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Perspective

Coupling fire and energy in the Anthropocene: Deploying scale to analyze social vulnerability to forced electricity outages in California☆

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ABSTRACT

Extreme events such as wildfires and winter storms result in disruptions to grid-based electricity delivery. Electricity supply disruptions are both reactive, whereby specific events cause damage to physical infrastructure, or anticipatory where electricity suppliers—namely electric utility companies—preemptively de-energize sections of an electrical grid or distribution network based on elevated potential of extreme conditions that may cause wildfire ignition. De-energization has been promoted as a strategy to mitigate risk of wildfire ignition and spread when active fires may encounter distribution/transmission lines. Provision of basic energy services such as electricity are necessary for maintaining a range of essential functions such as communication, which become critical during extreme events. In recent years, Public Safety Power Shutoffs (PSPS) have increasingly been deployed by utility companies in Western U.S states as wildfire risk increases due to combined impacts of anthropogenic climate change, fuel accumulation, and expansion of development in fire prone lands. While the PSPS policy was designed to reduce liability of utilities in igniting fires, there is a dearth of research critically analyzing how the policy affects social vulnerability for populations subjected to periods of de-energization during high-risk fire conditions. This article aims to deepen current understandings of the way scale can be deployed to illustrate the highly spatial nature of relationships coupling electricity supply outages with demographic data to advance limited knowledge on social vulnerability characteristics for specific communities subjected to PSPS. The research engages scale to compare social vulnerability to outages experienced both in Butte County, located in northern California and the state as a whole.

1. Introduction

After ignition on the morning of November 8, 2018, the Camp Fire razed the Northern Californian town of Paradise located in Butte County, resulting in the loss of eighty-five lives and over eighteen thousand buildings. To date, the Camp Fire is the deadliest and most destructive wildfire in California's history. Ignition of the fire was traced to a Pacific Gas and Electric (PG&E) transmission line. A worn C-hook purchased for 56 cents in 1919 and previously identified as needing repair failed [1], causing transmission lines to arc and igniting dry vegetation that was quickly fanned by strong winds [2]. The event, according to David James, the Wildfire Resiliency Plan Manager at Avista Corporation, an electric utility headquartered in Spokane, WA, "catalyzed the electric power industry in a way never seen before," as utilities began planning or integrating new strategies aimed at reducing risk of wildfire ignition and spread [3].

Facing multiple lawsuits and possible bankruptcy [4], PG&E ramped up a de-energization program called Public Safety Power Shutoffs (PSPS) that were first implemented by the utility in 2018. PSPS, however, have been occurring in California since 2013, when San Diego Gas and Electric first gained authorization from the California Public Utilities Commission (CPUC) to start de-energizing sections of its network during extreme weather conditions [5]. In 2018, the CPUC allowed all Investor-Owned Utilities in California to begin deploying PSPS across

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their networks [6].

As wildfire activity and fire weather extremes in Western U.S states has increased in recent decades [7,8], PSPS has been deployed by other electric utilities outside California. During the 2020 fire season, Portland General Electric and Pacific Power started de-energizing sections of their distribution network in Oregon during fire events [9], while Puget Sound Energy in Washington State started deploying PSPS in 2022 [10]. In May 2021, Oregon's Public Utility Commission drafted new temporary rules regarding communication and coordination protocols for PSPS in anticipation of more extreme fire seasons.

Under a nascent PSPS strategy, de-energizing sections of their electric network was purported by PG&E as a pre-emptive strategy to mitigate risk of wildfire ignition and avoid catastrophic outcomes during dry and windy conditions that are conducive to rapid rates of fire spread [11]. While powerline ignitions reflect only 1 % of wildfires in California [12], half of the 10 most destructive fires in California have been linked to energy systems [13]. As the CPUC has enacted policies aimed at hastening the development of micro-grids as a strategy to counter outages during de-energization [14], PSPS deployment must be understood as reactive, short-term risk mitigation tools, not long-term adaptation strategies. Moreover, in response to Senate Bill 901, the CPUC has passed several wildfire specific resolutions since 2020 aimed at reducing wildfire risk from electrical infrastructure [15]. Consequently, in addition to PSPS, electric utilities in California have engaged numerous strategies such as grid hardening, transmission corridor widening, fuel management and undergrounding of lines, to mitigate wildfire risk.

