study region comprised 19 oil and gas-producing states west of the Mississippi River, spanning from Washington and California in the west to Missouri and Louisiana in the east, as well as Alaska. We excluded Hawaii, Idaho, Iowa, Minnesota, and Washington, as none of these states had oil and gas wells. The 19 states in the study region were the most productive for crude oil in the country and included all states that produced at least 10 million barrels in 2021 [66].

Data

We assembled geospatial data on oil and gas wells, historical wildfires, and projected wildfire risk for the 19 western states with at least one oil or gas well. We obtained data on the extent of wildfires from two sources: Monitoring Trends in Burn Severity (MTBS) and the National Interagency Fire Center (NIFC). The MTBS dataset comprises wildfire data from multiple state and federal agencies: the Alaska Interagency Fire Center, California Department of Forestry and Fire Protection (CalFire), Bureau of Indian Affairs, Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, and U.S. Forest Service. The NIFC dataset included wildfires that were up to 1,000 acres in size. The final dataset comprised all wildfires in the western U.S. between 1984 and 2019 that were reported to these agencies and made publicly available. We removed the duplicates for wildfires that were represented in both datasets so that each wildfire only appeared once in our analytic dataset.

The wildfires dataset used in the current study included 65,971 individual wildfires encompassing 725,814 km^2 of burn area between 1984 and 2019 (Figure 1a). Among individual wildfires, there is substantial variation in burn area, with a mean of 10.8 ± 64.0 km^2 (median: 0.45; range: 0.001, 3,240.4). For this reason, in primary analyses we focused on the aggregate burn areas for each state and year, rather than assessments for individual wildfires. In a secondary analysis, we assessed how many wells were burned in each individual wildfire, to identify wildfire events with the greatest impact.

We obtained data on the locations of properties of oil and gas wells from Enverus DrillingInfo, a private data aggregation service, for all oil and/or gas wells drilled on or before December 31, 2019. To examine the timing of well siting, we used the following operational date variables: spud date, completion date, first production date, and last production date. Given missingness in some of these date observations for some wells, we used the earliest available date to determine whether a well had been sited prior to the wildfire. For the primary analyses, we assumed that these wells without any reported operational dates were sited before 1984 due to poor record-keeping practices at the onset of oil and gas development. Most wells (89.1%) had operation dates. The dataset used in our analyses included 1,671,699 oil and gas wells sited in the study region (Figure 1A).

Assessment of wells in historical wildfires

We determined how many wells were in wildfire burn areas for all historical wildfires in our dataset. We spatially aggregated all wildfire burned areas in each state and year, because some wildfires cross state boundaries and, in primary analyses, we were not focused on results for individual wildfires. Next, we determined how many oil and gas wells spatially intersected these aggregated state-year wildfire burn areas, including wells where the earliest operation date occurred before the wildfire year or was missing (and assumed to predate the study period). In a secondary assessment, we determined how many wells were located in each individual wildfire. To determine whether there were time trends with respect to increasing numbers of wells in wildfire burn areas, we fit Poisson regression models, both unadjusted and adjusted for state. We fit separate models by state to examine differences in time trends.

Assessment of wells in areas with high wildfire risk

To determine which areas had high historical or future wildfire risk, we used a dataset with the Keetch-Byram Drought Index (KBDI) calculated for 2017 (historical), as well as projected KBDI in 2046–2054 (mid-century) and 2086–2094 (late century)[4]. The KBDI is a fire index that is calculated from daily maximum temperature, daily precipitation, and annual accumulated precipitation, accounting for vegetation moisture content and the potential for wildfire to spread after ignition[4,67]. The index ranges from 0 (indicating complete soil saturation and no wildfire risk) to 800 (indicating extreme wildfire risk)[67]. For the projected future wildfire risk, Brown and colleagues calculated KBDI under representative concentration pathway (RCP) 8.5, a climate scenario which assumes relatively little mitigation of greenhouse gas emissions[4,68]. The historical KBDI values were available at a spatial resolution of 4 x 4 km, and projected mid-century (2046–2054) and late-century (2086–2094) KBDI values were available at a resolution of 12 x 12 km spatial resolution. In our assessments of wildfire risk in areas with oil and gas wells, we used two thresholds to consider historical and future wildfire risk: KBDI $\geq$ 600, indicating high wildfire risk, and KBDI $\geq$ 450, indicating a moderately high risk. At KBDI values of 600 or greater, wildfires are difficult or, at 750 or greater, impossible to control[4]. Some government agencies in the U.S. use KBDI $\geq$ 450 as a more conservative threshold to consider wildfire risks[43]. To estimate projected risks, we assigned the maximum KBDI in any season (spring, summer, fall) for each well and time period (historical, mid-century, late-century). For each KBDI threshold and time period, we determined which areas had moderately high (KBDI $\geq$ 450) or high wildfire risk (KBDI $\geq$ 600) in any season. Then, we determined how many wells intersected with the high wildfire risk areas in each of the three time periods.

Assessing population exposures

We obtained gridded population data from SocScape-30[41,42]. The dataset comprises estimates of the number of residents in each 30 x 30 m pixel across the U.S. and is derived from decennial census estimates using dasymetric methods. For the current study, we used gridded 1990 population data for the period 1984–1994, 2000 population data for 1995–2004, 2010 population data for 2005–2014, and 2020 population data for 2015–2019. To determine risk ratios for racial/ethnic groups exposed to high wildfire risk wells, we used the "Racial grids" product, which provides the same gridded population estimates for 2020 disaggregated into the following racial/ethnic groups: Hispanic and non-Hispanic Asian, Black, Native American/Alaska Native, Pacific Islander, other, and White.

For each state and year, we determined which wells sited prior to the wildfire year were located in wildfire burn areas. Next, we used the gridded population data to determine how many people resided within 1 km of these wells in each state and year. Prior studies have consistently found that residing within 1 km of oil and gas wells is associated with higher health risks[23,44–48], and this is less than the distance of 2.4 km from densely vegetated areas typically used to identify residents of the wildland-urban interface[9].

To investigate whether there were racial/ethnic disparities in exposures to high wildfire risk wells, we did a similar procedure as described above, but for wells in areas where KBDI was estimated to historically be ≥ 450 or ≥ 600. Using SocScape-30 data for 2020, we determined how many people resided within 1 km of these wells for all residents and residents disaggregated by race/ethnicity. Next, to determine whether there were racial/ethnic disparities in exposures to these wells, we calculated a group risk ratio for each racial/ethnic group as described previously[11]. We used the following formula:

$$RR = \frac{\frac{\sum Group_{exposed}}{\sum Group_{total}}}{\frac{\sum Population_{exposed}}{\sum Population_{total}}},$$

which is the ratio of the proportion of a sub-population of interest who were exposed to the proportion of the total population who were exposed. An RR greater than 1 indicates that the sub-population had disproportionately high exposure and an RR of less than 1 indicates disproportionately low exposure. We did this in aggregate for the entire study region and separately for each state with ≥ 10,000 exposed individuals.

