Online Appendix to "Mandatory vs. Voluntary Adapation to Natural Disasters: The Case of U.S. Wildfires"

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A Additional Data and Results

Appendix Figure 1: Year Built and Probability of Destruction – All Fires

Notes: Sample includes all ZTRAX single-family homes inside of observed wildfire perimeters. Red markers are share of homes of each vintage that are reported as destroyed in damage data.

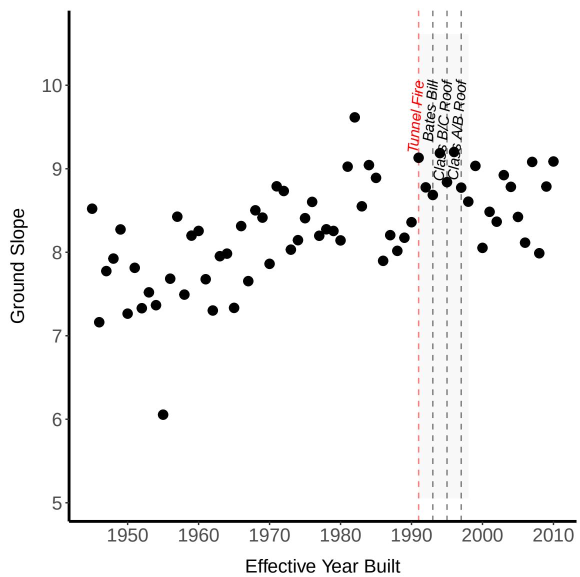
Appendix Table 1: Number of Homes per Code Area and Time Period

Area	Year Built	Number of Homes
SRA	Before 1998	20,544
SRA	1998–2007	3,815
SRA	2008–2016	827
LRA recommended VHFHSZ	Before 1998	14,087
LRA recommended VHFHSZ	1998–2007	2,515
LRA recommended VHFHSZ	2008–2016	474
LRA outside recommended VHFHSZ	Before 1998	3,513
LRA outside recommended VHFHSZ	1998–2007	212
LRA outside recommended VHFHSZ	2008–2016	37
Other states	Before 1998	1,974
Other states	1998–2007	601
Other states	2008–2016	244

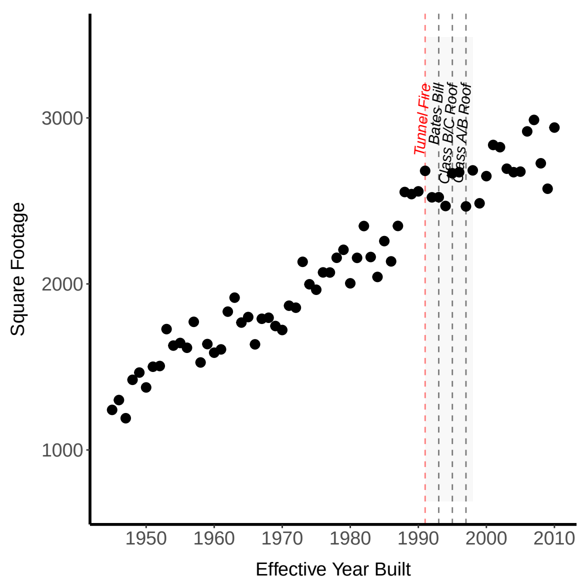
Notes: The No Codes treatment group includes the Other States and LRA outside recommended VHFHSZ groups. The Other States group excludes fires in areas with locally-adopted wildfire building codes (Appendix Table 6).

Appendix Figure 2: Other Characteristics by Year Built in Mandatory Code Areas

(a) Ground slope



(b) Building square footage



Notes: Means of other structure characteristics by effective year built for homes in SRA. Panel (a): ground slope at the home site from LANDFIRE (Rollins 2009). Panel (b): building square footage.

