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Supplementary material

High wildfire damage in interface communities in California

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Table A1.1: Area, destruction, and survival in each of 90 wildfires analyzed (89 between 1985 and 2013 and the 2017 Tubbs fire).

	Year	Area (sq km)					Destruction (buildings)					Survival (buildings)				
Fire name		Urban	Interface	Intermix	Rural	Total	Urban	Interface	Intermix	Rural	Total	Urban	Rural	Interface	Intermix	Total
Tubbs	2017	1.9	7.7	61.4	77.9	149	1,430	1,968	2,011	227	5,636	460	752	1,260	418	2,890
Tunnel / Oakland Hills	1991	1.3	4.1	0.5	1.5	7	203	1,709	91	10	2,013	390	876	16	27	1,309
Cedar	2003	0.0	19.5	156.2	910.4	1,086	0	446	1,054	190	1,690	0	4,863	4,998	1,217	11,078
Witch	2007	3.5	21.2	113.1	540.2	678	48	195	290	123	656	321	3,097	3,169	900	7,487
Old Topanga	1993	0.0	5.4	35.0	27.5	68	0	360	190	11	561	0	433	542	52	1,027
Old	2003	0.0	13.0	18.0	333.9	365	0	476	67	16	559	0	1,483	325	370	2,178
Santiago	2007	0.2	4.2	8.5	98.9	112	0	4	14	232	250	0	244	265	291	800
Angora	2007	0.0	0.7	6.6	4.9	12	0	193	52	4	249	0	101	65	4	170
Tea	2008	0.0	1.1	3.6	3.1	8	0	99	143	3	245	0	122	135	5	262
Laguna	1993	0.0	0.8	7.2	51.0	59	0	82	71	29	182	0	168	208	96	472
Painted Cave	1990	0.0	4.6	8.0	6.7	19	0	151	31	0	182	0	1,166	101	155	1,422
College Hills	1990	0.8	1.6	0.2	0.5	3	44	130	0	0	174	556	1,304	68	24	1,952
Paradise	2003	0.0	1.1	39.6	185.9	227	0	0	153	11	164	0	69	1,590	325	1,984
Rice	2007	3.1	11.0	13.7	12.7	41	6	91	41	16	154	216	837	425	49	1,527
Btu Lightning Complex (Long Branch-Jack)	2008	0.0	0.0	17.2	193.6	211	0	0	86	49	135	0	5	195	134	334
Humboldt	2008	0.0	0.0	28.2	68.0	96	0	5	104	11	120	0	3	345	75	423
Sayre	2008	0.0	1.0	3.0	41.5	45	0	54	19	34	107	0	197	73	45	315
Slide	2007	0.0	3.0	3.1	46.0	52	0	82	19	6	107	0	1,202	233	107	1,542
Station	2009	0.0	2.0	8.5	658.7	669	0	28	15	57	100	0	611	373	252	1,236
Grass Valley	2007	0.0	0.6	1.2	4.1	6	0	69	29	0	98	0	258	124	1	383
Summit	2008	0.0	0.0	0.2	14.5	15	0	0	3	71	74	0	0	3	37	40