Given the wide disparity we observed for Native American or Alaska Native people living in Utah for exposure to wells threatened by wildfire, we conducted a secondary analysis to determine how many wells were located on land managed by state or federally recognized tribes. To do this, we utilized the American Indian/Alaska Native/Native Hawaiian Area National Shapefile available from the U.S. Census Bureau[69].

Assessment of wells threatened by wildfire on federal land

To determine which wells were on federal land, we used a geospatial dataset from the National Atlas of the United States datasets include units with a minimum area of 640 acres that are owned or administered by the Bureau of Land Management, Bureau of Reclamation, Department of Defense, Department of Justice, Fish and Wildlife Service, or National Park Service[70].

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Declaration of Interests. The authors declare no competing interests.

Figures

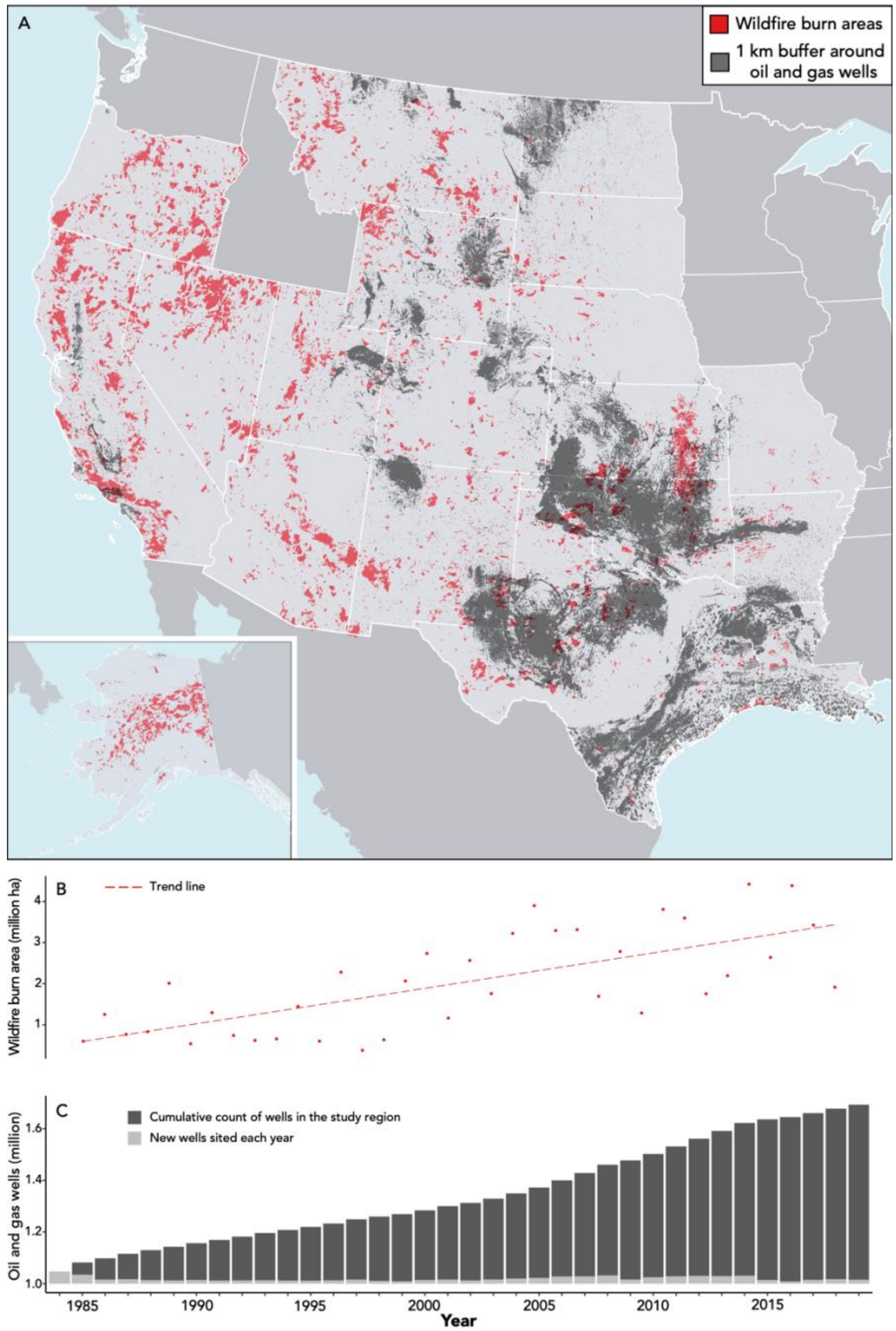

Figure 1. Map of study region and trends in wildfire and oil and gas activity. (A) Map of study area showing extent of wildfires that burned during the study period and 1 km buffers around all oil and gas wells drilled during or prior to the study period, 1984–2019. (B) Total area burned by wildfires in the study region by year with trend line. The trend line indicates a linear fit to the historical wildfire data, with an annual increase in wildfire area of 80,919 ha ($p < 0.01$), (C) Cumulative number of oil and gas wells in the study region by year (including both active and inactive wells) and, in lighter gray, the number of new wells sited each year.