Appendix Table 2: Number of Neighbors by Distance

Neighbor Count	0	10	20	30	40	50	60	70	80	90+
Wall-to-wall Distance, All Neighbors										
0	25,535	28,266	23,936	19,907	19,557	20,480	21,770	23,293	25,039	10,729
1	7,904	9,035	8,824	8,909	10,004	10,518	10,248	9,805	9,316	1,027
2	8,177	3,339	4,297	5,517	6,370	6,065	5,784	5,429	4,828	1,088
3	382	817	2,243	3,509	3,506	3,148	2,735	2,363	1,986	1,229
4	75	373	1,472	2,290	1,722	1,296	1,095	880	689	1,426
5	13	182	698	1,167	630	430	346	244	173	1,557
6	0	61	390	499	209	115	90	58	44	1,576
7	0	9	172	223	64	29	15	12	9	1,696
8+	0	4	54	65	24	5	3	2	2	21,758
Mean	0.61	0.5	0.89	1.2	1.1	0.96	0.87	0.78	0.69	7.4
Wall-to-wall Distance, To-code Neighbors										
0	39,420	40,125	39,082	38,345	38,157	38,242	38,335	38,470	38,803	23,942
1	1,610	1,549	1,887	2,206	2,558	2,620	2,588	2,654	2,558	5,293
2	1,005	344	618	810	801	737	735	653	516	3,874
3	37	45	259	425	348	315	281	209	151	2,846
4	11	23	153	182	136	126	115	77	45	2,045
5	3	0	47	85	54	35	24	22	12	1,385
6	0	0	26	25	23	8	7	1	1	948
7	0	0	7	8	5	2	0	0	0	634
8+	0	0	7	0	4	1	1	0	0	1,119
Mean	0.09	0.059	0.12	0.15	0.15	0.14	0.13	0.12	0.1	1.4
Centroid Distance, All Neighbors										
0	128,963			31,821	28,094	24,606	23,935	24,775	25,911	6,967
1	13,416			11,172	11,351	10,694	11,381	11,930	11,812	1,173
2	7,955			5,307	5,615	6,758	7,709	7,524	7,139	1,485
3	516			1,195	2,602	4,168	4,300	3,850	3,530	1,592
4	114			555	1,415	2,418	2,021	1,583	1,374	1,906
5	11			206	703	1,110	720	497	417	2,134
6	3			50	338	426	203	137	120	2,260
7	6			16	145	110	45	24	21	2,351
8+	0			6	65	38	14	8	4	30,460
Mean	0.21			0.58	0.86	1.1	1.1	0.96	0.9	8.7
Centroid Distance, To-code Neighbors										
0	147,970			47,795	46,864	46,169	45,777	45,835	45,879	26,428
1	2,148			1,909	2,439	2,719	2,949	3,120	3,213	7,140
2	821			512	636	841	976	876	815	5,030
3	38			69	233	349	410	335	299	3,579
4	6			26	95	171	154	115	93	2,565
5	1			12	42	46	43	38	23	1,743
6	0			5	11	28	15	7	4	1,191
7	0			0	7	3	4	1	1	830
8+	0			0	1	2	0	1	1	1,822
Mean	0.026			0.066	0.1	0.13	0.14	0.13	0.12	1.5

Notes: This table shows the distribution of count of neighbors at various distances. "To-code neighbors" are neighbors built after WUI building codes. For the centroid distance measure, the first bin includes 0 to 30 meters.

Appendix Table 3: Controlling for spillovers in own-effect estimates

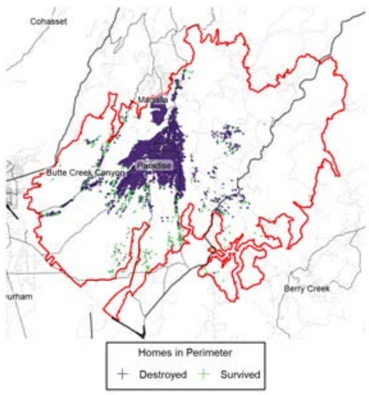
	(1)	(2)	(3)
1998–2007	-0.091***	-0.091***	-0.113***
	(0.008)	(0.008)	(0.010)
2007–2016	-0.129***	-0.128***	-0.145***
	(0.015)	(0.015)	(0.016)
Ground slope (deg)	0.006***	0.006***	0.006***
	(0.001)	(0.001)	(0.001)
1 pre-code nearby homes		0.020***	
		(0.007)	
2+ pre-code nearby homes		0.029***	
		(0.009)	
1 post-code nearby home		0.001	
		(0.013)	
2+ post-code nearby homes		0.000	
		(0.016)	
Fuel Model FE	✓	✓	✓
Street FE	✓	✓	
Incident FE			✓
Observations	34,791	34,791	34,791
R^2	0.63	0.63	0.42