To date, the bulk of research examining PSPS has largely been developed from a power system engineering or grid optimization position [16–19], household scale adoption or micro-grid development as an adaptation/resiliency solution [9,20–22]. Moreover, while there are some salient studies investigating human responses [23–25] and vulnerability [26], they have largely utilized web-based sampling to survey affected populations. Consequently, there is a dearth of research from geographers examining demographic characteristics of resident populations within PSPS zones. As studies of vulnerability are rarely positioned below county or census tract levels [27], there is also a lack of research critically investigating the scalar mismatch between widely used social vulnerability indexes and complex socioenvironmental dynamics shaping empirical outcomes.

Moreover, as argued by Wong-Parodi [23], for many residents, particularly members of marginalized communities, PSPS actually increases risk. As detailed by Abatzoglou et al. [11], "*disproportionately adverse impacts were felt in disadvantaged communities both in rural areas and across portions of the urbanized San Francisco Bay Area, including the direct financial impact of preparing for and recovering from outages of initially unknown duration, while individuals with disabilities who rely on electricity for respiratory support systems such as breathing aids and mobility devices such as electric wheelchairs faced substantial challenges during PSPS in 2019.*" Ongoing PSPS events are anticipated to widen existing gaps between marginalized and affluent groups, both of which are increasingly found peri-urban or wildland urban interface (WUI) areas that are affected by PSPS [28], as wealthier residents can build resiliency at the household scale by purchasing generators and solar plus storage systems to maintain electricity during outage periods [25]. It is widely understood that weather-based hazards and impacts from climate change disproportionately affect underserved populations including minorities, women, and those with disabilities, see; [29–32].

Additionally, while social vulnerability is taken into consideration for programs to mitigate impacts of PSPS, there is no evidence detailing social vulnerability factoring into criteria when electric utilities make decisions regarding PSPS deployment or broader policies. Consequently, there is a need to better understand how PSPS may cause unintentional harm, create new vulnerabilities and increase risk as outcomes will be spatially uneven and disproportionately impact specific communities, or resident populations within communities based on socio-demographic characteristics. Spatial complexities of social vulnerability characteristics within resident populations subjected to periods of de-energization during high-risk fire weather is not sufficiently understood and this study aims to shed light on this critical gap in research.

2. Measuring social vulnerability in the Anthropocene

Extreme events such as winter storms [33] and fire weather are exacerbated by anthropogenic climate change [34]. These extremes disrupt grid-based energy supplies [9,23,25,26,35] and cause damage to associated infrastructure [35] along with health and vitality of proximate communities [36]. Powerline-caused wildfires are particularly problematic as they often start with stress– or tree– induced downed powerlines due to winds and are rapidly spread by these same winds creating challenges for fire suppression. Studies have shown that these fires are significantly larger than other fires [37].

The concept of vulnerability is at the heart of the large and interdisciplinary literature on natural hazards. Vulnerability is commonly used by researchers to explore the potential impacts of a given hazard event or general type of hazard and is understood as having three primary elements. The first element, exposure, is defined as the potential for an impact from a given hazard event. The second, sensitivity, refers to the magnitude or range of a potential impact if an event occurs. Last is adaptive capacity, or the ability of a group of people to act in ways that reduce either their sensitivity or exposure or both [38].

The related concept of *social vulnerability* focuses more specifically on the characteristics of human populations that might differentially affect any of the above aspects of vulnerability [39]. Social vulnerability analyses have become a central hazard mitigation planning tool and several indicators have been developed that assess several population characteristics in a geographic area. For instance, the U.S. Centers for Disease Control developed a Social Vulnerability Index (SVI) that measures 16 social factors, including economic status, age, gender, race and ethnicity, education, housing, and transportation access [40]. The SVI and other similar indices typically draw on census-based demographic variables to identify areas with higher potential levels of social vulnerability to potential environmental hazards (medium to long-term) or hazard events (shorter-term) e.g., [41].

Though common, the utility and meaningfulness of such indicators has been challenged. For example, Hinkel [42] argued that social vulnerability indicators are too often treated as 'one-size-fits-all' approaches that can be socially misaligned to the type of hazard in question by measuring the wrong demographic variable(s), can assess population characteristics at too large of a spatial scale to be meaningful to the localized nature of most hazard events, or are otherwise mismatched conceptually with policy-related hazard mitigation efforts, such as increasing hazard awareness within a region. Nonetheless, social vulnerability indicators at various geographic or spatial scales and their aggregated demographic variables remain central tools used to identify groups of vulnerable people, communities, and places (Ibid).