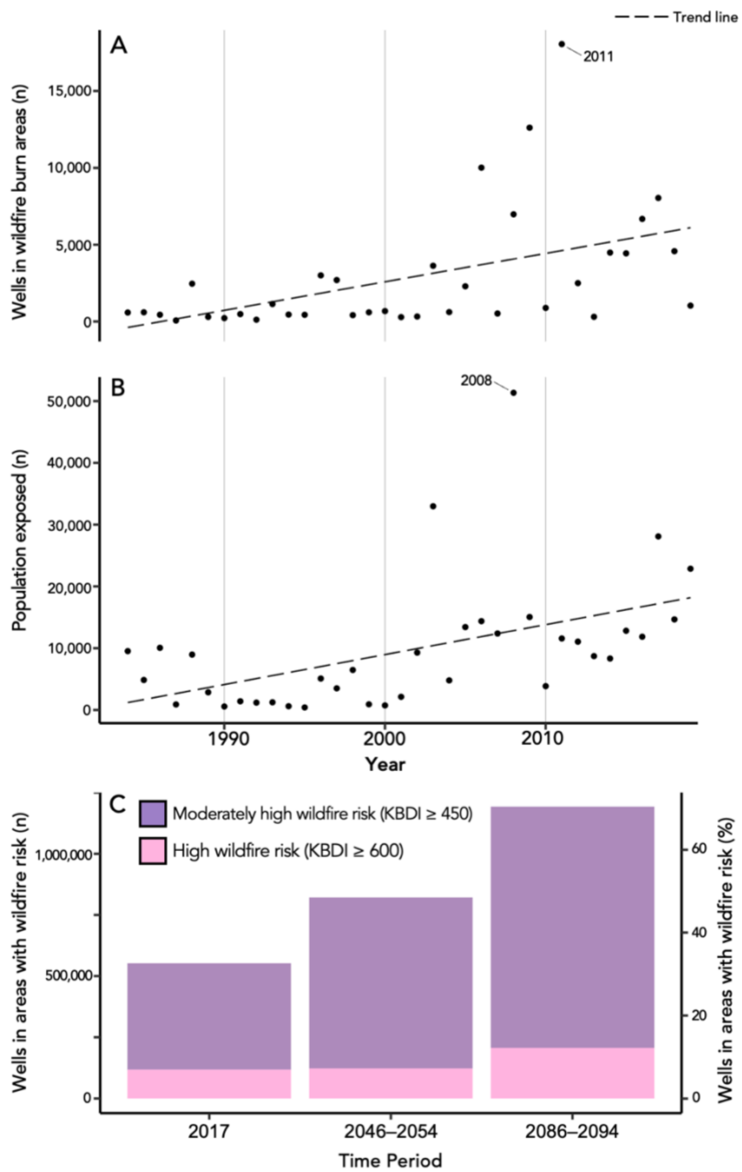

Figure 2. Results for intersections of wildfires, wells, and populations. Results from the (A, B) retrospective and (C) projected analyses investigating risks associated with wildfire in areas with oil and gas wells. (A) The count of oil and gas wells in wildfire burn areas by year with trend line. Each point represents the total number of wells located in wildfire burn areas across the study region each year. The trend line indicates a linear fit to the historical data on wildfire-threatened well counts, with an annual increase of 186 ($p < 0.01$). (B) Estimated population exposed to wells in wildfire burn areas, with trend line. Each point represents the total population living within 1 km of oil and gas wells located in wildfire burn areas across the study region each year. The trend line indicates a linear fit to the historical data on exposed population, with an annual increase of 485 ($p < 0.01$). (C) Estimates for the number of wells (and, on righthand y-axis, percent of all oil and gas wells) in areas projected to have moderately high wildfire risk (KBDI ≥ 450) or high (KBDI ≥ 600) wildfire risk

historically (2017), in mid-century (2046–2054), and in late century (2086–2094). KBDI, Keetch-Byrum Drought Index.

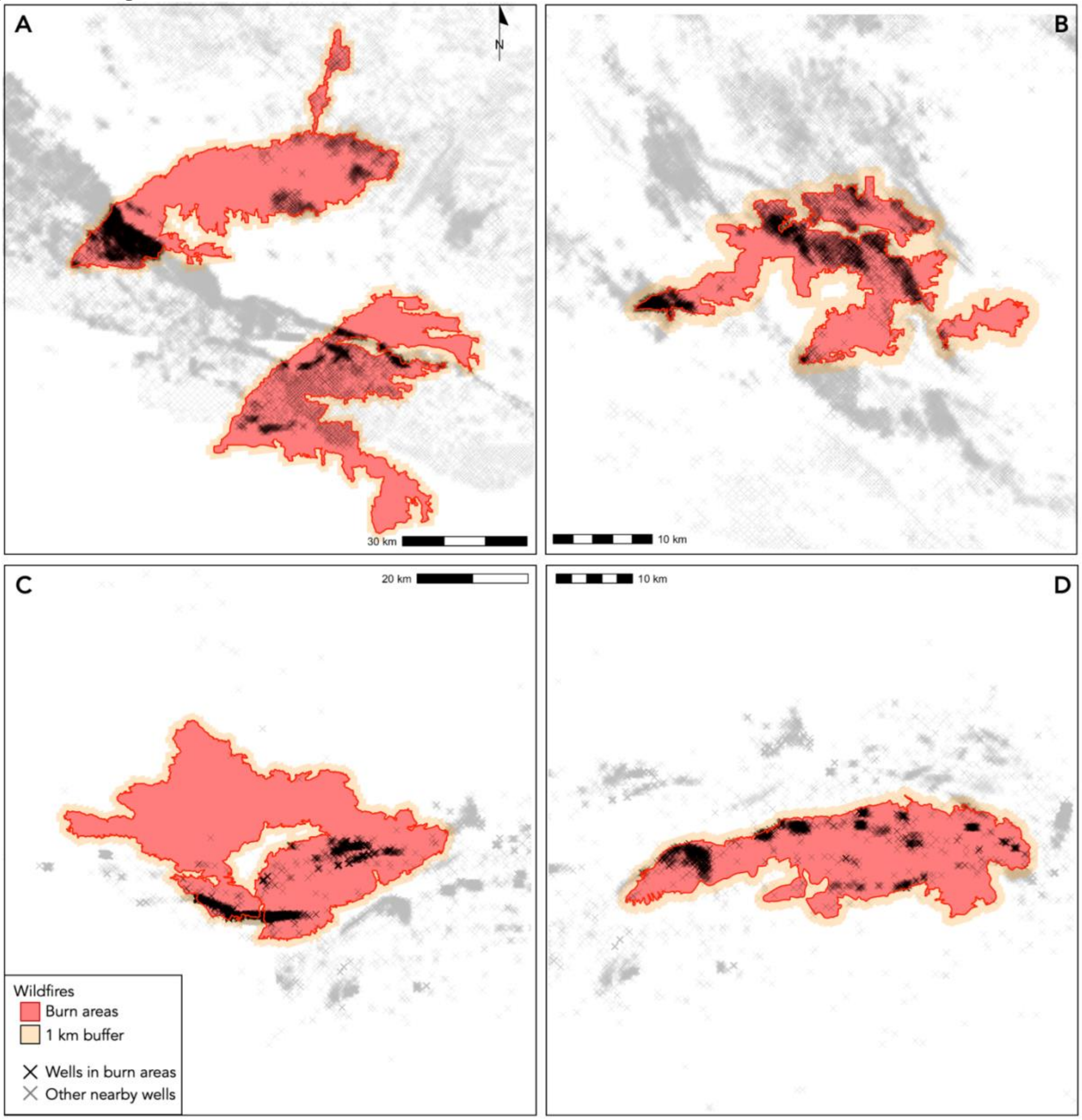

Figure 3. Wildfires with the most oil and gas wells located in the burn area. (A) The East Amarillo Complex Fire in Texas in 2006 had 3,845 oil and gas wells in the burn area. (B) The Loco-Healdton Fire in Oklahoma in 2009 had 3,035 wells in the burn area. (C) The 2017 Thomas Fire in California had 2,181 wells in the burn area. (D) The 2003 Simi Fire, also in California, had 1,994 wells in the burn area.