Notes: Table shows estimates and standard errors from three separate OLS regressions. Columns (1) and (3) are street fixed effects and incident fixed effects specifications. Column (2) is a street fixed effects regression that also controls for the number of pre- and post-code homes within 10 meters of wall-to-wall distance. The sample in all three columns is limited to California homes in SRA and LRA VHFHSZ areas (since we are only able to calculate wall-to-wall distances for California homes). We pool the SRA and LRA VHFHSZ code areas given the similar estimates in Table 1. Standard errors are clustered by street.

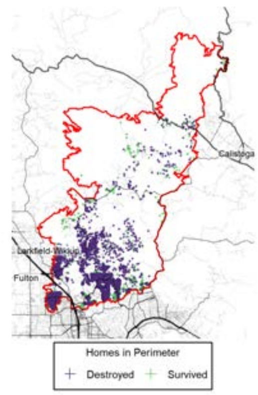
B Additional Maps

Appendix Figure 3: Additional Incident Maps

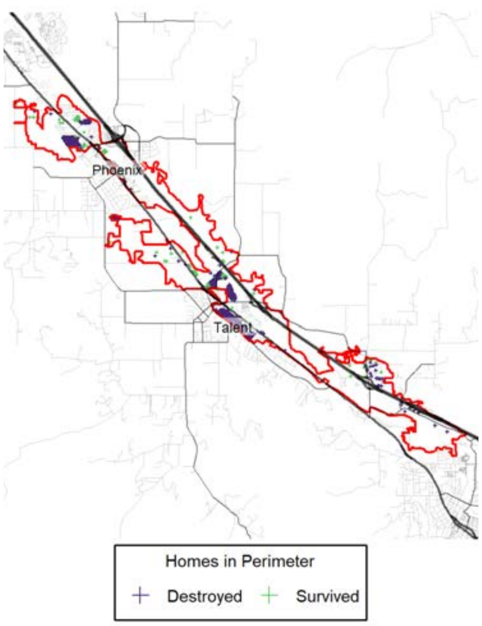
(a) Camp Fire (CA, 2018)



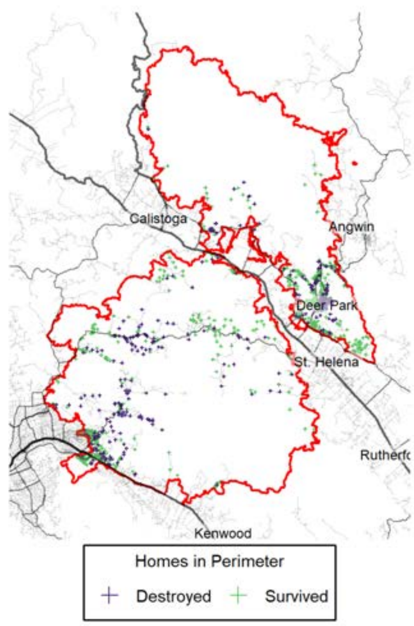
(b) Tubbs Fire (CA, 2017)



(c) Almeda-Obenchain (OR, 2020)



(d) Glass Fire (CA, 2020)