When factoring in the changes in fire conditions brought on by anthropogenic climate change and fuel accumulation, social vulnerability becomes an exceedingly nuanced concept and largely driven by context specific circumstance. As a result, challenges arise when attempting to define indicators for locations, particularly at larger spatial scales, see; [43–45], as spaces contain distinct geographic features which influence both social and biophysical vulnerability. The context driven nature of vulnerability characteristics for resident populations means there are obvious shortcomings when creating and implementing broad policies that cover large and diverse geographies, such as PSPS, as they do not account for social or biophysical diversity and inherent differences which are fundamental to much geographic inquiry.

Complicating these issues are questions of geographic scale, a central intellectual and organizational tool for geographic inquiry [46]. The concept of geographic scale, commonly used to refer to either the spatial level or scope/extent of a phenomena or process, has been the subject of repeated waves of theorization and debate in both physical and human geography since the early 1980s [47]. Many problems associated with scale have been identified, including that physical processes are not always directly linked across successively smaller-to-larger scales, that human phenomena observed at a given scale is simultaneously constructed through actions at multiple other scales, that the way in which information is collected and organized into spatial areas can affect the results of any analysis, and how the amount of detail that is (or can be) observed is related to a priori decisions about the scale at which the observation is made. Nonetheless, the recognition of scale as a central analytic concern in need of greater attention remains uneven in many literatures, including discussions of the suitability and limitations of various measures of social vulnerability as noted by Mendes et al. [48] and Spielman et al. [49]. Therefore, as research emerges on new issues that connect to questions of social vulnerability, such as PSPS, researchers must be ready to adopt questions of scale early in the development of research questions and frameworks.

3. The study

This pilot study employs an exploratory spatial data analysis e.g., [50] of social vulnerability in communities across Northern California affected by PSPS in 2019. Using spatial and demographic data on PSPS zones, we first assess who was being affected by these outages using key criteria typically associated with lower resilience to natural hazard impacts in the literature [51,52], especially to risks of wildfire for those in peri-urban and WUI areas. These include sex, age, ethnicity, income, language and internet accessibility [28]. Next, we compare the demographic makeup of the population at sub-Census tract scales within PSPS zones against the wider population at both the state and county levels, and investigating those affected by the shutdowns.

It is important to note, in this pilot study we are investigating risk for vulnerable populations in relation to the potential for negative consequences resulting from PSPS apart from losses or impacts from wildfires per se. Risk of exposure to wildfires [45,53] in the western U.S. is well studied, and vulnerable populations typically exhibit a concentration of vulnerable sociodemographic characteristics when compared to the population at large. Because PSPS zones are defined largely based on the potential for large wind-driven wildfires, those findings cannot be totally decoupled from ours. Nonetheless, PSPS reflects a recent policy approach by utilities that is purportedly driven by a fire prevention strategy and one which intersects with demands for energy production, transmission, and distribution networks during heighted periods of wind-driven fire risk. Consequently, we need to critically consider the range of additional risks that pre-emptive shutdowns will generate and better understand who is bearing these effects. While it is still unclear how effective PSPS has been at mitigating the risk of wildfire ignition, we argue that PSPS could be considered as a new kind of co-hazard that will continue to be associated with wildfires. Therefore, there may be unique risks that arise from de-energization and such risks will be unevenly distributed across a shutdown area.

4. Site and sociodemographic indicator selection

We focus on two spatial scales of analysis, both defined by the geographic extent of PSPS shutdowns in 2019. First, we assess the demographic makeup of social vulnerability among all Census block groups statewide. At this scale, however, we exclude any block groups that are part of the San Diego Gas & Electric (SDG&E) and Southern California Edison (SCE) utility service areas as these utilities had public safety power shutdowns in 2019 but no information is available about where the shutdowns occurred. While most social vulnerability indicators focus on counties or census tracts (e.g., [40]), PSPS events have a different spatial organization, following power grid networks that often disregard such administrative spaces. Accordingly, we use block groups as they are the smallest Census geography that provides measurable aspects of demographic information common to social vulnerability indicators. We then compare this PSPS population to those unaffected by the shutdowns, finding that conventional demographic elements of social vulnerability are not well aligned with the shutdown zones.