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Corral	2007	0.0	2.0	10.0	10.2	22	0	34	32	7	73	0	305	202	18	525
Juniper	1996	0.0	0.4	14.3	11.5	26	0	2	33	31	66	0	80	681	78	839
Poomacha	2007	0.0	1.6	26.4	164.2	192	0	16	33	17	66	0	87	823	217	1,127
Freeway Complex	2008	0.0	10.9	14.7	93.2	119	0	34	6	12	52	0	2,734	276	82	3,092
Jones	1999	0.0	12.4	39.2	56.8	109	0	10	25	15	50	0	281	958	177	1,416
Baldwin Hills	1985	1.2	0.0	0.0	0.6	2	48	0	0	0	48	1,044	0	0	2	1,046
Jesusita	2009	0.0	0.8	11.9	21.9	35	0	13	21	13	47	0	110	233	53	396
Marek	2008	0.0	0.7	4.6	14.7	20	0	41	1	0	42	0	66	147	41	254
Grand Prix	2003	0.5	6.3	5.7	193.1	206	0	10	9	8	27	61	532	106	128	827
Buckweed	2007	0.0	1.6	28.0	137.7	167	0	4	11	11	26	0	405	524	89	1,018
Gladding	2008	0.0	1.1	2.6	0.5	4	0	5	11	4	20	0	21	58	2	81
Gavilan	2002	0.0	0.9	2.6	19.9	23	0	0	19	0	19	0	130	113	26	269
Harmony	1996	0.4	5.9	14.8	16.6	38	0	7	1	11	19	86	210	121	57	474
Telegraph	2008	0.0	0.0	11.5	124.0	135	0	0	18	0	18	0	0	36	18	54
Williams	1997	0.0	0.0	9.2	16.4	26	0	0	3	15	18	0	0	140	90	230
Pines	2002	0.0	0.4	12.5	251.8	265	0	0	16	1	17	0	9	146	75	230
Padua	2003	0.0	1.6	5.7	35.5	43	0	7	3	6	16	0	292	77	18	387
Simi	2003	0.3	3.3	27.0	405.6	436	0	0	2	14	16	65	347	382	456	1,250
Canyon 4	1999	0.0	0.2	8.7	1.6	10	0	2	12	0	14	0	47	611	42	700
Ranch	2007	0.0	1.5	5.1	143.2	150	0	6	3	5	14	0	214	262	151	627
Clover	2013	0.0	0.0	7.6	25.8	33	0	0	6	6	12	0	0	276	175	451
Manton	2005	0.0	0.0	4.1	5.2	9	0	0	9	3	12	0	2	77	27	106
Sesnon	2008	0.0	1.8	9.9	50.0	62	0	6	1	5	12	0	211	106	99	416
Hackberry Complex	2005	0.0	0.0	0.5	282.7	283	0	0	3	8	11	0	0	1	25	26
Mountain	2003	0.0	0.0	14.1	29.0	43	0	0	9	2	11	0	0	337	101	438
Gloria	2009	0.0	0.0	0.1	27.0	27	0	0	0	10	10	0	0	2	31	33
West	2010	0.0	0.0	0.1	7.2	7	0	0	0	10	10	0	0	0	20	20
Geysers	2004	0.0	0.0	0.1	48.7	49	0	0	1	8	9	0	0	1	35	36
Ophir	2008	0.0	0.5	2.3	1.4	4	0	0	8	1	9	0	0	46	0	46

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Bull	2010	0.0	0.1	4.5	65.2	70	0	3	2	3	8	0	53	49	1	103
Melton	2004	0.0	0.0	4.3	11.7	16	0	0	2	6	8	0	0	29	19	48
Crown	2010	0.0	1.0	3.1	52.8	57	0	0	2	5	7	0	2	54	19	75
La Brea	2009	0.0	0.0	0.0	340.8	341	0	0	0	7	7	0	0	0	4	4
Sheep	2009	0.0	0.0	1.1	29.0	30	0	0	1	5	6	0	0	2	20	22
Coyote	2003	0.0	0.0	0.4	77.4	78	0	0	0	5	5	0	0	17	18	35
Pattison	2004	0.0	0.2	11.4	0.0	12	0	0	5	0	5	0	24	213	0	237
Pleasure	2004	0.0	0.0	0.0	10.6	11	0	0	0	5	5	0	0	0	32	32
Shockey	2012	0.0	0.0	1.7	9.0	11	0	0	0	5	5	0	0	21	3	24
Tesla	2005	0.0	0.0	0.0	26.9	27	0	0	0	5	5	0	0	0	38	38
Basin Complex	2008	0.0	0.3	7.2	658.3	666	0	0	4	0	4	0	0	33	34	67
Basin Complex (Indians)	2008	0.0	0.0	0.0	239.1	239	0	0	0	4	4	0	0	0	9	9
Beck	2006	0.0	0.1	0.1	6.9	7	0	0	0	4	4	0	0	0	0	0
Craig	2008	0.0	0.0	0.0	7.1	7	0	0	0	4	4	0	0	0	4	4
Hidden	2000	0.0	0.0	1.1	11.1	12	0	0	0	4	4	0	0	5	17	22
Yellow	2008	0.0	0.0	0.0	134.5	134	0	0	0	4	4	0	0	0	23	23
Canyon Complex (Friend-Darnell)	2008	0.0	0.0	1.8	15.1	17	0	0	0	3	3	0	0	9	0	9
Constantia	2010	0.0	0.0	0.0	6.1	6	0	0	0	3	3	0	0	0	8	8
Copper	2002	0.0	0.1	0.9	76.1	77	0	0	0	3	3	0	7	15	107	129
Hill	2011	0.0	0.1	0.9	4.4	5	0	0	1	2	3	0	10	7	2	19
Oak Glen 3	2009	0.0	0.0	2.2	6.0	8	0	0	0	3	3	0	8	29	5	42
Sand	2012	0.0	0.0	0.0	5.6	6	0	0	0	3	3	0	0	0	0	0
Topanga	2005	0.0	3.9	14.9	78.9	98	0	0	0	3	3	0	258	301	121	680
Big Meadow	2009	0.0	0.0	0.5	31.2	32	0	0	0	2	2	0	0	16	17	33
Buck	2012	0.0	0.0	0.1	10.3	10	0	0	0	2	2	0	0	0	10	10
Concow	2000	0.0	0.0	3.1	4.0	7	0	0	2	0	2	0	0	49	12	61
Croy	2002	0.0	0.0	0.2	12.4	13	0	0	0	2	2	0	0	0	13	13
East	2004	0.0	0.0	0.0	5.7	6	0	0	0	2	2	0	18	0	0	18