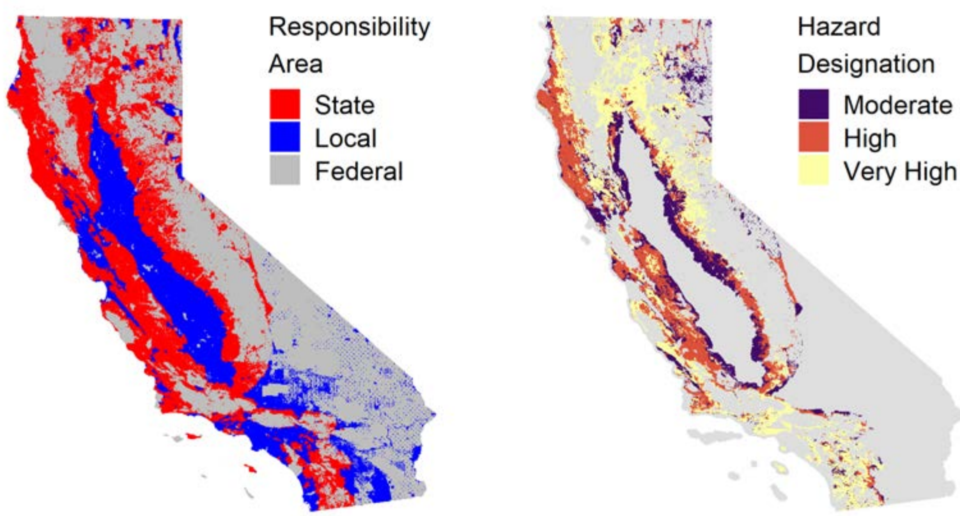


Notes: Additional examples of merged inspection, ZTRAX, and fire perimeter data. See Figure 2 notes for details.

Appendix Figure 4: Responsibility Areas and Fire Hazard Severity Zones in 2019

(a) Responsibility Areas

(b) Fire Hazard Severity Zones



C Geocoding and Ground-truthing Homes and Damage Data

Rules for choosing street address-based locations

Section 2.2 explains how building footprints and parcel boundary GIS data are used to assign structure rooftop locations for the majority of homes in the data (87%). For the remaining 13%, street-address based geocodes from the ESRI premium geolocator are used. We use ESRI geocodes whenever any of these conditions exist for a given property:

1. Accurate parcel GIS boundary data are not available for the county.
2. The merge on assessor parcel number (APN) between all homes in a given incident and the parcel boundary data yields a merge rate below 95% (an indication of inconsistently-formatted APNs). For such incidents, all homes are located using ESRI locations.
3. A single parcel polygon contains 4 or more building footprint shapes. In our testing, this condition often indicates formerly-large parcels that were subdivided and developed subsequent to the date of the parcel boundary data and prior to the wildfire.

Ground truthing with aerial imagery

To ensure the quality of the location and damage assessment data, we evaluated a random sample of homes by hand using high resolution aerial images from NearMap as a ground truth (as in Figure 1). For each wildfire, we randomly chose 1 home (if any existed) with more than 10 neighbors within 200 meters and 1 home (if any existed) with fewer than 10 neighbors within 200 meters. We downloaded the NearMap image tiles containing these homes. Each downloaded image tile contains potentially other homes as well. We evaluated all homes in each image (stopping at 20 homes if there were more than 20 in one image).

Location: We assessed location accuracy using only *pre-fire* imagery (incidents with no available pre-fire imagery are excluded from the count). Rooftop locations were considered accurate if the assigned location was on top of the structure roof visible in the NearMap image. Even small deviations from the parcel rooftop were coded as errors, due to the need for accuracy in the neighbor analysis. Because we suspected that our footprint-based method would yield more accurate locations than street address-based geocoding, and that more rural areas would have poorer accuracy, we assessed accuracy separately for incidents geocoded with either method; and for areas with more or less than 10 neighbors located within 200 meters of a home.

Damage Reports: We assessed damage report accuracy using imagery taken within 365 days after the wildfire. If no imagery in this time window was available, the incident is excluded from the count. Damage reports were considered accurate if the reported structure outcome (Destroyed/Survived) matched the state of the structure visible in the NearMap imagery.

Appendix Table 4: Accuracy of Rooftop Locations and Damage Reports

	Error Rate	Homes	Images
Location Error Rates			
Footprint Geocodes, 10+ within 200 m	0.008	252	18
Footprint Geocodes, 0–9 within 200 m	0.069	72	19
Address Geocodes, 10+ within 200 m	0.275	51	3
Address Geocodes, 0–9 within 200 m	0.125	16	5
Damage Error Rate			
All	0.011	556	86

Notes: Error rate is the share of homes with incorrect locations or damage outcomes.