Second, we explore the same demographic question at the county scale using the case of Butte County, California. Butte County contains the town of Paradise and has been subject to numerous PSPS events since 2019. Moreover, Butte County has also seen significant fire activity since the Camp Fire of 2018, most notable the North Complex Fire in 2020 which was the fifth most destructive in California's history [13]. Butte county also represents a site of frequent potential PSPS based on the co-occurrence of dry fuels and critical fire weather conditions [11]. Again, using demographic information at the block group level, we find that the shutdown zones within the county are poorly aligned with conventional understandings of social vulnerability. Further we find that the scale of analysis matters as the many chosen variables indicated different patterns at the county versus the state scale.

For this study we selected seven sociodemographic variables based on their potential to influence vulnerability during PSPS events. Determining sociodemographic variables for this pilot study was informed by prior literature, and the variables selected were identified as being the most critical in the context of PSPS deployment. Age was identified as it influences response time to alerts, mobility and decision-making processes [54–56]. Second, white populations tend to have higher degrees of resilience and less vulnerability to environmental hazards in the literature, so we chose to analyze the percentage of white residents subject to PSPS [57]. Third, communicating in English is necessary to receive and understand warnings and alerts, so limited English-speaking households was a variable measured for the study [45,59]. Fourth, to provide a counter variable to white households, Hispanic populations are often more vulnerable to environmental hazards as they suffer from marginalization, are commonly located in lower socioeconomic neighborhoods and are generally less resilient when compared to white residents [58–60]. Fifth, there is a well-established understanding of the correlation between socioeconomic status and vulnerability [61], therefore, households in poverty (as defined by the Census for 2018) were identified as a key indicator. Sixth, to counter our measure of socioeconomic status, we also added wealth as a key variable and examined households with an annual income of over $100,000. Finally, internet connections provide timely information about extreme weather conditions, fire alerts and thus were considered an essential indicator for this study [62,63]. While indicators such as vehicle ownership which facilitates mobility, disability and pre-existing health conditions would have also been useful, these data are not available at the census block group level so were omitted. While many indices include other variables that are unavailable at the block group level, each of the measures we chose are both available at the block group level and are typically included in widely used indices, including the SVI.

5. Data and methods

Spatial data on the 2019 PSPS shutdowns were made publicly available by PG&E in GIS shapefile format. The data were acquired in early 2020 as described in [11] and identified areas that were de-energized at any point during the year. These areas extended across 48 of the 58 counties in California as shown in Fig. 1 below; many of these counties were not rated as having highly vulnerable populations according to the 2018 SVI. Additional spatial information on public utility service areas is available through the California State Geoportal. The SDG&E and SCE service areas were used to exclude block groups as both utilities had shutdowns in 2019. However, there are no publicly available georeferenced data to determine precisely where these occurred.

The spatial extent of the PSPS shutdown zones did not align with typical administrative boundaries, such as city or county jurisdictions, as