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Gorman	2005	0.0	0.1	1.1	8.7	10	0	0	0	2	2	0	1	12	29	42
Griffith Park	2007	0.0	0.0	0.2	4.4	5	0	0	0	2	2	8	10	4	13	35
Hemlock	2001	0.0	0.0	0.0	4.5	5	0	0	0	2	2	0	0	0	0	0
Mataguay	2004	0.0	0.0	0.0	36.8	37	0	0	0	2	2	0	0	1	18	19
Powerhouse	2013	0.0	0.7	12.1	118.1	131	0	0	0	2	2	0	145	266	139	550
Quail	2006	0.0	0.0	0.0	20.0	20	0	0	0	2	2	0	0	0	21	21
SHU Lightning Complex (Moon)	2008	0.0	0.0	0.7	147.1	148	0	0	0	2	2	0	0	20	38	58
SHU Lightning Complex (Motion)	2008	0.0	0.0	0.1	118.7	119	0	0	0	2	2	0	0	0	13	13
Wild	2008	0.0	0.0	1.1	15.5	17	0	0	1	1	2	0	0	4	15	19
Yuba	2009	0.0	0.0	1.3	15.0	16	0	0	2	0	2	0	0	15	15	30
Armstrong	2004	0.0	0.0	0.6	3.8	4	0	0	0	1	1	0	0	12	17	29
SHU Lightning Complex (Pine)	2008	0.0	0.0	0.0	8.0	8	0	0	0	1	1	0	0	0	9	9

Part 2

We investigated whether building proximity influenced destruction by calculating the mean and standard deviation of the distance from destroyed and surviving buildings to the a) nearest, b) nearest destroyed, and c) nearest surviving building in each of the WUI/non-WUI types. We found that destroyed buildings were often closer to other destroyed buildings and further from surviving buildings, yet variability was high and we found no significant trends (See Table A2.1 and Figure A2.1). Because many factors other than building proximity determine whether a building is destroyed, this high variability was unsurprising (Syphard *et al.* 2012; Alexandre *et al.* 2016).

In regards to the 30 m home ignition zone described by Cohen (2000), destroyed buildings in urban and interface areas had, on average, overlapping home ignition zones ($\leq$ 60 m between buildings), indicating that owners of homes that were destroyed by the fire in these areas often did not have full control over all surrounding fuel that may have led to the ignition of their home. In fact, the nearest destroyed building would have often been within the home ignition zone ($\leq$ 30 m between destroyed buildings), which means that burning homes themselves may have contributed substantially to the fire moving between buildings. While standard deviation of these distances was high and differences were not significant, the trend in values indicates that shorter distances between homes may have affected destruction rates and that home-to-home ignition may have played an important role in the spread of fire in urban and interface WUI areas. Further investigation into the role of home-to-home ignition in the spread of wildfire in more densely populated areas could improve preparation for, and response to, wildfires in these areas (Butsic *et al.* 2015; Clark *et al.* 2016; Mahmoud and Chulahwat 2018).