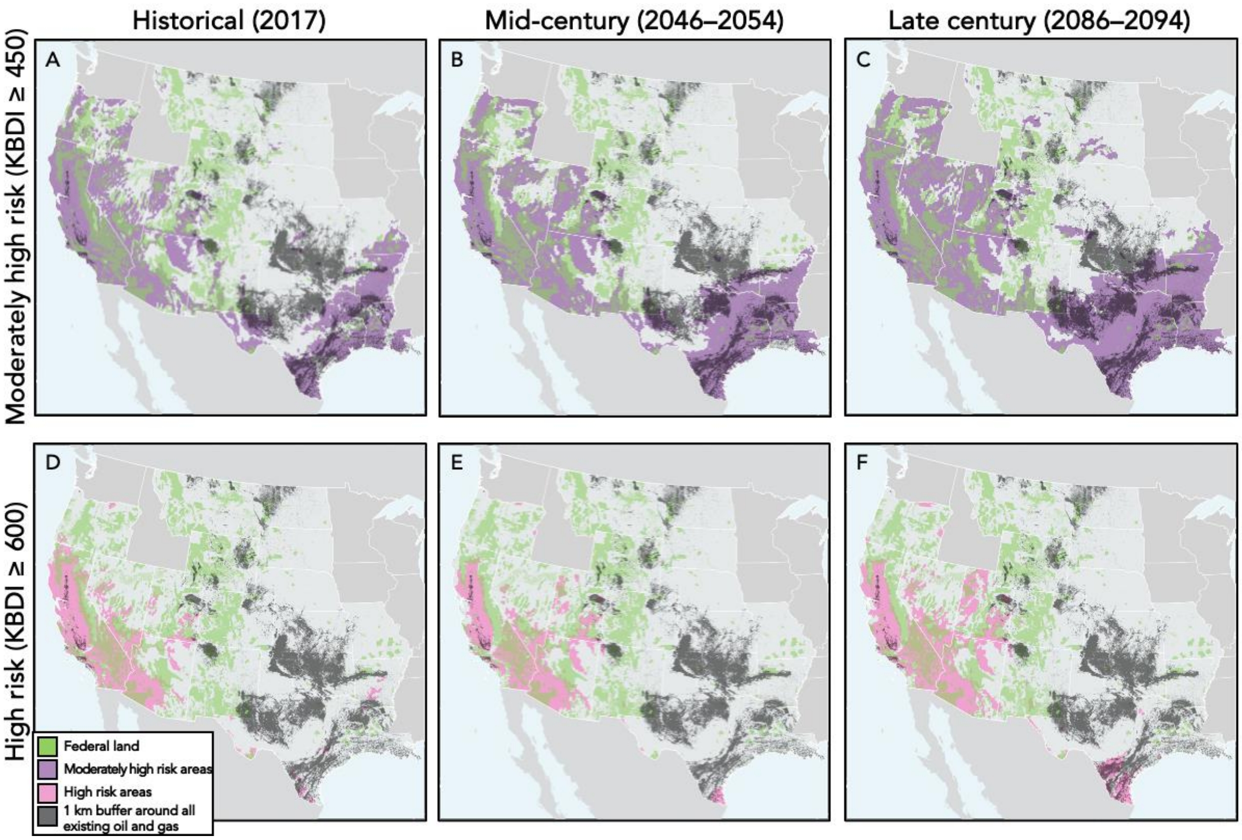

Figure 4. Projections of areas with wells and wildfire risk. In the western U.S., these are the locations of oil and gas wells that were sited before 2020, areas subject to wildfire risk, and the extent of federally managed land. We assessed how many wells are in areas with moderately high wildfire risk, which we defined maximum estimated seasonal KBDI ≥ 450 (A–C), as well as areas with high risk, defined as maximum estimated seasonal KBDI ≥ 600 (D–F). We considered wildfire risk in three time periods: historical (2017, left column), mid-century (2046–2054, middle), and late-century (2086–2094, right). States included in the study region are shown in light gray. KBDI, Keetch-Byrum Drought Index.

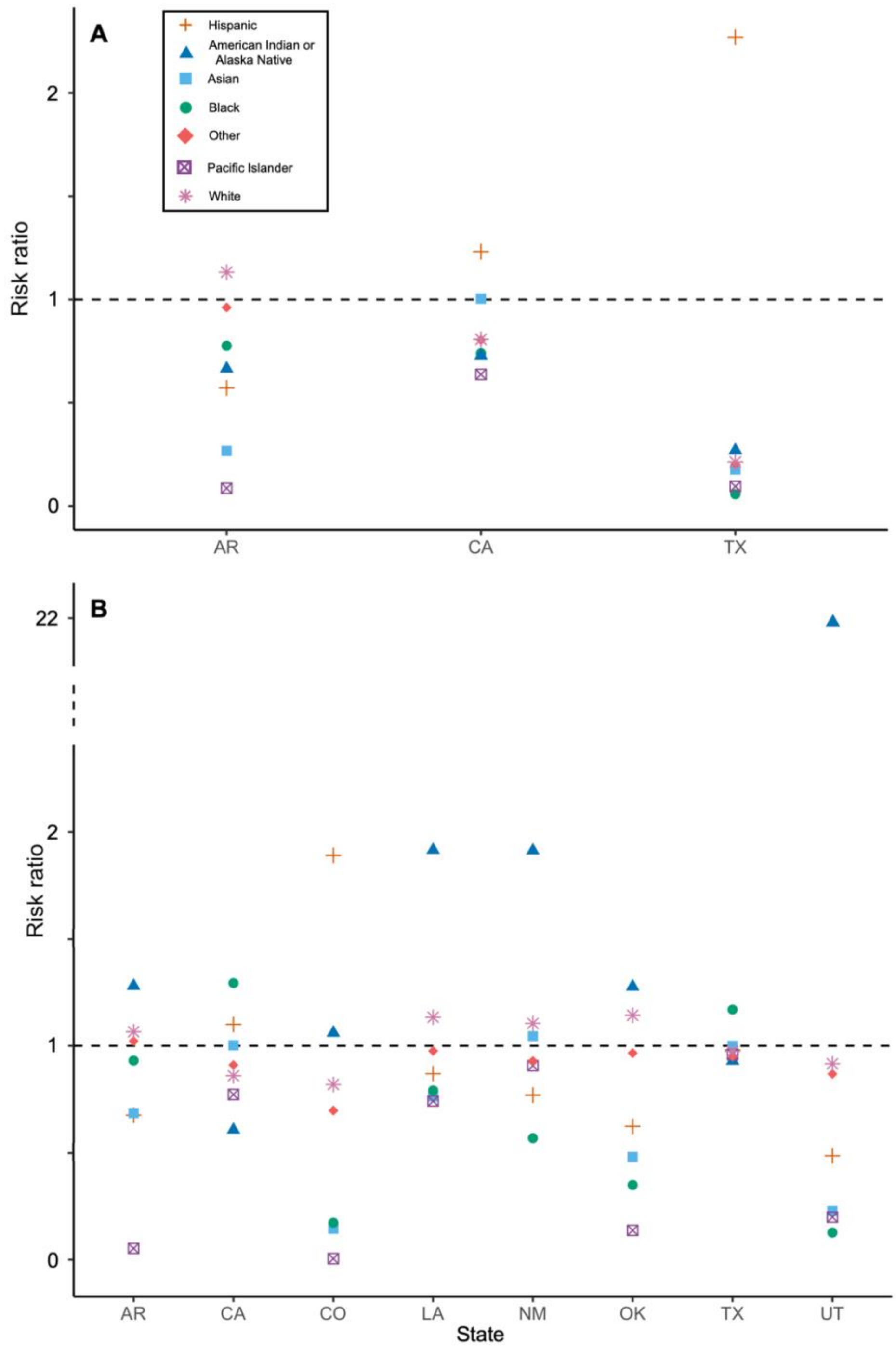

Figure 5. Racial/ethnic disparities in exposures to wildfire-threatened wells. Estimated risk ratios (RR) for each racial/ethnic group for exposure to wells that historically (2017) had high wildfire risk, disaggregated by state. We considered two thresholds for wildfire risk, including (A) areas high wildfire risk where the Keetch-Byrum Drought Index (KBDI) was ≥ 600 and (B) areas with moderately high wildfire risk where KBDI was ≥ 450. An RR > 1 indicates that the group has disproportionately high exposure compared to statewide representation, and an RR < 1 indicates the group has disproportionately low exposure compared to the group's statewide representation.

