

Do Fires Discriminate? Socio-Economic Disadvantage, Wildfire Hazard Exposure and the Australian 2019–20 ‘Black Summer’ Fires

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Abstract

We examine the relationship between socio-economic disadvantage and exposure to environmental hazard with data from the catastrophic 2019–2020 Australian wildfires (Black Summer) that burnt at least 19 million hectares, thousands of buildings and was responsible for the deaths of 34 people and more than one billion animals. Combining data from the National Indicative Aggregated Fire Extent (NIAFE) and 2016 Socio-Economic Indexes for Areas (SEIFA), we estimate the correlation between wildfire hazard exposure and an index of community-level socio-economic disadvantage. Wildfire hazard exposure is measured as the interaction between the percentage of area burnt and proximity of the fire to settlements. The results reveal a significant positive relationship between fire hazard exposure and socio-economic disadvantage, such that the most socio-economically disadvantaged communities bore a disproportionately higher hazard exposure in the Black Summer than relatively advantaged communities. Our spatial analysis shows that the socio-economic disadvantage and wildfire hazard exposure relationship exists in inner regional, outer regional and remote areas of New South Wales and Victoria, the two worst-hit states of the Black Summer catastrophe. Our spatial analysis also finds that wildfire hazard exposure, even within a small geographical area, can vary substantially depending on the socio-economic profiles of communities. A possible explanation for our findings is resource gaps for fire suppression and hazard reduction that favours communities with a greater level of socio-economic advantage.

1. Introduction

As the planet warms, the number of catastrophic wildfires is growing worldwide at an alarming rate (Jolly et al. 2015; Lindenmayer and Taylor 2020). The unprecedented scale of devastation caused by wildfires in the United States, Australia and Brazil in 2019–2020 foreshadows the shifting ground of global wildfire risk in a changing climate. Spatio-temporal trends from 1979 to 2013 reveal an 18.7% increase in global fire-season length and 25% increase in fire susceptibility of the world's vegetated surface (Jolly et al. 2015). The frequency and intensity of large-scale wildfires have increased in the past two decades and is expected to increase further in the coming decades (Sharples et al. 2016; Abram et al. 2021; Lindenmayer and Taylor 2020).

In terms of the historical record, 2019 was both the warmest and the driest ever recorded in Australia (Filkov et al. 2020). An increasing temperature trend is observed over much of Australia in the past century with the average surface air temperature increasing by 1°C since 1910 (BoM and CSIRO 2018). The risks of higher temperatures are compounded in years where there is below average rainfall (Grose et al. 2014; BoM and CSIRO 2018). Notably, south-eastern and south-western Australia are becoming drier, with May to July rainfall in south-eastern Australia seeing the largest decrease, by around 20% since 1970, and an 11% decrease in April to October rainfall since the late 1990s (BoM and CSIRO 2018).

High temperatures and low rainfall combined led to low soil moisture levels and a cumulative Forest Fire Danger index (FFDI) in 2019 that was the highest on record for 60% of Australia's land area. These very high-risk conditions were the trigger for the largest series of wildfires, in terms of area and over one summer, ever experienced in Australia. These Black Summer fires resulted in the burning of at least 19 million hectares, destruction of more than 2,400 buildings, and loss of 34 human lives (Filkov et al. 2020) and more than one billion animals (Richards et al. 2020). The fires, even by a global comparison, burned the highest percentage of any continental forest biome (21%) from 2000–2019 (Boer and de Dios 2020).

Socio-economic disadvantage encompasses the relative inability of individual and communities to access economic and social resources and to participate in society (Australian Bureau of Statistics 2018a). Socio-economic disadvantage is a broader concept than poverty as it goes beyond financial resources to encompass a wide array of non-financial, social and community resources that account for ethno-linguistic and religious differences, and the availability, accessibility and affordability of public goods and services. All else equal, those who suffer from the greatest socio-economic disadvantage have the fewest resources of their own to cope with disasters. Thus, disadvantage is key to understanding how climate change risks (Leichenko and Silva 2014; Hallegatte et al. 2020) and other 'natural' disasters, including wildfires (Cottrell, 2005), affect heterogeneous populations differentially.

Our work builds on the existing literature that has examined the link between poverty or socio-economic disadvantage and environmental risks. This link varies across countries, communities and hazard types. Studies on flooding and cyclone or hurricane show that socio-economic disadvantage is frequently associated with a higher likelihood of being affected by a hazard (e.g., living on a flood-plain near a river susceptible to flooding) and fewer resources to mitigate its impact (e.g., insurance may be unavailable or unaffordable) (Brouwer et al. 2007; Akter and Mallick 2013; Elliott and Pais 2006; McDougall 2007).