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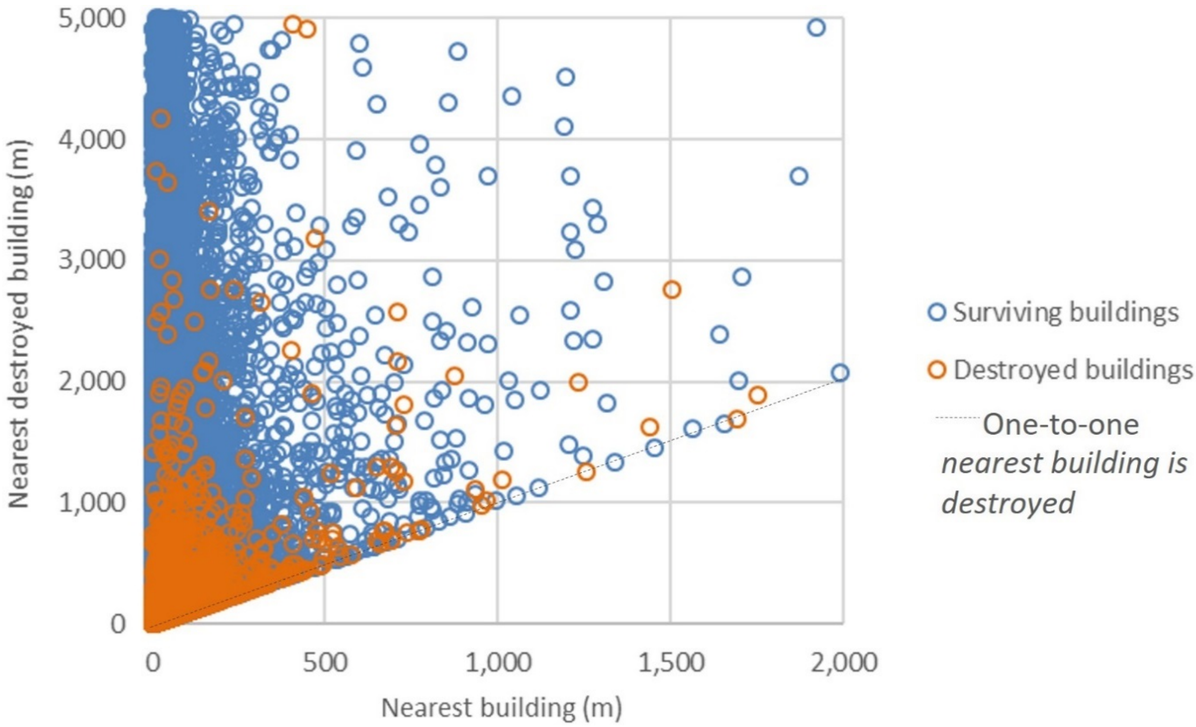
Table A2.1: Distance from destroyed and surviving buildings to the nearest destroyed, surviving, and any building.

WUI class & building fate	Nearest building (m) mean *(st. dev)*	Nearest destroyed building (m) mean *(st. dev)*	Nearest surviving building (m) mean *(st. dev)*
Urban			
destroyed	27 *(19)*	39 *(55)*	51 *(25)*
survived	23 *(16)*	1,509 *(1,765)*	24 *(17)*
Interface			
destroyed	22 *(21)*	32 *(60)*	74 *(74)*
survived	25 *(20)*	948 *(1,420)*	26 *(22)*
Intermix			
destroyed	48 *(56)*	111 *(263)*	112 *(148)*
survived	45 *(49)*	999 *(1,754)*	47 *(54)*
Rural			
destroyed	69 *(161)*	186 *(1,059)*	417 *(587)*
survived	76 *(172)*	1,898 *(3,590)*	82 *(201)*
Overall			
destroyed	37 *(75)*	81 *(453)*	139 *(282)*
survived	38 *(69)*	1,119 *(1,950)*	40 *(79)*

Figure A2.1: Scatterplot showing the distribution of destroyed and surviving buildings regarding the distance to the nearest building and the distance to the nearest destroyed building. A one-to-one line is shown to mark where the nearest building is a destroyed building (the distances are equal). Distances over 5,000 m from the nearest destroyed building or 2,000 m from the nearest building are not shown.