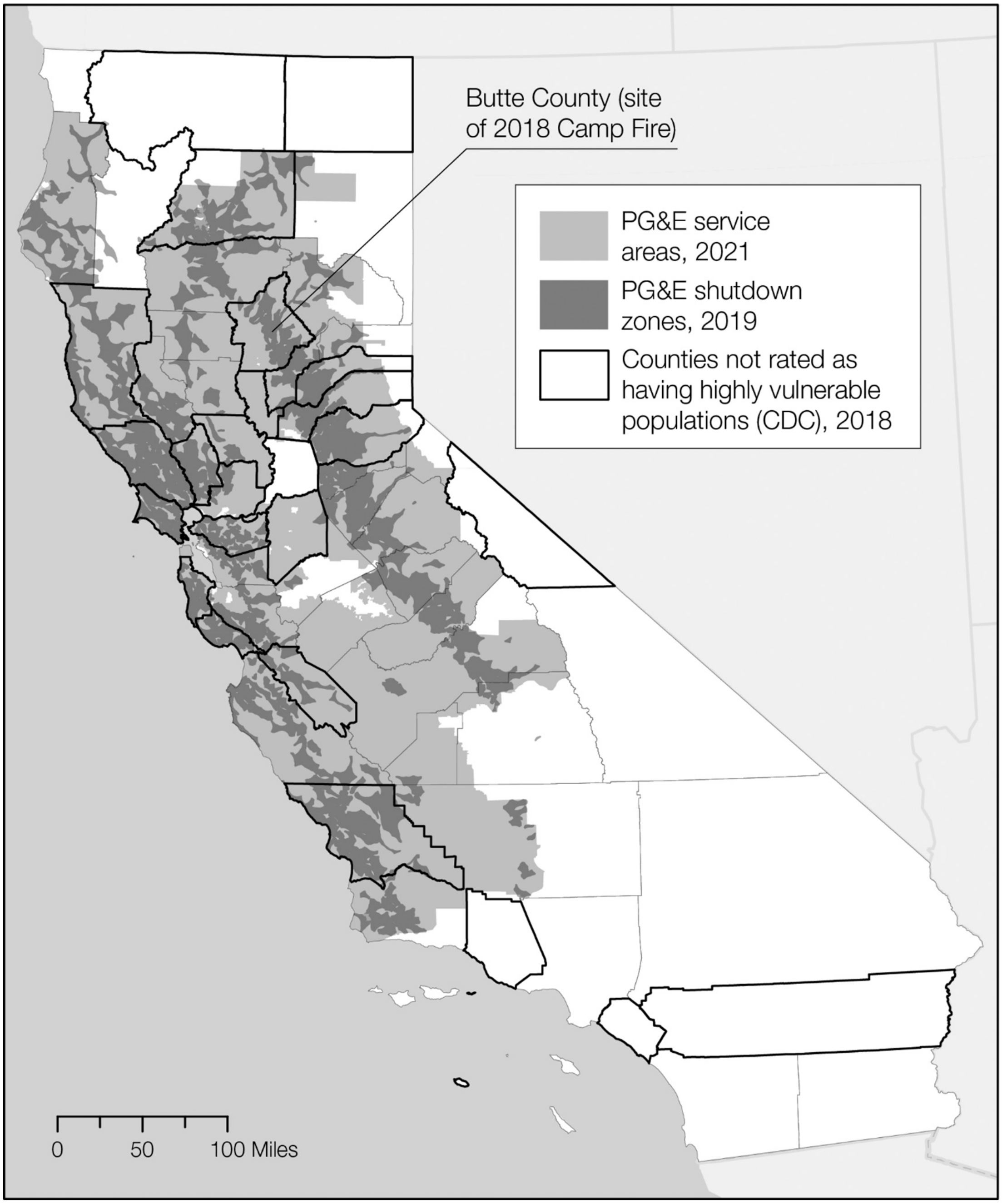

Fig. 1. 48 out of 58 counties in California were affected by PG&E power shutdowns in 2019. Of the affected counties, several rated as not having highly vulnerable populations according to the CDC's 2018 Social Vulnerability Index. Butte County, site of the devastating Camp Fire in 2018, was among them. Map by authors.

power grids often transcend such local or regional administrative spaces [64]. Using a GIS, we overlaid these shutdown zones with demographic information at the block group level from the US Census's American Community Survey for 2019 (2015–2019 American Community Survey, publicly released 5-year estimates). Block groups that intersected the PG&E PSPS zones were identified for our analysis, even if the overlap was minimal. This resulted in 3838 affected block groups in 2019, which contained an estimated total population of 5,870,283 or 15 % of the state's population at the time. Of these block groups, two-thirds (2551 out of 3838) had at least 90 % of the land area of the block group affected by the shutdowns and over 81 % had at least half of the land area affected.

As social vulnerability indices rely on census-collected demographic data that are not available at the smallest census collection geographies (census blocks), most indices have been developed for and applied to counties or census tracts which limits their utility for more spatially disaggregated analyses [65]. Accordingly, rather than use a spatially mismatched indicator, we first identified several key demographic variables that are available at the block group level and then compared these variables within PSPS zones to non-affected areas.

Shutdowns impacted parts of 48 out of California's 58 counties in 2019, resulting in outages affecting 15 % of the state's population and 16 % of its households. However, in Butte County, the percentage of affected population and households was 63 % and 64 % respectively.

6. Results

A comparative analysis of sociodemographic measures for both the state of California and within Butte County yielded some surprising results. Table 1 below summarizes the quantitative findings between affected and unaffected block groups at both scales and provides a comparison metric as a percentage for each scale and as an absolute value of difference between the state and county scale (Table 1). As advanced age is a consistent concern associated with vulnerability to environmental hazards in the literature, we assessed the percentage of older residents (65 years and up) in affected and unaffected block groups at both scales. Consistent with the literature on advanced age and social vulnerability, older populations were found at higher percentages in block groups affected by PSPS and those that weren't at both the state and county. Age was the only variable of the seven chosen for the study to display this outcome. The percentage of white populations affected by PSPS at the state scale was significantly higher (12.7 %), but statistically insignificant at the county scale, where white populations in affected and unaffected areas were nearly identical. Counter to white populations, limited English speaking households were less affected by PSPS at the both the state and county scale, which is in contrast to expectations based on existing literature from prior studies.