The link between socio-economic disadvantage and wildfire hazard is not so straightforward and may vary depending on land use pattern, characteristics of the population that live in wildfire prone locations (regional, rural and peri- and rural-urban interfaces) and socio-economic and institutional arrangements surrounding wildfire risk reduction. For example, earlier studies in the United States find that low-income rural populations with less formal education are more at risk of wildfires or bear a disproportionately high burden of its direct and indirect impacts (Lynn and Gerlitz 2005; Ojerio et al. 2011). More recent studies from the United States reveal a negative association between socio-economic disadvantage and wildfire sensitivity or overall wildfire risk (Wigtill et al. 2016; Davies et al. 2018; Paveglio et al. 2016; Paveglio et al. 2018). Wigtill et al. (2016) and Davies et al. (2018), for instance, show that socio-economically advantaged population (e.g., white and rich) inhabit highly wildfire-

prone locations due to these locations' high environmental amenities and corresponding property values. Likewise, Paveglio et al. (2016, 2018) find a positive relationship between income, education and sensitivity to potential wildfire losses in Montana and Idaho.

The interlinkage between socio-economic disadvantage and wildfire hazard exposure has not been studied in Australia using large-scale data. The only study that comes closest to exploring this link in Australia uses qualitative data from a farming district (Wulgulmerang) of East Gippsland, Victoria (Whittaker et al. 2012). The study finds that declining farm incomes, depopulation, and low access to essential services increase residents' exposure to wildfires. Given the growing frequency and intensity of extreme wildfire events in Australia and rapidly expanding settlements in peri- and rural-urban sprawls (Koksal et al. 2019; Foster et al. 2013), an in depth understanding of the interlinkage between socio-economic disadvantage and wildfire hazard exposure is important for informing Australia's wildfire hazard risk reduction strategies (Royal Commission into National Natural Disaster Arrangements 2020). Unlike in the United States, wildfire prone locations of Australia, particularly the peri- and rural-urban fringes, are inhabited by a larger percentage of socio-economically disadvantaged communities compared with inner city locations (Alexandra 2020). The relatively higher value properties in Australia are concentrated around the central or near central locations in the capital cities where wildfire hazard exposure is the lowest. Hence, the interlinkage between wildfire exposure and socio-economic disadvantage in Australia is likely to be different to the United States.

Our study contributes to *understanding disaster risk* which is a priority area (Priority 1) for action identified by the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations 2015). The four specific ways we enhance understanding of disaster risk is as follows. First, we examine the link between socio-economic disadvantage and wildfire hazard exposure in Australia utilising the broad spatial coverage of the Black Summer fires at the Statistical Area 1 (SA1) level, which is the second smallest geographical unit designated in the Australian Statistical Geography Standard (ASGS) (Australian Bureau of Statistics 2016). This is the first large-scale quantitative study in Australia in the context of an unprecedented extreme wildfire event. Second, in addition to exploring the link at the national level, we examine whether wildfire hazard exposure is correlated with remoteness of the settlements. Wigtil et al. (2016) examined spatial variation of the link but only at two levels, i.e., wildland-urban interface and non-wildland-urban interface. We examine this relationship at five levels of remoteness (i.e., major cities, inner regional, outer regional, remote and very remote areas). Third, it uses a novel approach to measure wildfire exposure. The most used indicator for wildfire exposure is fire extent, i.e., the spatial coverage of a fire (Lindenmayer and Taylor 2020; Jolly et al. 2015) or settlement proximity to a wildfire (Hazlett and Mildemberger 2020). We use a multidimensional index to measure wildfire hazard exposure that accounts for both fire extent and fire proximity to settlements. Finally, our study uses *actual* fire hazard exposure (instead of *potential* or *simulated* hazard exposure) of a large spatial variation covering a combined area of approximately 12 million hectare that was burned at different times. Thus, while there was similarity in terms of high fire hazard conditions in different locations, the fires that occur were multiple and separate events.

2. Theoretical Framework

The disaster literature defines risk (expectation of loss) as a function of hazard (potential for loss or harm from adverse events), vulnerability (susceptibility to losses from adverse events) and exposure (the presence of population or other elements of interest in a location which is susceptible to hazard) (IPCC 2014). Hazard is the future or possible occurrence of a natural or human induced event which has the potential to inflict harm on vulnerable and exposed elements (IPCC 2014). Vulnerability is the propensity of a system to suffer negative consequences when impacted by adverse events (IPCC 2014). The degree of vulnerability depends on a system's sensitivity (e.g., a house built with highly flammable materials) and adaptive capacity (e.g., personal firefighting equipment, purchase of adequate insurance) (IPCC 2014). According to these conceptualizations, vulnerability is a pre-existing and internal property of a system while exposure represents an external property. Both vulnerability and exposure are necessary elements but, by themselves, are not sufficient determinants of risk.