Table 1. Wells in high wildfire risk areas by state and time period. Count (column %) of wells in areas projected to have moderately high (KDBI ≥ 450) or high (KBDI ≥ 600) wildfire risk historically (1994–2004), in mid-century (2046–2054), and in late-century (2086–2094).

	KBDI ≥ 450			KBDI ≥ 600		
State	2017	2046–2054	2086–2094	2017	2046–2054	2086–2094
Arizona	43 (0.0)	53 (0.0)	54 (0.0)	1 (0.0)	1 (0.0)	2 (0.0)
Arkansas	35,652 (6.5)	35,233 (4.3)	44,227 (3.7)	682 (0.6)	0 (0.0)	0 (0.0)
California	128,936 (23.4)	130,628 (15.9)	131,007 (11.0)	103,878 (87.7)	104,338 (85.4)	109,801 (53.4)
Colorado	2,252 (0.4)	1,098 (0.1)	7,763 (0.7)	5 (0.0)	31 (0.0)	51 (0.0)
Kansas	687 (0.1)	98 (0.0)	4,849 (0.4)	0 (0.0)	0 (0.0)	0 (0.0)
Louisiana	72,077 (13.1)	95,718 (11.7)	118,395 (9.9)	2,149 (1.8)	0 (0.0)	0 (0.0)
Missouri	15 (0.0)	4 (0.0)	46 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Montana	0 (0.0)	0 (0.0)	445 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
North Dakota	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Nebraska	2 (0.0)	0 (0.0)	181 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
New Mexico	15,383 (2.8)	52,515 (6.4)	80,898 (6.8)	8 (0.0)	867 (0.7)	876 (0.4)
Nevada	101 (0.0)	116 (0.0)	117 (0.0)	99 (0.1)	58 (0.0)	66 (0.0)
Oklahoma	6,133 (1.1)	36,316 (4.4)	143,491 (12.0)	0 (0.0)	0 (0.0)	0 (0.0)
Oregon	68 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
South Dakota	65 (0.0)	0 (0.0)	165 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Texas	269,936 (48.9)	443,346 (54.0)	631,453 (52.9)	9,753 (8.2)	4,500 (3.7)	76,320 (37.1)
Utah	20,190 (3.7)	23,599 (2.9)	26,569 (2.2)	1,888 (1.6)	12,391 (10.1)	18,554 (9.0)
Wyoming	136 (0.0)	1,830 (0.2)	3,726 (0.3)	0 (0.0)	0 (0.0)	0 (0.0)
All	551,676	820,554	1,193,386	118,409	122,186	205,670

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Supplemental Figures

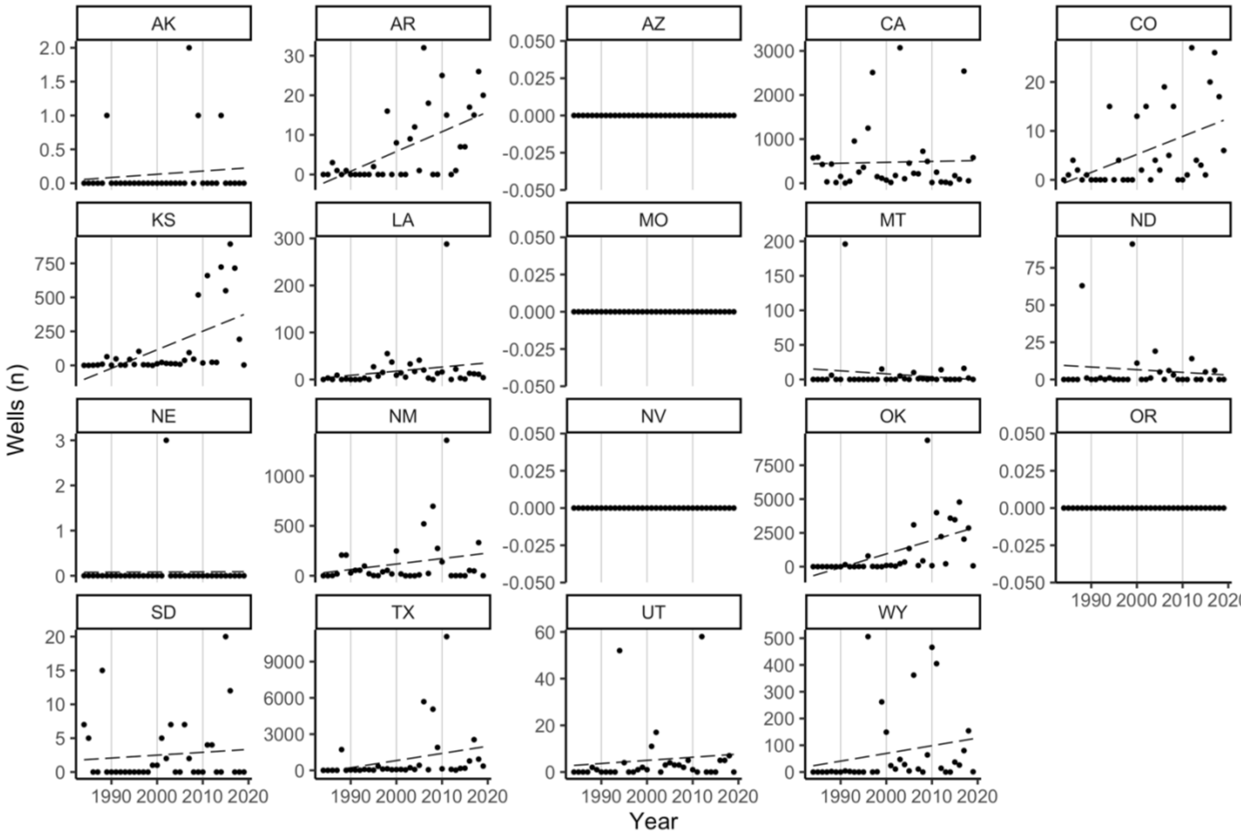

Figure S1. Wells in wildfire burn areas by state-year. Count of oil and gas wells located in historical wildfire burn areas by state and year with trend lines (dashed lines) representing linear fits to the data, included for illustrative purposes only. Note that the scale of the y-axis varies by state.