Of the variables with significant statistical outcomes at both scales, Hispanic populations and households in poverty were notable for two additional reasons. First, consistent across both of these variables were lower levels of affected block groups at both the state and county scale, which is counter to the expectations based on existing literature from prior studies. Moreover, the largest differences between affected and unaffected block groups were associated with these two variables. At the state scale, both variables had almost identical percentage differences between affected and unaffected block groups (Hispanic −18.3 %, Poverty −18.5 %), although the patterns diverged at the county scale (Hispanic −8.4 %, Poverty −16.5 %). Nonetheless, these two variables had the two largest overall differences between PSPS and unaffected areas at both scales. Thus, Hispanic populations and households in poverty present as distinct from many of the other variables.

Our analysis of relative wealth by examined households with an annual income of over $100,000, illuminated an inconsistent scalar effect, with more residents in affected block groups at the state scale, but fewer residents in affected block groups for Butte County. Finally, for households without access to the internet, the scalar patterns were also mixed, with fewer affected block groups at the state scale and slightly more at the county.

Table 2 below presents a qualitative summary and interpretation of our findings. We assigned a classification system to detail our qualitative interpretation of outcomes from the variables chosen for the study. Our basic classification groups variable into either scalar or percentage different, or literature expectations.

Overall, the results point to scalar inconsistencies for several variables (white populations, wealthy households, and households without internet), either in terms of the statistical differences between shutdown and unaffected areas, the direction of change at both state and county scales, the magnitude of those changes between the scales, or a combination of these factors. Even when scalar effects were consistent, we also observed meaningful differences between affected and unaffected block groups for Hispanic populations and households in poverty and, for limited English-speaking households, a difference that was inconsistent with the expectations from the literature. Only the variable for older populations performed as expected by the literature in a consistent direction across both scales of analysis. When assessed together, each of these variables presents a set of demographic elements that could be used as a basis to conduct more grounded and community-engaged qualitative research at multiple scales to better understand complexities and lived experiences of PSPS and localized effects of environmental hazards, such as devastating wildfires.

7. Discussion

Our exploratory study highlighted two interrelated issues that both point toward concerns in using typical social vulnerability indices to understand the impacts of pre-emptive electricity power shutdowns such as PG&E's PSPS program in California. The first, which is in concert with emerging arguments in the social vulnerability literature, is about the need to reexamine indices like the SVI for any vulnerability analysis centered at large geographic scales. As we argue, information aggregated at larger spatial scales, such as states or Census tracts, are likely a spatial mismatch with most hazard impacts and may obfuscate as much as illuminate (e.g., [42,66]). The need to shift to fine-grained data on social vulnerability is not unique to PSPS, but the geography of

Table 1
Common social vulnerability indicators within both PSPS-affected and unaffected block groups at both the state and county scale. Older populations were found in higher proportions within PSPS-affected block groups at both scales. However, many other indicators were inconsistent with the expectations of the literature, inconsistent across scales, or both. **Bold percentages in black** indicate statistical differences between the means of affected and unaffected areas at $p < 0.001$, tests were performed in R. **Both households in poverty and Hispanic population variables had the largest differences between PSPS-affected and unaffected block groups at both scales.

	California (less SDG&E and SCE)			Butte County			Comparison
Census variable	PSPS block groups (n=3,102)	Unaffected block groups (n=10,412)	Difference (PSPS % - Unaffected %)	PSPS block groups (n=104)	Unaffected block groups (n=93)	Difference (PSPS % - Unaffected %)	Abs. value of state diff. - county diff.
Population age 65 plus	**18.0%**	**12.8%**	5.2%	**20.8%**	**13.9%**	6.9%	1.7%
White population	**69.4%**	**56.7%**	12.7%	82.2%	81.6%	0.6%	12.1%
Limited English households	**4.6%**	**10.9%**	-6.3%	**1.9%**	**3.0%**	-1.1%	5.2%
Hispanic population**	**20.9%**	**39.2%**	-18.3%	**12.2%**	**20.6%**	-8.4%	9.9%
Households in poverty**	**27.6%**	**46.1%**	-18.5%	**44.0%**	**60.5%**	-16.5%	2.0%
Households over $100k	**42.7%**	**34.0%**	8.7%	**19.9%**	**23.1%**	-3.2%	11.9%
Households without internet	**10.0%**	**13.4%**	-3.4%	**14.2%**	**12.6%**	1.6%	5.0%