A key finding of the existing disaster literature is that the biophysical properties of an area alone do not fully determine hazard exposure and vulnerability to climate related natural disasters. Hazard exposure is also determined by a broad set of socio-economic and demographic factors such as wealth, social status, age, gender, ethnicity (IPCC 2014). In this perspective, and according to Cutter's Hazards-of-Place (HOP) Model (Cutter 1996), exposure to hazard is a complex interaction of socio-economic and biophysical conditions of a place. For instance, in the context of wildfires, the frequency, severity and nature of wildfire in a location are, in part, determined by land use (e.g., area in forest or grassland), settlement patterns (e.g., along a river or on a ridge), vegetation management (e.g., degree of hazard reduction) and compliance with fire warnings (Hawbaker et al. 2013; Syphard et al. 2013).

Socio-economic factors may influence wildfire hazard exposure in four ways. First, socio-economically disadvantaged communities may live in more wildfire prone locations due to housing affordability (Alexandra 2020). Second, allocation of public resources for preparedness, hazard reduction and suppression may disproportionately favour the most advantaged communities (Royal Commission into National Natural Disaster Arrangements 2020). For instance, evidence from the United States shows that poor households are less likely than non-poor households to benefit from federal programs designed to reduce wildfire risk (Lynn and Gerlitz 2005; Brunet et al. 2001). Third, socio-economically advantaged communities may be able to commit greater volunteer time to fire suppression (McLennan and Birch 2005) and, during a fire season that continues for a long time, volunteer firefighter numbers may decline proportionally more in areas where people's incomes are more reliant on small businesses or casual or hourly employment (Volunteering Australia 2020). Finally, ignition risk caused by malicious intent and/or negligence may be lower in socially advantaged communities. For instance, poor academic achievements, substance abuse, unemployment, the absence of a mother or father

figure through childhood, are common characteristics of arsonists in Australia (Bell et al. 2018; Ellis-Smith et al. 2019). Such characteristics are also relatively more prevalent in socio-economically disadvantaged than advantaged communities.

3. Data

3.1. Measuring wildfire exposure

Fire data were collected from the National Indicative Aggregated Fire Extent (NIAFE) dataset published by the Department of Agriculture, Water and the Environment (2020) and was developed using inputs from the national Emergency Management Spatial Information Network Australia (EMSINA) and other supplementary sources, such as relevant state and territory agencies and the Northern Australian Fire Information website. These data present a record of total fire extent starting from 1 July 2019 to 25 May 2020.

Our outcome variable of interest is wildfire hazard exposure. Wildfire hazard exposure is operationalised as the interaction between fire extent and proximity of fire to settlements. Previous studies operationalised this construct using fire extent (i.e., area burnt) (Ager et al. 2018) or residents' proximity to a wildfire (Hazlett and Mildenerger 2020). The reason for combining these two indicators is that fire extent alone does not fully capture wildfire hazard. For instance, it is possible that a large share of an area was burnt, but the hazard exposure was low because the fire was far away from settlements. We undertake separate analyses using fire extent and fire proximity to settlements as dependent variables to test the robustness of our findings.

Our focus is on the immediate effects of wildfires (extent and proximity) rather than on either the short or long-term health consequences of smoke and which may exceed the direct loss of life from fire. For example, the Black Summer wildfires are estimated to have caused more than 400 excess deaths (any smoke-related cause), more than 1,100 hospitalisations for cardiovascular problems and more than 1,300 presentations to emergency departments with asthma over the period 1 October 2019 to 10 February 2020 (Arriagada et al. 2020).

Fire extent is a continuous variable that is calculated as the percentage of burnt area in a SA1. Proximity is an ordinal variable comprising eight integer values ranging from 1 to 8. A high value of proximity indicates low distance between a settlement and a fire. Wildfire hazard exposure is an index generated by interacting fire extent and fire proximity. The index takes a value between 0 and 800. A high value of wildfire exposure means both fire extent and fire proximity are high and vice versa.

3.2. Index of Relative Socio-Economic Disadvantage (IRSED)

Our key independent variable is the Index of Relative Socio-Economic Disadvantage (IRSED). The IRSED is one of the four indices of Socio-Economic Indexes for Areas (SEIFA) prepared by the Australian Bureau of Statistics. Using information from Census data, SEIFA assigns scores and classifies each SA1 based on the collective socio-economic advantage and disadvantage of its population. SEIFA scores are not available for areas that do not have sufficient population or have a high rate of missing responses for the key variables. SEIFA include the following four indices:

- Index of Relative Socio-Economic Disadvantage (IRSED)
- Index of Relative Socio-Economic Advantage and Disadvantage (IRSEAD)
- Index of Economic Resources (IER)
- Index of Education and Occupation (IEO).