D Expected Utility and Cost Effectiveness

A more complete measure, *expected utility benefit*, accounts for the additional insurance benefits from mitigation due to the reduced probability of bearing uninsured losses. This section derives the expected utility benefit of universal mitigation relative to no mitigation, which is enough to identify the break-even wildfire hazards in Table 3. Since insurance premiums are actuarially fair in the model, insurers break even by construction and utility differences are fully represented in household expected utility. In the absence of mitigation investment, expected utility for a homeowner with utility function U and initial wealth (permanent income) w_0 is,

$$p^F p^D U(w_0 - L^U - k) + (1 - p^F p^D) U(w_0 - k) \tag{8}$$

Under a universal mitigation mandate, this same homeowner's private expected utility after undertaking mitigation is,

$$p^F (p_i^D - \sum_{j=1}^{N} \tau_{ij}) U(w_0 - L^U - \tilde{k} - m) + [1 - p^F (p_i^D - \sum_{j=1}^{N} \tau_{ij})] U(w_0 - \tilde{k} - m) \tag{9}$$

where $\tilde{k} = p^F(p^D - \tau_{ii})L^I$, the actuarially fair insurance premium after mitigation. We express expected utility for the gambles in (8) and (9) in terms of certainty equivalents CE^0 and CE^M respectively. The net expected utility benefit across households can then be expressed as $\sum_{i=1}^{N} CE_i^M$ - CE_i^0, or the sum of households' willingness to pay for the mitigation gamble as opposed to the no-mitigation gamble.

Implementing the expected utility calculation requires strong assumptions. Households have a constant relative risk aversion (CRRA) utility function $U(c) = \frac{c^{\gamma-1}}{\gamma-1}$. Permanent income is \$1,000,000. We further simplify the calculation of the expected utility measure by using a two-period model where households choose their mitigation investment at time 0 and then consume their wealth net of realized wildfire costs in period 1. To mirror the 40-year horizon of the risk-neutral cost effectiveness calculation, we discount period 1 costs using the mean of annual discount factors over 40 years ($\frac{1}{40} \sum_{t=1}^{40} \frac{1}{(1+0.05)^t}$). Future work could relax these simplifications by embedding our estimates into a life cycle model of consumption, savings, and mitigation which would capture savings behavior and differential ability to smooth losses according to age and other factors. Such a model goes well beyond the goal of the exercise in this section, which is to benchmark the degree to which uninsured loss exposure might affect the broad benefits of mitigation mandates.

E Voluntary Mitigation Takeup Without Building Codes

The net benefits of mandating universal mitigation in Section 5.2 depend on the share of homes that would have been voluntarily built to these codes in the absence of a legal requirement to do so. Because detailed data on structure characteristics are not available for most of the at-risk homes we observe, we do not have the data to assess this voluntary takeup rate for the full sample. However, recent damage inspection data from CAL FIRE make it possible to estimate this proportion for the subset of homes exposed to wildfire during the 2019 and 2020 fire seasons (in earlier years, damage inspection data are entirely or mostly limited to destroyed homes but these more recent fires also include information on a group of undamaged exposed homes). This is the best available information on mitigation takeup of which we are aware. To roughly estimate takeup of mitigation investments in the absence of building codes, we examine reported characteristics for homes built before 1990 (when no areas in our sample had binding wildland building codes).

Table 5 documents the proportions of these homes that were "fire-ready" across several structural features, including siding, eaves, vent screens, and windows. For each feature, the "Fire-ready?" columns count the number of homes that have features that are definitely fire-ready, not fire-ready, and unknown. The final column, "% Fire-ready", is the percentage of homes with fire-ready features (using only homes where fire-readiness could be determined). A significant limitation of this dataset is that more than half the homes in the dataset do not report sufficiently detailed information to allow us to determine whether they were built with fire-ready construction materials or techniques. In particular, when information on roofing is provided, it is often limited to a general description of the material used, not its fire resistance rating (which can vary within materials).