Table 2
Comparison of findings from the spatial and scalar analysis of common social vulnerability indicators. Older populations were more exposed to PSPS events at both scales, a consistent finding with the literature. However, white populations, limited English households, households over $100k annual income, and households without internet were inconsistent with either the expectations from the literature, inconsistent across scales, or inconsistent across the PSPS-affected and unaffected areas. Therefore, all variables should be of interest to future research, albeit for different reasons.

	Description	Interpretation
Census variable	Summary of results from Table 1	Key variable? (scalar differences, percentage difference, or literature expectations)
Population age 65 plus	More older residents in PSPS areas; consistent across scales	Yes — literature expectations (consistent); age was the only indicator higher for affected block groups at both state and county scales.
White population	More white residents in PSPS areas but insignificant difference at county scale	Yes — scalar differences; inconsistent effect across scales and insignificant difference at county scale
Limited English households	Fewer limited-English households in PSPS areas; consistent across scales	Yes — literature expectations (inconsistent); the indicator had fewer households in affected block groups at both state and county scales
Hispanic population	Fewer Hispanic residents in PSPS areas; larger difference at state scale	Yes — percentage difference; significant differences between affected and unaffected block groups at both state and county scales
Households in poverty	Fewer households in poverty in PSPS areas; consistent across scales	Yes — percentage difference; significant differences between affected and unaffected block groups at both state and county scales
Households over $100k	More wealthy households in PSPS areas at state scale, fewer at county scale	Yes — scalar differences; inconsistent effect across scales with mixed directions of differences
Households without internet	Fewer households w/o internet at state scale, more at county scale	Yes — scalar differences; inconsistent effect across scales with mixed directions of differences

electricity distribution networks, as the case of California has demonstrated, is a particularly poor match for most social vulnerability indices and remains a significant barrier in hazard planning and mitigation within communities and localities. The smallest level of analysis possible with the SVI, for example, is the Census tract. The land area encompassed by the 2019 shutdowns was 22,486 square km; when aligned with SVI data at the tract level, the area of the associated tracts would be 193,424 square km, much of which would include unpopulated areas, such as federal lands. Without recourse to vulnerability data at a spatial scale that reflects the process in question, the usefulness of current data and models will remain in question. In the case of Butte County, this is evident as, according to the CDC's 2018 SVI, the county's population characteristics did not align with the typical understanding of a highly vulnerable population.

Second, researchers also need to be aware of the potential scalar effects involved in aggregating data at any spatial scale. As our comparative analysis shows, what may appear to be a key variable at one scale might be non-meaningful at another. For example, at the state scale white populations appear to be overrepresented in PSPS zones. But at the county scale, that difference vanished. Evidence about how whiteness may affect vulnerability and risk associated with power shutdowns may therefore not be present or detectable at all scales. Another scalar effect is inconsistency in the relationships between elements of social vulnerability in shutdown and unaffected areas at different scales. For examples, some patterns were similar at both scales, such as higher percentages in shutdown areas, lower in unaffected area (older and white populations) or vice versa (Hispanic populations, limited English-speaking households, households in poverty) while a few variables exhibited inverse patterns at different scales (households without internet, wealthier households). Further, the magnitude of the shift in the differences were mostly, but not uniformly, larger at the state scale. The recognition and treatment of issues of scalar effects such as these are unevenly treated in the literature but important inconsistencies between scales of analysis should be expected.

As a consequence of both of these issues, future research therefore needs to focus data collection and analysis at the most granular spatial scale possible. While this study was positioned at the Census block group, it is likely that complexities key to understanding social vulnerability were still flattened or lost through the aggregation of data at the county scale. The highly nuanced nature of social vulnerability—and corresponding measures of resilience—are best understood through community-engaged research methods which allow for data collection at the household scale, a spatial scale where future outage-based research could be positioned. One salient example where household-scale studies of social vulnerability intersecting with PSPS could prove valuable are in PG&E's Medical Baseline, Portable Battery and Disability Disaster Access and Resources (DDAR) Programs created in response to the heightened risk for vulnerable residents [32].