The list of variables used to generate each of these indices are presented in Supplementary Material (SM) 1. Note that the values of the variables used to construct the SEIFA indices are not available in the dataset.

Given that the focus of this study is to explore the link between socio-economic disadvantage and wildfire hazard exposure, we use the IRSED for our main analysis. The IRSED is presented as raw scores and deciles. Deciles divide SA1s into ten groups based on their raw scores. We use deciles for our main analysis because it allows us to test for non-linearity in the relationship. As per the original coding, a low value of the IRSED means a high proportion of relatively disadvantaged population in an area. For example, a low value of the IRSED means a high proportion of the population earn a low income, live in a private dwelling with one or no bedrooms and/or a higher percentage of household with children and a jobless parent and/or a high incidence of no internet access and/or poor English language proficiency and so on (Australian Bureau of Statistics, 2018a). For ease of interpretation and consistency with the concept of disadvantage, we recode IRSED deciles in reverse order as IRSED_r. For example, IRSED decile 10 is coded as IRSED_r decile 1, decile 9 is coded as 2 and so on.

3.3. Other Data

The Forest Fire Area Data for 2011–2016[1] (Department of Agriculture, Water and the Environment 2019a) is used to control for historical wildfire hazard exposure of SA1s. This dataset documents the number of times an area within an SA1 experienced fire from 2011–2016. Other relevant features of SA1s, such as remoteness, forest cover etc. are collected from a variety of government sources (see SM2 for the list of data sources).

4. Empirical Framework

The empirical analyses examined the correlation between wildfire hazard exposure and the recoded deciles of the socio-economic disadvantage of communities (i.e., the *IRSED_r*). Our null and alternative hypotheses were:

H_0 : Wildfire hazard exposure is uncorrelated with *IRSED_r*.

H_A : Wildfire hazard exposure is correlated with *IRSED_r*.

The following reduced-form fixed-effects regression model is used to test this hypothesis:

$$\text{Wildfire Exposure}_i = \beta_1 \text{IRSED}_r_i + \beta_2 X_i + \lambda + u_i \quad (1)$$

In equation (1), i stands for SA1. *Wildfire Exposure* is the interaction of fire extent (i.e., total burnt area as a percentage of the total size of a SA1) and proximity of fire to settlements. *IRSED_r* is recoded deciles (i.e., a higher value means higher disadvantage). X is a vector of SA1-level control variables including population density, population density squared, average fire extent during 2011–2016, remoteness, forested area as a percentage of the total area, distance from the coast, and presence of a fire station and number of business. The term λ is SA3 fixed effects, which is the most parsimonious specification possible given the nature of the data[1]. It captures a wide array of unobserved characteristics at the SA3-level that are likely to be correlated with *IRSED_r* and wildfire hazard exposure. For example, they capture variation in climatic pattern, drought condition, vegetation mosaic, infrastructure condition and other factors related to location. The robust error term u_i may include SA1 level unobserved factors; we assume that the variables included in X are uncorrelated with *IRSED_r*.

4.2 Robustness tests

First, we re-ran our original specification keeping wildfire hazard exposure as the dependent variable but replacing our key independent variable, i.e., *IRSED_r*, by alternative measures of socio-economic disadvantage, being *IRSEAD_r*, *IER_r* and *IEO_r*. These models are estimated to check whether the possible socio-economic disadvantage and wildfire hazard exposure association is sensitive to the way socio-economic disadvantage is measured. Second, we re-ran the specification outlined in equation 1 using wildfire extent and proximity separately as indicator of wildfire exposure. These two models test whether the hypothesised relationship between wildfire hazard exposure and socio-economic disadvantage holds when wildfire hazard exposure is operationalised using fire extent or fire proximity to settlement.

5. Results

5.1 Regression results

Our analysis sample includes all SA1s that experienced fire incidents during 2019–2020 fire season and for which SEIFA data are available. The analysis sample excludes observations from the Northern Territory and northern areas of Western Australia, South Australia and Queensland[1] as burned area in northern Australia represents controlled fires that are part of the natural landscape management dynamics (Department of Agriculture, Water and the Environment 2020). Table 1 presents the descriptive statistics of key variables for the analysis sample.

The main results from Tobit regression models are presented in Table 2. We use Tobit models because our dependent variable is censored. More specifically, the *Wildfire Exposure* index cannot take negative value or a value greater than 800. Columns 1 and 2 present the estimated coefficients obtained, respectively, from a bivariate and a full model.