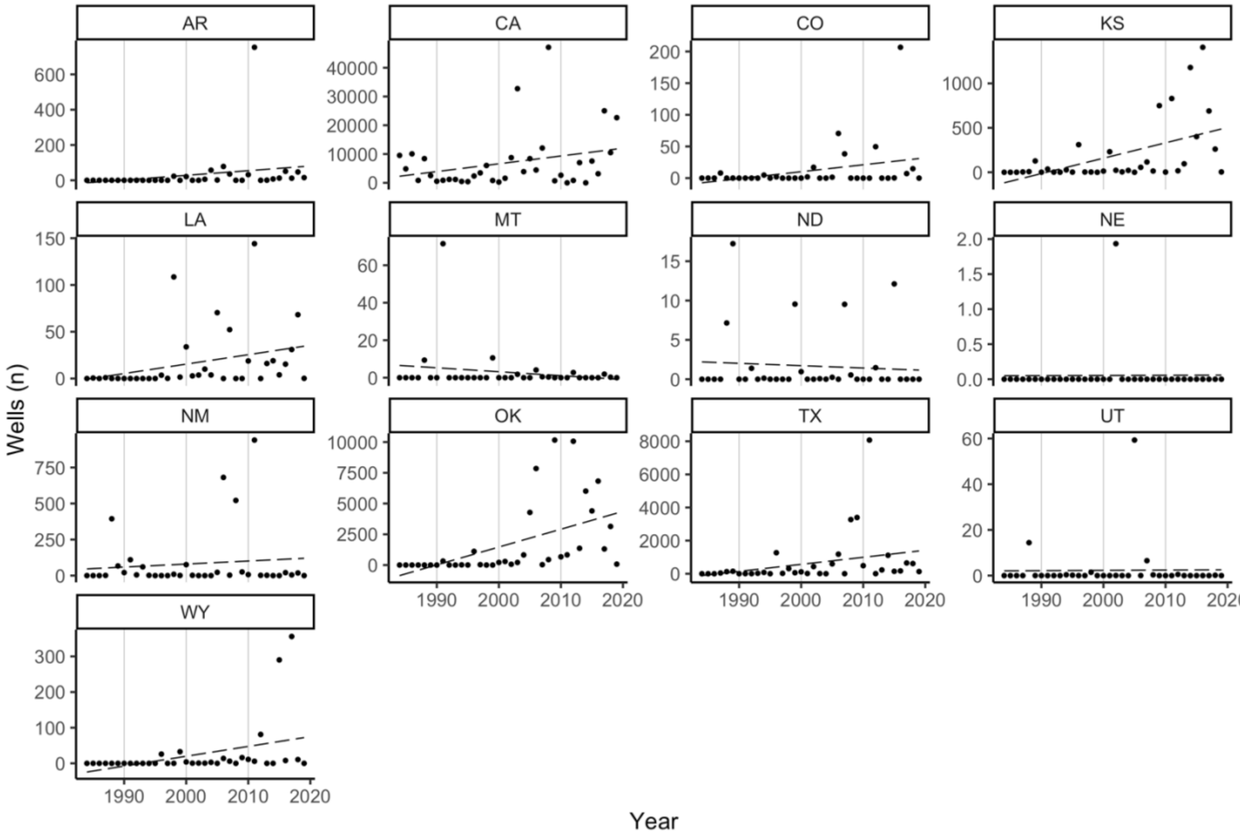

Figure S2. People living near wildfire-impacted wells by state-year. Population exposed to wells in historical wildfire areas by state and year with trend lines (dashed lines) representing linear fits to the data, included for illustrative purposes only for states with > 0 people exposed. We defined exposure as residing within 1 km of wells in burn areas. Note that the scale of the y-axis varies by state.

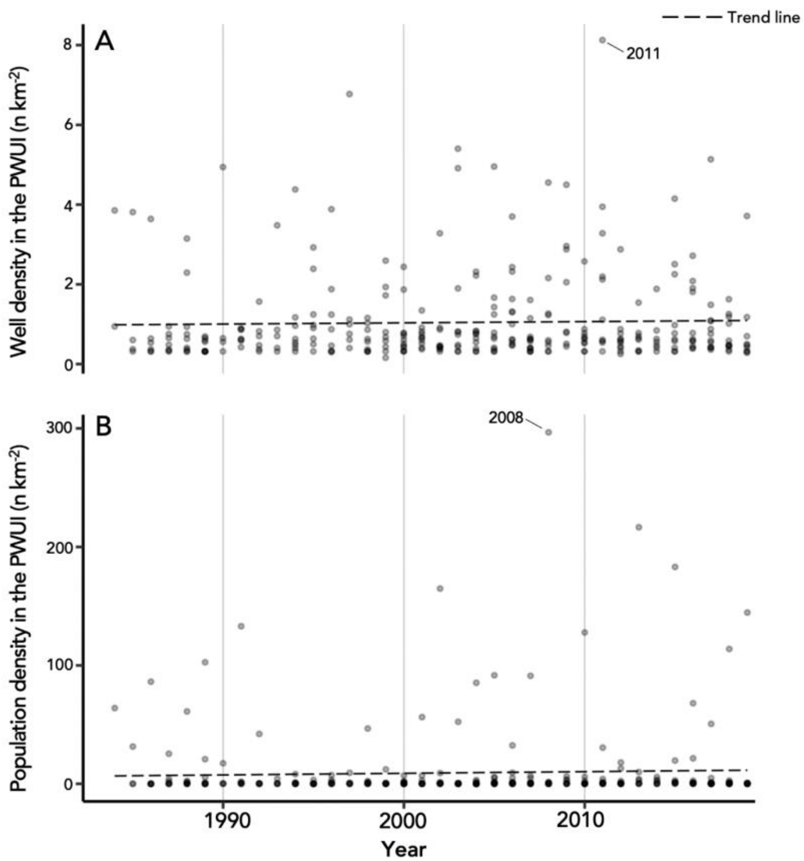

Figure S3. Density of wells and population in the petro-wildland urban interface (PWUI). (a) Total density of wells in areas within 1 km of any wells located in wildfire burn areas. (b) Total population in areas within 1 km of wells located in wildfire burn areas. In both panels, each point represents a state-year, and the trend line represents a linear response function. We did not observe any significant trends with respect to well or population density in the PWUI.

Supplemental Tables

Table S1. Results for wildfire burn area, impacted wells, and exposed population. Total wildfire burn area, count of oil and gas wells located in wildfire burn areas, and the estimated population exposed to these wells (residing ≤ 1 km) by year.