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Part 3

While California fire management and law discuss the WUI, legislation is often based on mapped Fire Hazard Severity Zones, and divided between Sate and Local Responsibility Areas. CAL FIRE's statewide fuel-based maps of communities at risk have been criticized for not corresponding to actual wildfire impacts in southern CA. Syphard et al. (2012) found that property loss was evenly divided among hazard levels and that the majority of property loss occurred in areas not designated as at-risk. These wildfire threat maps were based on information on vegetation and distance to people and communities. CAL FIRE now uses fire hazard severity zones (FHSZ) that capture hazard more completely, but wildfire impacts have not been evaluated for these zones. Therefore, we investigated destruction within these zones to test the accuracy of the FHSZ designations.

Methods

We analyzed wildfire destruction and area within each FHSZ for the Tubbs fire and past California wildfires. For data on wildfire destruction and survival we used our digitized building locations for the 89 wildfires where buildings were lost from 1985-2013 (buildings at the time of the wildfire within the wildfire perimeter totaled 63,667, of which 8,722 were destroyed). We also created a subset of wildfires that destroyed at least 100 buildings (n=18; excluding the Tubbs fire).

We then calculated total buildings destroyed and surviving, as well as wildfire area among different designations of FHSZ. We used FHSZ classifications, combining state responsibility areas (SRAs) and local responsibility areas (LRAs), as mapped by CAL FIRE. These maps evaluate hazard or the physical conditions that create a likelihood that an area will burn over a 30 to 50-year period, based on factors such as fuel, slope, and wildfire weather (they do not consider likelihood of damage in terms of built environment or modifications such as fuel reduction or defensible space; http://frap.fire.ca.gov/projects/hazard/Fire_Hazard_Zoning_workshop_1_8.ppt, http://www.fire.ca.gov/firepreventionfee/sra_faqs#2). Ratings of FHSZs can be very high, high, or moderate; other areas are non-urban (typically areas without wildland vegetation such as agricultural areas) or urban unzoned areas (CAL FIRE 2007). These areas are mapped throughout the state, and then determined to be SRAs or LRAs based on local jurisdictions http://frap.fire.ca.gov/projects/hazard/Fire_Hazard_Zoning_workshop_1_8.ppt). We used the most recent maps, from 2007, for all wildfires that occurred from 1985-2013, as we lacked historical data on FSHZs. We present information on building loss and area by zone, combining SRAs and LRAs. Policy implications vary based on SRA or LRA, however: California state codes and regulations to reduce wildfire risk apply in all SRA-rated areas (very high, high, or moderate) and only the very high LRA areas (localities may also adopt more stringent regulations). State-level requirements include standards for fire-resistant materials for new buildings and defensible space requirements for all buildings (new construction and existing buildings; http://www.readyforwildfire.org/Fire-Safety-Laws/). As of 2011 all homes in rated SRA areas are also charged a $150 fee per year to pay for wildfire prevention services within the SRA (through though Assembly Bill X1 29, though this law has been suspended as of 2017 after the passing of Assembly Bill 398; http://www.fire.ca.gov/firepreventionfee/). We calculated the percent area, proportion of destruction, and destruction rate within each of these FHSZ designations.