In column 1, all coefficients for the nine *IRSED_r* deciles are positive and significant at the 1% level. In column 2, the coefficients remain statistically significant at least at the 5% level, except for the coefficient of decile 2 when control variables and SA3 fixed effects are accounted for. Each coefficient of the *IRSED_r* decile estimates the difference in *Wildfire Exposure* index value between decile 1 (the most advantaged group) and the corresponding decile. For example, in column 2, the estimated coefficient of decile 3 is 77.300 ($p < 0.05$). This coefficient implies that, on average, the SA1s that are classified as decile 3 experienced 77.310 points higher wildfire exposure relative to the SA1s that were classified as decile 1, all else constant. The *Wildfire Exposure* index scores of the SA1s classified as decile 8, 9 and 10 (most disadvantaged groups), on average and all else being constant, are 106.500, 96.220 and 144.400 points higher than the SA1s of decile 1 (the most advantaged SA1s), respectively. The remaining coefficients can be interpreted in a similar way.

To visualise the difference in wildfire exposure across *IRSED_r* deciles, we plotted the mean and 95% confidence intervals of the predicted values (evaluated at the mean values) of wildfire hazard exposure across *IRSED_r* deciles (Figure 1). The figure shows that the predicted value of the wildfire exposure index is lowest for decile 1 (the least disadvantaged SA1s). The average predicted wildfire exposure index significantly ($p < 0.01$) increases for decile 2. The predicted wildfire exposure index score does not vary significantly among deciles 2 to 7 which implies that the SA1s of these deciles were more or less equally exposed to wildfires. The wildfire exposure index scores shift up significantly ($p < 0.001$) for SA1s that are classified as *IRSED_r* deciles 8, 9 and 10 implying that the most disadvantaged SA1s were most exposed to Black Summer fires. Note that the

differences in predicted wildfire hazard exposure scores between these three most disadvantaged deciles and the rest of the seven deciles are statistically insignificant. These results imply the presence of non-linearity in the interlinkage of wildfire hazard exposure and socio-economic disadvantage.

Turning our attention to the control variables (Table 2), wildfire hazard exposure has a significant positive correlation with forest cover. This is because forested areas have more fuel load and are, hence, more prone to large fire extent during a wildfire. The history of wildfire exposure (i.e., average percentage of area burnt from 2011–2016) also has a significant positive correlation with 2019–2020 wildfire exposure. This implies that areas prone to wildfires in a regular year were more likely to experience a high wildfire hazard exposure in 2019–2020. The coefficient for distance from the coast has a significant negative correlation with wildfire hazard exposure at the 5% level, i.e., all else being constant, wildfire hazard exposure in inland areas was significantly *lower* than coastal areas.

Among other control variables, the coefficient for population density has a significant positive correlation with wildfire hazard at the 10% level in column 2, i.e., densely populated areas were significantly more exposed to wildfires. The number of fire stations is not a significant covariate of wildfire hazard exposure but the coefficient of the number of businesses in an area is negative and significant at the one percent level in column 2. This means that the areas that had high business activities were significantly less exposed to wildfire hazard.

The coefficients for remoteness are positive and significant at the 1% and 5% level in column 2. Here, the base level for remoteness is ‘major cities’. Our finding from the estimated coefficients is that, as expected, major city areas experienced significantly lower wildfire hazard exposure than inner and outer regional areas and remote and very remote areas. Note also that the SA1s with less wildfire hazard exposure may still incur a substantial smoke-related health burden associated with wildfires that may be located a large distance away from them (Arriagada et al. 2020).

5.2 Robustness tests

SM3 presents the results of three Tobit regression models in columns 1, 2 and 3 that use *IRSEAD_r*, *IER_r* or *IEO_r* deciles as the key independent variable, respectively. The coefficients of *IRSEAD_r* (SM3, column 1) are all positive (except for the coefficient of decile 2) but only the coefficient for decile 10 (most disadvantaged SA1s) is significant ($p < 0.05$). All coefficients of *IER_r* (SM3, column 2) are positive and significant at least at the 10% level (except for the coefficient of decile 2). All coefficients of *IEO_r* (SM3, column 3) are positive and significant at least at the 10% level (except for the coefficient of decile 2). These findings suggest that the interlinkage between socio-economic disadvantage and wildfire exposure is, in general, consistent across various measures of socio-economic disadvantage. The strength of the positive correlation may vary depending on the way socio-economic disadvantage is operationalised.

In SM4, column 1, we present the results of a Tobit regression model that uses wildfire extent as the dependent variable instead of the interaction of wildfire extent and proximity. *IRSED_r* deciles are used as the key independent variable. Consistent with our main findings (presented in Table 2), the results presented in SM4 and column 1 show wildfire extent is significantly higher for all larger *IRSED_r* deciles relative to *IRSED* decile 1, all else being constant. In SM4, column 2, we present the results of an ordered probit regression model with wildfire proximity to settlements as the dependent variable. We used an ordered probit regression model because proximity is an ordered variable varying between 1 (furthest) and 8 (closest). The coefficients for *IRSED_r* are positive and significant at least at the 10% level for the top three deciles (most disadvantaged SA1s) implying that the most disadvantaged SA1s were located in closest proximity to wildfires compared to less disadvantaged SA1s.