Year	Wildfire burn area (ha)	Wells in burn area (n)	Population exposed (n)
1984	602,209.2	581	9,525
1985	1,253,676.9	597	4,852
1986	768,511.4	439	10,057
1987	832,876.7	68	891
1988	2,010,035.1	2,457	8,959
1989	541,075.3	297	2,862
1990	1,296,768.7	219	561
1991	743,006.3	482	1,410
1992	622,271.7	117	1,195
1993	658,800.7	1,135	1,247
1994	1,446,068.7	451	604
1995	602,993.2	435	410
1996	2,280,789.9	2,996	5,088
1997	379,930.1	2,693	3,503
1998	637,257.2	413	6,474
1999	2,067,019.3	595	915
2000	2,735,354.4	675	735
2001	1,164,822.6	282	2,133
2002	2,565,568.7	322	9,286
2003	1,758,787.5	3,624	32,973
2004	3,222,355.7	610	4,786
2005	3,895,885.3	2,288	13,423
2006	3,290,233.5	10,013	14,379
2007	3,313,674.7	519	12,386
2008	1,694,684.9	6,979	51,352
2009	2,781,341.8	12,613	15,044
2010	1,287,646.0	882	3,856
2011	3,806,427.0	18,047	11,575
2012	3,595,269.9	2,493	11,050
2013	1,753,263.5	302	8,712
2014	2,194,524.4	4,489	8,331
2015	4,418,817.6	4,441	12,816
2016	2,638,634.8	6,677	11,848
2017	4,382,270.5	8,040	28,089

2018	3,423,890.7	4,580	14,666
2019	1,914,660.7	1,031	22,860
All	72,581,404.6	102,882	348,853

Table S2. Individual wildfire impacts. The most extreme fires in terms of the number of wells in or near the burn area.

Incident Name	State	Year	Wells in burn area (n)	Wells ≤ 1 km of burn area (n)
East Amarillo Complex	TX	2006	3,845	5,178
Loco-Healdton	OK	2009	3,035	5,630
Thomas	CA	2017	2,181	3,077
Simi	CA	2003	1,994	2,359
Unnamed	OK	2015	1,826	3,295
Glass	TX	2008	1,769	2,323
Unnamed	OK	2014	1,709	2,850
Big Country Fire	TX	1988	1,691	2,579
Unnamed	OK	2011	1,657	2,796
Lokern	CA	1997	1,600	2,485
Ratcliff City-Tatums	OK	2009	1,498	2,312
Perryton	TX	2017	1,387	1,787
Freedom Hill	OK	2012	1,312	1,666
Rhea	OK	2018	1,221	1,679
PK Complex	TX	2011	1,219	1,943
Velma West	OK	2009	876	1,904
Ratcliff City	OK	2006	848	1,907
OKS-Starbuck	OK	2017	781	1,067
Piru	CA	2003	769	819
Michell County Complex	TX	2011	746	1,930

Table S3. Projected county level impacts with high wildfire risk. Count of wells by county in areas estimated to have high wildfire risk (KDBI ≥ 600) historically (2017), in mid-century (2046–2054), and in late-century (2086–2094). For each time period, these are the top 20 counties with wells in high wildfire risk areas.

2017		2046–2054		2086–2094	
County/Parish (State)	Wells (n)	County/Parish (State)	Wells (n)	County (State)	Wells (n)
Kern (CA)	67,703	Kern (CA)	67,728	Kern (CA)	67,736
Fresno (CA)	5,782	Uintah (UT)	9,732	Uintah (UT)	12,790
Los Angeles (CA)	5,741	Los Angeles (CA)	6,382	Los Angeles (CA)	7,493
Ventura (CA)	2,991	Fresno (CA)	5,782	Fresno (CA)	5,782
Orange (CA)	2,651	Orange (CA)	2,650	Webb (TX)	5,376
Webb (TX)	1,818	Ventura (CA)	2,462	Dimmit (TX)	4,784
Monterey (CA)	1,568	Monterey (CA)	1,578	La Salle (TX)	4,574
Caddo (LA)	1,501	Hidalgo (TX)	1,409	Ventura (CA)	4,089
Zapata (TX)	1,362	San Juan (UT)	1,143	Bexar (TX)	3,983
San Juan (UT)	1,188	Sutter (CA)	787	McMullen (TX)	3,573
Fayette (TX)	892	San Juan (NM)	786	Duval (TX)	3,232
Pecos (TX)	848	Colusa (CA)	769	Zapata (TX)	3,030
Sutter (CA)	787	Solano (CA)	680	Frio (TX)	3,026
Colusa (CA)	769	Glenn (CA)	677	Starr (TX)	2,864
Starr (TX)	700	Kings (CA)	661	Atascosa (TX)	2,767
Solano (CA)	680	Willacy (TX)	542	Medina (TX)	2,726
Glenn (CA)	677	Yolo (CA)	528	Orange (CA)	2,653
Kings (CA)	661	Santa Barbara (CA)	501	Duchesne (UT)	2,513
Dimmit (TX)	631	Grand (UT)	496	Hidalgo (TX)	2,116
Bossier (LA)	538	Sacramento (CA)	432	Santa Barbara (CA)	2,023

Table S4. Wildfire-threatened wells on federal land. Wells on federal land by state, including the count and percentage of wells located in areas projected to have high wildfire risk (KDBI ≥ 600) and on federal land.

	Wells, n		Wells in high wildfire risk areas (KBDI ≥ 600) on federal land, n (% of wells on federal land)		
State	All	On federal land	2017	2046–2054	2086–2094
AK	3,693	0	0	0	0
AR	44,259	876	0	0	0
AZ	90	0	0	0	0
CA	123,936	37,653	19,691 (52.3)	20,105 (53.4)	22,143 (58.8)
CO	60,181	5,401	0	0	0
KS	55,528	515	0	0	0
LA	107,640	2,204	0	0	0
MO	881	2	0	0	0
MT	22,246	1,967	0	0	0
ND	35,425	4,905	0	0	0
NE	6,425	7	0	0	0
NM	109,637	50,033	1 (< 0.01)	3 (< 0.01)	4 (< 0.01)
NV	120	11	8 (72.7)	0	0
OK	261,259	4,361	0	0	0
OR	74	0	0	0	0
SD	1,864	371	0	0	0
TX	691,024	3,522	46 (1.3)	112 (3.2)	212 (6.0)
UT	31,400	7,322	147 (2.0)	2,028 (27.7)	3,469 (47.4)
WY	116,017	46,956	0	0	0
Total	1,671,999	166,106	19,893 (12.0)	22,248 (13.4)	25,828 (15.5)

Table S5. Projected county level impacts with moderately high wildfire risk. Count of wells by county in areas estimated to have moderately high (KDBI ≥ 450) wildfire risk historically (2017), in mid-century (2046–2054), and late-century (2086–2094). For each time period, these are the top 20 counties with wells in areas with moderately high wildfire risk.