Results

All destructive wildfires in California, and more destructive wildfires that destroyed at least 100 buildings had area that fell overwhelmingly into very high-risk areas (86% and 90%, respectively). For all California wildfires that destroyed buildings and wildfires that destroyed at least 100 buildings, less than 14% and less than 10% of area burned fell into high and moderate rated areas combined. The Tubbs fire departed from these patterns, with nearly 70% of area in high and moderate areas (over 50% in moderate areas) and a smaller proportion of area in very high risk areas. All California wildfires that destroyed buildings, and wildfires that destroyed at least 100 buildings had less than 1% of area in urban unzoned areas; the Tubbs had just under 4% of total wildfire area in this category. However, the highest proportion of buildings lost to wildfire in the Tubbs fire were in urban unrated areas (39%), a departure from past wildfire losses (2% for all wildfires combined, and only a fraction of a percent more for wildfires that destroyed at least 100 buildings). The total number of buildings lost in each zone for the Tubbs fire diminished as severity zones increased in risk (Table A3.1). These results were different from other wildfires; for all wildfires and for wildfires that destroyed at least 100 buildings, nearly all of the losses occurred in very high hazard zones. When combined, the very high and high hazard zones contained 91% of all losses for both wildfires that destroyed at least 100 buildings and all destructive wildfires.

Destruction rates allow us to determine the proportion of buildings in each zone that were lost to wildfires. For all destructive California wildfires combined, destruction rates are relatively low (below 13% in all categories) and generally increase with risk severity (lowest destruction rates in urban unrated areas (4%), and similar destruction rates in high and very high risk severity zones (13%)), though non-wildland, non-urban areas had a relatively high destruction rate of 10% (Table A3.1). Patterns in wildfires that destroyed at least 100 buildings were broadly similar, reaching a maximum of 18% in very-high hazard zones. The Tubbs departed from historical patterns; all destruction rates were substantially higher than those seen in more destructive wildfires and in all destructive wildfires together (minimum of 34%, maximum of 73%). In each zone, rates of destruction in the Tubbs fire were 2 to 15 times higher than equivalent loss rates in the more destructive wildfires. For the Tubbs fire, the highest destruction rates were in the high and urban unrated areas (both over 70%); destruction rates in very high and moderate risk zones were lower (but still over 50%).

Discussion

California's FHSZs rated as 'very high' or 'high' captured most of the destruction in most wildfires, but not in wind-driven wildfires such as the 2017 Tubbs fire. Improved models that integrate extreme fire weather, such as Santa Ana and Diablo winds, may allow for increased accuracy of the mapped hazard across the state of California, thus better alerting residents of their relative risk and helping them to make informed decisions about where to live, as well as appropriate building materials and defensible space (Moritz et al. 2014).

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Table A3.1: Area and destruction within the CAL FIRE designated Fire Hazard Severity Zones in destructive wildfires and all CA wildfires in our sample.

	Tubbs	Over 100 buildings destroyed	All CA
Area (%)			
Very high	26.4	89.7	86.2
High	18.6	6.1	7.9
Moderate	51.1	3.4	5.4
Non-Wildland/Non-Urban	0.5	0.7	0.4
Urban Unrated	3.5	0.1	0.1
Proportion total destruction (%)			
Very high	5.3	78.0	77.9
High	22.3	13.2	13.3
Moderate	33.2	6.2	6.2
Non-Wildland/Non-Urban	0.2	0.3	0.6
Urban Unrated	39.0	2.3	2.0
Destruction rate (%)			
Very high	49.9	17.9	12.5
High	70.5	16.7	12.6
Moderate	60.5	10.9	9.3
Non-Wildland/Non-Urban	34.3	9.7	10.2
Urban Unrated	72.9	5.0	4.3

Part 4

We investigated whether destruction rate changed over time. We plotted both overall destruction rate and destruction rate in urban, interface WUI, intermix WUI, and rural areas over time and fit each distribution with a linear model to test for significance. We found no significant trends (Figure A3.1), but caution that our data for older fires was sparse due to limitations on the imagery available to collect data for these older fires. Therefore, although our exploratory analysis reveals no significant trends, this could be an interesting area of further exploration. Similarly, because our data are limited for older fires, we were not able to carry out any analyses that examined overall destruction over time, but see Dennison *et al.* (2014) and Westerling *et al.* (2006), who found more large wildfires and a longer wildfire season in the western United States since the 1980s.

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Figure A3.1: Grid of scatterplots showing how destruction rate changes over time in a) all fires, b) urban non-WUI, c) interface WUI, d) intermix WUI, and e) rural non-WUI areas. Each point represents one fire (n=89). Linear models were fit, but none were significant, and are not shown.