5.3 Results of the spatial analysis

Figures 1, 2 and 3 present the spatial distribution for the interlinkage of *IRSED_r* scores and wildfire hazard exposure in Australia, New South Wales (NSW) and Victoria, respectively. This analysis explores whether the interlinkage between socio-economic disadvantage and wildfire hazard exposure is specific to remoteness of a location. We categorise the quantitative wildfire hazard exposure into three levels for ease of mapping [low (=1), medium (=2) and high (=3)] and *IRSED_r* deciles into three levels as *IRSED_r3* [least disadvantaged (=1), disadvantaged (=2) and most disadvantaged (=3)].

The qualitative levels are based on the quantitative values for wildfire hazard exposure index. Low wildfire hazard exposure is when the wildfire hazard exposure index value for an area is less than 100. Wildfire hazard exposure index values greater than 100 but less than 300 are categorised as a medium and those greater than 300 are categorised as a high. *IRSED_r* deciles 1–4 are classified as the least disadvantaged group, deciles 4–6 are grouped as disadvantaged, and deciles 7–10 are categorised as most disadvantaged.

According to Figure 2, the wildfire hazard exposure and *IRSED_r3* interlinkage is most pronounced in the eastern states of Australia, specifically NSW and Victoria. Wildfire hazard exposure in these two states was significantly higher than Western and South Australia which is consistent with previous findings of spatial distribution of wildfire hazard exposure in Australia (Lindenmayer and Taylor 2020). See SM5 and SM6 for the spatial distribution of wildfire hazard exposure across states.

Focusing on NSW (Figure 3), the 2019–2020 wildfires were a major city, inner and outer regional phenomenon. Remote and very remote areas of NSW were not severely hit. In Victoria (Figure 4), the 2019–2020 wildfire hazard was more prominent in outer regional and remote areas, with the most pronounced wildfire hazard and *IRSED_r3* interlinkage.

To understand how remoteness[2] intersects with the wildfire hazard exposure and IRSED interlinkage, we estimated the mean value of wildfire hazard exposure for *IRSED_r3* categories across five regional strata in NSW and Victoria. The results of the analysis are presented in Table 3. Column 1 presents the results for the NSW sample. In major city areas in NSW, wildfire hazard did not vary significantly across *IRSED_r3* levels. In inner regional areas, disadvantaged ($p < 0.001$) and the most disadvantaged ($p < 0.01$) communities experienced significantly higher wildfire hazard exposure than the least disadvantaged areas. However, the wildfire exposure level of disadvantaged and most disadvantaged communities of inner regional NSW did not vary significantly ($p = 0.871$). The largest difference in wildfire hazard exposure across *IRSED_r3* is observed for the outer regional areas of NSW. The most disadvantaged areas in the outer regional NSW were exposed to the highest wildfire hazard among all remoteness-*IRSED_r3* combinations. The difference of this group's wildfire exposure with the rest of the groups is significant at the 1% level.

Next, we examined the spatial distribution of the wildfire hazard exposure and *IRSED_r3* interlinkage in Victoria. Like NSW, the most disadvantaged SA1s experienced significantly higher wildfire hazard exposure in outer regional and remote areas, relative to the least disadvantaged and disadvantaged SA1s in those locations.

6. Possible Mechanisms

Wildfire risk management in Australia is comprised of three components: (a) prevention, i.e., reduction of fuel load (at lower danger fire weather conditions) and also ignitions; (b) physical preparation to minimise spread, i.e., creating firebreaks, access roads, and water supply infrastructure; (c) use of early detection systems and rapid deployment of firefighters and equipment.

Prevention and physical preparation are classified as hazard reduction activities. Australia's disaster resilience framework is centred on the idea of shared responsibility that requires local community and emergency service agencies to work together for both hazard reduction and fire suppression activities (McLennan and Handmer 2012). This approach shifts the responsibility from the central authority to individuals and the local community with the assumption that communities and individuals at risk understand the risk and have the capacity to prevent, prepare and respond to it.

The first possible causal mechanism for why socio-economically disadvantaged communities suffered greater wildfire hazard exposure in the Black Summer fires could be differences in fire suppression capability among communities and the level of support received from the government. This difference may arise because firefighting service in Australia is run by professional and volunteer firefighters. In general, professional firefighters who are trained to fight structural fires are deployed in higher density areas with more valuable buildings. For instance, it has been observed in the US that where residents have a greater willingness to pay (in terms of property taxes) for these services and demand higher levels of fire protection because their properties are, in general, more valuable (Brunet et al. 2001).