The Medical Baseline Program (MBP) offered discounts and early emergency notifications for PSPS to customers dependent on electronically-powered medical or assistive technology devices while the Portable Battery Program aimed to keep electrons flowing by providing fully subsidized batteries for MBP eligible customers in high fire-threat districts or those who experienced two or more PSPS events since 2020. Customers who didn't qualify for the Portable Battery Program but who lived in a tier 2 or 3 high fire-threat district or have experienced two or more PSPS events since 2020 and rely on electronically-powered medical or assistive technology devices which are not compatible with portable batteries, were eligible for the DDAR program—a more extensive policy covering the entire state. The spatial delineation of tiers in high fire-threat districts, however, resulted in individual households being classified as eligible or ineligible for the Portable Battery and DDAR programs irrespective of medically reliant customers with high social vulnerability or those with low social vulnerability and high resilience.

8. Conclusion

This study has demonstrated the urgent need to deploy scalar analysis as a tool to more comprehensively understand social vulnerability in an era beset by environmental hazards and anthropogenic climate change [44,45,51]. Specifically, the study has demonstrated the need to recalibrate commonly fixed spatial scales through which social vulnerability indicators are assessed. As the prevalence and behavior of large wildfires across the Western United States has shifted in recent decades, so too must the way in which assessments are undertaken for social vulnerability [44,50], specifically in high fire risk areas subjected to outages both planned or not. Assessments need to engage more flexible, less rigid principles to account for the highly dynamic nature of environmental hazards shaped by human-induced climate change in the Anthropocene [67].

While all variables measured in this study were salient based on a qualitative interpretation of our statistical analysis, we suggest age is a significant indicator of social vulnerability when considering heightened fire activity in conjunction with PSPS. Our analysis illuminated higher levels of PSPS across both the state of California and in Butte County during 2019.

Residents over 65 years of age represented over 75 % of fatalities in the Camp Fire [68], while over half of all fatalities in the 2020 Bear Fire, which was one component of the North Complex fires also located in

Butte County, were residents aged 65 and older (Ibid). Older residents are more susceptible to outages in electricity given the greater prevalence of chronic medical problems (e.g., oxygen tanks) that require energy [69,70]. Thus, critically investigating age at fine grained spatial scales will be critical in future research.

As indicated by the percentage of block groups in shutdown areas, Butte County (53 % of block groups affected) was disproportionately impacted by PSPS when compared to the state of California less the SDG&E and SDE utility areas (30 % of block groups affected), indicating a substantial and largely reactionary risk mitigation approach by PG&E in the year following the Camp Fire [11]. Such a widespread PSPS strategy, therefore, was more likely a reaction to the ongoing litigations faced by utilities until additional mitigation efforts can be implemented [1,4]. While the official discourse regarding PSPS remains one of mitigating the risk of wildfire ignition, PSPS likely increases risk to socially vulnerable populations in high fire-risk areas [26,50]. Consequently, PSPS could be considered a new type of hazard itself, and one with a unique social vulnerability signature that confounds the expectations of traditional understandings of hazards built into indicators like the SVI. Currently a range of online geospatial tools can be used to investigate wildfire risk to communities [71], energy infrastructure [72], fire risk to energy infrastructure [73], social vulnerability [74], with many specific to California [75–77]. While these tools are useful in developing a broad understanding of specific challenges, such as fire, energy or social vulnerability, few actually seek to understand the relationship between them, and most offer data analysis at the county or census tract scale [78].

This study has demonstrated how social vulnerability indexes such as the widely used SVI tool developed by the CDC, have higher degrees of efficacy at broader spatial scales such as Census Tracts [51] and in areas of higher homogeneity such as urban middle or higher-class suburbs where prevailing sociodemographic indicators tend to have higher stability, and are less in flux [29]. It is possible that areas such as Butte County, and others increasingly subject to extreme events, not limited to wildfires, will experience higher rates of outmigration [79]. Specifically, it will likely be residents of a higher socioeconomic status, as they are better positioned for mobility to avoid ever increasing risks and lived experiences of environmental hazards, particularly as they intersect with energy supply outages in the Anthropocene.

CRediT authorship contribution statement

Thomas Ptak: Conceptualization, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Steven M. Radil:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **John T. Abatzoglou:** Writing – review & editing. **Julie Brooks:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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