With these limitations in mind, we observe a large range in the % of homes that are fire-ready across features, from 29% for eaves to 54% for windows. In keeping with our other assumptions that deliver a conservative estimate of building code benefits, we take 1/3 – on the lower end of this range – as our estimate of the proportion of exposed homes that were built voluntarily to be fire-resilient in areas not subject to wildfire building codes.

Appendix Table 5: Pre-Building Codes Fire Readiness

		Fire-ready?			
Feature	Homes	Yes	No	Unknown	% Fire-Ready
Siding	9,352	1,324	2,982	5,046	30.7
Eaves	9,352	967	2,420	5,965	28.6
Vent screens	9,352	1,830	2,057	5,465	47.1
Windows	9,352	2,232	1,890	5,230	54.1

Notes: Table estimates fire readiness characteristics for pre-1990 homes surveyed by CAL FIRE damage inspection teams in 2019 and 2020. Fire-ready siding is metal, brick, or vinyl, while not fire ready siding is wood. Non fire-ready eaves are those that are unenclosed. Non fire-ready vent screens are unscreened or screened with mesh larger than 1/8". Non fire-ready windows are single paned. For all features, unknown homes were those where the feature was marked as "Other" or "Unknown" in the original damage inspection data. The "% Fire-ready" column is the percent of homes that are determined to be fire ready for that feature, excluding homes for which fire-readiness could not be determined.

F Full List of Wildfires in the Dataset

This table lists the fires in the final merged dataset. It reports the count of single family homes destroyed and the count of single family homes inside the final fire perimeter (exposed). These counts may differ from reported counts of "structures lost" for individual incidents because we focus on single family homes and do not include outbuildings (sheds, detached garages, and other miscellaneous structures).

Appendix Table 6: Full List of Fires and Single Family Home Counts

	State	Year	Destroyed	Exposed	Share Destroyed
California					
CZU Lightning Cmplx	CA	2020	450	1,372	0.33
North Complex	CA	2020	396	621	0.64
LNU Lightning Cmplx	CA	2020	360	1,078	0.33
Glass	CA	2020	269	923	0.29
Creek	CA	2020	188	735	0.26
Slater	CA	2020	51	88	0.58
Bobcat	CA	2020	43	195	0.22
BEU Lightning Cmplx	CA	2020	36	128	0.28
Zogg	CA	2020	24	70	0.34
Laura 2	CA	2020	8	14	0.57
SQF Complex	CA	2020	8	42	0.19
Lake	CA	2020	7	28	0.25
Valley	CA	2020	4	73	0.05
Willow	CA	2020	4	13	0.31
Sheep	CA	2020	3	58	0.05
Bond	CA	2020	3	103	0.03
Stagecoach	CA	2020	2	10	0.20
Jones	CA	2020	2	15	0.13
SCU Lightning Cmplx	CA	2020	2	33	0.06
Gold	CA	2020	1	7	0.14
Quail	CA	2020	1	25	0.04
Oak	CA	2020	1	5	0.20
Blue Ridge	CA	2020	1	139	0.01
Branch	CA	2020	0	4	0.00
Pond	CA	2020	0	2	0.00
Kincade	CA	2019	36	170	0.21
Tick	CA	2019	16	605	0.03
Getty	CA	2019	8	128	0.06
Saddleridge	CA	2019	3	182	0.02
Mountain	CA	2019	2	8	0.25
Camp	CA	2018	8,247	10,279	0.80
Carr	CA	2018	742	1,672	0.44
Woolsey	CA	2018	656	6,831	0.10