Professional firefighters in NSW, one of the worst-affected states in the Black Summer fires, number some 7,000, and are paid for by the state government and operate under a single state structure (Fire and Rescue NSW). Similar arrangements exist in other Australian states. Professional firefighting services are supplemented by state-supported rural part-time fire services based in rural communities that comprise, in NSW alone, more than 70,000 volunteers (Langford 2019). Australian states provide equipment and training to the volunteers as part of the rural fire services in each state, and there is a longstanding and proud tradition of volunteers in rural communities providing much of the human power for rural fire prevention. Rural firefighters also have a comprehensive understanding of local weather condition and they deal with seasonally occurring large-scale landscape fires in difficult conditions.

Professional firefighters can also be deployed in rural and remote areas if rural firefighting capability is deemed inadequate. Professional firefighters deliver a higher-quality service, as measured by response and losses per reported fire relative to volunteer firefighters for whom a national standard of competency requirements and accreditation protocol are currently lacking (Brunet et al. 2001; Royal Commission into National Natural Disaster Arrangements 2020). Thus, residents of peri-urban and rural-urban interface, with professional firefighting services and higher median incomes, should be expected to receive a better firefighting service than persons residing in regional or rural areas (who, typically, have a rural firefighting service and lower median incomes). Indeed, using US data, Brunet et al. (2001) find a significant negative relationship between median household income, average years of education and population density and the proportion of residents in state counties that are serviced by volunteer firefighters.

It is possible that the relative advantage of a professional firefighting service may be represented in terms of a gradient of resources or quality in terms of volunteer firefighting services in rural services without professional firefighters. In other words, more disadvantaged and smaller rural communities may receive a lower level of rural firefighting service, in general, than larger, more affluent rural communities. If this is the case, then the disadvantage may arise from either the allocation of equipment at a state level, prioritisation of fire mitigation services such that larger communities are prioritised over smaller communities when resources are scarce relative to need, or other factors concerning volunteering.

Another possible way to explain the socio-economic disadvantage and wildfire hazard exposure interlinkage is that disadvantaged communities live in hazardous locations because of their low property values. However, our spatial analysis refutes this hypothesis for Australia. Our model controls for the history of wildfire hazard exposure and the percentage of forest cover in an area. This means that the poverty and wildfire hazard association estimated by our regression model is independent of the history of wildfire hazard exposure and forest density. Thus, location alone is unlikely to be a potential driver of the socio-economic disadvantage and wildfire hazard interlinkage.

A third pathway through which socio-economically disadvantaged communities might face a greater wildfire hazard exposure is arson risk. Various statistics suggest that 40–50% of the fires in Australia are deliberately lit, and another 47% are accidental, i.e., failure to comply with guidelines (Beale and Jones 2011). Arsonists are predominantly male youth and unemployed middle-aged men with a history of mental illness, substance abuse and criminal records (Bell et al. 2018; Ellis-Smith et al. 2019). Disadvantaged communities are more likely to have a higher proportion of such individuals than relatively less-disadvantaged communities, increasing their exposure to wildfire hazard. However, fire service authorities in NSW and Victoria confirmed that only a small proportion (<1%) of the 2019–2020 wildfires were deliberately lit, with most started by lightning (Nguyen et al. 2020). Thus, in our view, fire source is *not* a likely explanation of the positive relationship between socio-economic disadvantage and wildfire hazard exposure.

A final possible pathway could be heterogeneity in hazard reduction capabilities across communities. The report of the Royal Commission into National Natural Disaster Arrangements (2020) echoes a similar concern. The Royal Commission find that, although disaster preparedness, response and recovery are responsibilities of state and territory governments, there is a practice of delegating these responsibilities to local governments who are not necessarily adequately resourced to meet those responsibilities. The Royal Commission also noted that resource sharing arrangements between local and state/territory governments and among local governments to support surge capacity are in many cases informal, ad-hoc and inadequate. Knowledge about local governments' capacity and capabilities to manage natural disasters is also insufficient at the state/territory government level which impedes efficient resource allocation for disaster risk reduction and response.

7. Discussion

The objective of this study was to examine the interlinkage between socio-economic disadvantage and wildfire hazard exposure in the context of the 2019–2020 Black Summer fires of Australia. Consistent with Cutter's Hazards-of-Place (HOP) Model, our analyses reveal the actual hazard exposure varies significantly within geographical areas that have the similar biophysical conditions but vary widely in terms of socio-economic characteristics. Our findings are consistent with studies that investigated a similar link between hazard exposure and poverty or socio-economic disadvantage for floods, cyclones and hurricanes (Brouwer et al. 2007; Akter and Mallick 2013; Elliott and Pais 2006; McDougall 2007) but our findings differ to the recent studies from the United States (Davies et al. 2018; Wigtil et al. 2016).