2017		2046–2054		2086–2094	
County/Parish (State)	Wells (n)	County/Parish (State)	Wells (n)	County (State)	Wells (n)
Kern (CA)	67,736	Kern (CA)	67,736	Kern (CA)	67,736
Caddo (LA)	20,087	Eddy (NM)	25,540	Eddy (NM)	27,509
Los Angeles (CA)	16,205	Caddo (LA)	21,680	Lea (NM)	27,269
Uintah (UT)	14,790	Los Angeles (CA)	16,479	Caddo (LA)	21,680
Union (AR)	11,433	Uintah (UT)	15,404	Wichita (TX)	17,087
Webb (TX)	9,946	Wichita (TX)	12,663	Los Angeles (CA)	16,479
Gregg (TX)	8,785	Lea (NM)	12,242	Andrews (TX)	16,428
Rusk (TX)	8,259	Union (AR)	11,444	Uintah (UT)	15,540
Eddy (NM)	7,808	Webb (TX)	9,985	Ector (TX)	14,923
Ward (TX)	7,599	Archer (TX)	9,684	Stephens (OK)	12,999
Upton (TX)	7,593	Gregg (TX)	8,785	Carter (OK)	12,782
Pecos (TX)	7,388	Rusk (TX)	8,378	Creek (OK)	12,206
Crane (TX)	6,606	Crane (TX)	8,106	Union (AR)	11,444
Orange (CA)	5,899	Ward (TX)	7,599	Midland (TX)	11,242
Fresno (CA)	5,782	Young (TX)	7,587	Archer (TX)	10,359
Reeves (TX)	5,535	Pecos (TX)	7,017	Upton (TX)	10,222
Duval (TX)	5,369	Union (LA)	6,907	Martin (TX)	10,020
Ventura (CA)	5,334	Ector (TX)	6,903	Webb (TX)	9,985
Winkler (TX)	5,319	Wise (TX)	6,403	Crockett (TX)	9,882
Ouachita (AR)	5,223	Jack (TX)	6,149	Okmulgee (OK)	9,820

Table S6. Wildfire-threatened wells on federal land. Wells on federal land by state, including the count and percentage of wells located in areas projected to have moderately high wildfire risk (KDBI ≥ 450) and on federal land.

	Wells, n (%)		Wells in moderately high wildfire risk areas (KBDI ≥ 450) on federal land, n (% of wells on federal land)		
State	All	On federal land	2017	2046–2054	2086–2094
AK	3,693	0	0	0	0
AR	44,259	876	167 (19.1)	373 (42.6)	876 (100)
AZ	90	0	0	0	0
CA	123,936	37,653	37,059 (98.4)	37,606 (99.9)	37,623 (99.9)
CO	60,181	5,401	28 (0.5)	43 (0.8)	1,436 (26.6)
KS	55,528	515	2 (0.4)	0	1 (0.2)
LA	107,640	2,204	1,175 (53.3)	1,819 (82.5)	2,204 (100)
MO	881	2	0	0	1 (50.0)
MT	22,246	1,967	0	0	2 (0.1)
ND	35,425	4,905	0	0	0
NE	6,425	7	0	0	0
NM	109,637	50,033	7,548 (15.1)	26,142 (52.2)	35,508 (71.0)
NV	120	11	8 (72.7)	11 (100)	11 (100)
OK	261,259	4,361	57 (1.3)	189 (4.3)	2,132 (48.9)
OR	74	0	0	0	0
SD	1,864	371	24 (6.5)	0	48 (12.9)
TX	691,024	3,522	859 (24.4)	3,176 (90.2)	3,342 (94.9)
UT	31,400	7,322	3,238 (44.2)	4,168 (56.9)	5,619 (76.7)
WY	116,017	46,956	20 (< 0.01)	1,214 (2.6)	1,934 (4.1)
Total	1,671,999	166,106	50,185 (30.2)	74,741 (45.0)	90,737 (54.6)

Table S7. Historical population exposure by state. Cumulative population exposed (residing ≤ 1 km) to wells in wildfire burn areas by state during any study year, 1984–2019.

State	Population exposed (n)
Alaska	0
Arkansas	1,154
Arizona	0
California	252,644
Colorado	423
Kansas	6,635
Louisiana	609
Missouri	0
Montana	103
North Dakota	60
Nebraska	2
New Mexico	2,998
Nevada	0
Oklahoma	60,542
Oregon	0
South Dakota	0
Texas	22,734
Utah	83
Wyoming	866
Total	348,853

Table S8. Population at risk of exposure by state. Estimated population currently residing within 1 km of wells in areas with moderately high (KBDI ≥ 450) or high (KBDI ≥ 600) wildfire risk.

	Population exposed (≤ 1 km from wells)	
State	KBDI ≥ 450	KBDI ≥ 600
Alaska	0	0
Arkansas	268,858	10,523
Arizona	98	2
California	5,595,328	2,597,330
Colorado	13,141	0
Kansas	2,697	0
Louisiana	539,234	2,299
Missouri	0	0
Montana	0	0
North Dakota	0	0
Nebraska	2	0
New Mexico	73,721	7
Nevada	1	1
Oklahoma	35,318	0
Oregon	217	0
South Dakota	749	0
Texas	4,070,345	303,859
Utah	16,799	1,435
Wyoming	2,093	0
All	10,618,601	2,915,457

Table S9. Assessment of exposure disparities, moderately high wildfire risk. Group risk ratios (RR) for exposures to wells areas that historically had moderately high wildfire risk (KBDI ≥ 450), stratified by racial/ethnic group and restricted to states with at least 10,000 people exposed. An RR > 1 indicates that the racial/ethnic group has disproportionately high exposure compared to the group's representation across the population, and an RR < 1 indicates the group has disproportionately low exposure.

State	Hispanic	NH Asian	NH Black	NH Native American / Alaska Native	NH Pacific Islander	NH Other	NH White
Arkansas	0.68	0.68	0.93	1.28	0.05	1.02	1.07
California	1.10	1.00	1.29	0.61	0.77	0.91	0.86
Colorado	1.89	0.15	0.17	1.06	0.00	0.70	0.82
Louisiana	0.87	0.76	0.79	1.92	0.74	0.98	1.13
New Mexico	0.77	1.04	0.57	1.91	0.91	0.93	1.10
Oklahoma	0.62	0.48	0.35	1.28	0.14	0.97	1.14
Texas	0.98	1.00	1.17	0.93	0.96	0.95	0.97
Utah	0.49	0.23	0.13	21.93	0.20	0.87	0.92
All	1.22	1.27	1.31	0.45	0.68	0.85	0.78

NH, non-Hispanic

Table S10. Assessment of exposure disparities, high wildfire risk. Group risk ratios (RR) for exposures to wells in areas that historically (2017) had high wildfire risk (KBDI ≥ 600), stratified by racial/ethnic group and restricted to states with at least 10,000 people exposed. Most people of the 2,915,457 people residing within 1 km of high wildfire risk wells are in California (n = 2,597,330), followed by Texas (n = 303,569) and Arkansas (n = 10,523). An RR > 1 indicates that the racial/ethnic group has disproportionately high exposure compared to the group's representation across the population, and an RR < 1 indicates the group has disproportionately low exposure.

State	Hispanic	NH Asian	NH Black	NH American Indian / Alaska Native	NH Pacific Islander	NH Other	NH White
Arkansas	0.57	0.27	0.78	0.67	0.09	0.96	1.13
California	1.23	1.00	0.74	0.73	0.64	0.80	0.81
Texas	2.27	0.18	0.06	0.27	0.10	0.20	0.21
All	1.54	1.57	0.43	0.37	0.74	0.81	0.61

NH, non-Hispanic