Appendix Table 6: Full List of Fires and Single Family Home Counts *(continued)*

	State	Year	Destroyed	Exposed	Share Destroyed
Ranch	CA	2018	31	200	0.16
West	CA	2018	22	238	0.09
Klamathon	CA	2018	19	53	0.36
Holiday	CA	2018	9	33	0.27
Steele	CA	2018	8	15	0.53
Pawnee	CA	2018	6	27	0.22
Cranston	CA	2018	5	66	0.08
Meyers	CA	2018	3	4	0.75
Delta	CA	2018	3	21	0.14
Holy	CA	2018	1	147	0.01
Carder	CA	2018	1	1	1.00
Marsh	CA	2018	1	5	0.20
Silver	CA	2018	1	2	0.50
Creek	CA	2018	0	1	0.00
Tubbs Fire	CA	2017	3,730	4,607	0.81
Thomas	CA	2017	496	2,311	0.21
Nuns	CA	2017	380	1,396	0.27
Atlas	CA	2017	229	665	0.34
Redwood	CA	2017	106	185	0.57
Cascade	CA	2017	61	229	0.27
Sulphur	CA	2017	38	112	0.34
Helena	CA	2017	27	89	0.30
Creek	CA	2017	26	611	0.04
Laporte	CA	2017	25	87	0.29
Lilac	CA	2017	21	311	0.07
Detwiler	CA	2017	18	156	0.12
Ponderosa	CA	2017	9	15	0.60
Canyon 2	CA	2017	9	198	0.05
Wall	CA	2017	6	36	0.17
Skirball	CA	2017	5	76	0.07
Estate	CA	2017	2	5	0.40
Mission	CA	2017	2	14	0.14
Laverne	CA	2017	2	9	0.22
Hill	CA	2017	2	8	0.25
Railroad	CA	2017	2	6	0.33
Alamo	CA	2017	1	13	0.08
Stone	CA	2017	1	3	0.33
Cherokee	CA	2017	0	2	0.00
Canyon	CA	2017	0	24	0.00
Clayton	CA	2016	52	138	0.38
Erskine	CA	2016	51	546	0.09
Soberanes	CA	2016	15	54	0.28
Grade	CA	2016	4	11	0.36

Appendix Table 6: Full List of Fires and Single Family Home Counts *(continued)*

	State	Year	Destroyed	Exposed	Share Destroyed
Goose	CA	2016	1	5	0.20
Chimney	CA	2016	0	9	0.00
Valley	CA	2015	827	1,697	0.49
Butte	CA	2015	151	439	0.34
Round	CA	2015	31	130	0.24
Rocky	CA	2015	11	50	0.22
Tassajara	CA	2015	2	9	0.22
Cocos	CA	2014	30	156	0.19
Clover	CA	2013	12	20	0.60
Silver	CA	2013	4	68	0.06
Shockey	CA	2012	5	9	0.56
Ponderosa	CA	2012	2	4	0.50
Ponderosa	CA	2012	0	2	0.00
49er	CA	2009	63	125	0.50
Humboldt	CA	2008	47	189	0.25
Trabing	CA	2008	13	60	0.22
Martin	CA	2008	0	4	0.00
Witch	CA	2007	516	5,812	0.09
Grass Valley	CA	2007	152	432	0.35
Paradise2003	CA	2003	29	520	0.06
Other States					
Goodwin	AZ	2017	2	6	0.33
Yarnell	AZ	2013	79	212	0.37
EastTroublesome	CO	2020	272	573	0.47
CameronPeakFire†	CO	2020	72	552	0.13
MM 117 Fire†	CO	2018	7	85	0.08
Black Forest†	CO	2013	423	767	0.55
Waldo Canyon†	CO	2012	295	892	0.33
HighparkFire†	CO	2012	171	536	0.32
Almeda-Obenchain	OR	2020	414	599	0.69
HolidayFarm	OR	2020	325	594	0.55
BeachieCreek-Santiam	OR	2020	219	359	0.61
EchoMountainComplex	OR	2020	125	289	0.43
ColdSprings	WA	2020	10	70	0.14
OkanoganComplex	WA	2015	34	393	0.09
CarltonComplex	WA	2014	111	629	0.18
Eagle Road Fire	WA	2014	6	726	0.01

†Excluded from "other states" comparison group due to locally-adopted WUI building standards.

Appendix References

Rollins, Matthew G. 2009. “LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment.” *International Journal of Wildland Fire* 18 (3): 235–249.