Our results reveal considerable non-linearity in the correlation between wildfire hazard exposure and socio-economic disadvantage. This is a novel contribution of our study. Previous studies that examined the relationship between socio-economic disadvantage and environmental risk exposure, rarely tested the non-linear pattern of the interlinkage. We find that the wildfire hazard exposure did not increase linearly with an increase in socio-economic disadvantage. The difference in wildfire hazard exposure was most prominent between the SA1s of the top three disadvantaged deciles and the remaining seven deciles. In particular, the variation in wildfire hazard exposure significantly differs between the most advantaged SA1s (decile 1) and relatively less advantaged SA1s (deciles 2–7). The difference in wildfire hazard exposure between most disadvantaged SA1s and the rest remains consistent across all measures of socio-economic disadvantage tested in our analyses although the magnitude of the correlations varies across measures of socio-economic disadvantage.

As expected, forest and population density are significantly positively correlated with 2019–2020 wildfire hazard exposure. High forest density means high fuel load and high population density increases ignition risks due to high level of human activities in an area. We also find a history of hazard exposure is significantly and positively correlated with Black Summer fire hazard exposure. After controlling for all these confounders, socio-economic disadvantage remains a significant correlate of the wildfire hazard exposure.

Our spatial analyses reveals that the interlinkage between wildfire hazard exposure and socio-economic disadvantage is not a major city phenomenon. This interlinkage is most prominent in inner regional, outer regional, and remote Australia. We hypothesise this is because of the availability of professional firefighting services in major city areas compared to the rest of the geographical areas where fire suppression is done by volunteer firefighters in a large landscape under highly difficult weather conditions. This is further evidenced by our regression result that shows areas with a high-level business activity are less exposed to wildfire hazard.

We used a novel wildfire hazard exposure index to capture two dimensions of wildfire hazard exposure, namely, fire extent and fire proximity to settlements. This operationalisation of wildfire hazard can be used, where applicable, in future analyses for a more comprehensive understanding of wildfire hazard exposure of communities. We also find that the interlinkage between wildfire hazard exposure and socio-economic disadvantage remains positive and significant even when the wildfire hazard exposure is operationalised using either wildfire extent or wildfire proximity.

8. Conclusions

Our findings make an important contribution to the understanding disaster risk, the first priority area for action of the Sendai Framework for Disaster Risk Reduction 2015–2030 which urges for a greater integration of scientific knowledge and understanding on all dimensions of disaster risk to design appropriate preparedness and effective response strategies. Contrary to the findings reported by the studies from the United States, our results reveal that socio-economically disadvantaged communities experienced highest wildfire exposure during 2019–2020 fire season in Australia.

Our findings establish that this link between socio-economic disadvantage and wildfire exposure was least prominent in major cities but was prevalent in the fire affected locations of inner and outer regional locations and in rural Australia.

In disaster risk management and planning contexts, the built environment receives the highest priority when it comes to exposure analysis. Socio-economic disadvantage is taken into account primarily for vulnerability analysis (in terms of sensitivity and adaptive capacity) (Royal Commission into National Natural Disaster Arrangements 2020). Our study reveals that socio-economic disadvantage of communities are strong determinants of disaster exposure; hence, they should also be taken into careful consideration when developing strategies to reduce disaster risks. Additionally, as noted by others (Bowman et al. 2020), the spatial mapping of wildfire extent, wildfire proximity to settlements in a national database is another important way to improve wildfire prevention and planning.

Future studies should test the potential pathways through which the hazard exposure and socio-economic disadvantage link is determined. Future studies should also explore the interlinkages among the other components of wildfire risk, namely, hazard and vulnerability (i.e., sensitivity and adaptive capacity). This should offer a more holistic understanding of the spatial distribution of wildfire risk and socio-economic vulnerability in Australia. Additionally, our wildfire hazard exposure model does not account for smoke exposure. Smoke exposure not only leads to health risks but also inflicts economic costs due to a reduction in demand for services in areas that are not directly impacted by the fire. Thus, future analyses should also account for smoke pollution to capture a broader understanding of the link between wildfire hazard exposure and socio-economic disadvantage.

References

- Abram NJ, Henley BJ, Sen Gupta A et al (2021) Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Commun Earth Environ* 2(1):1-17. <https://doi.org/10.1038/s43247-020-00065-8>
- Ager AA, Palaiologou P, Evers CR, Day MA, Barros AM (2018) Assessing transboundary wildfire exposure in the southwestern United States. *Risk Analysis* 38(10):2105-2127. <https://doi.org/10.1111/risa.12999>
- Akter S, Mallick B (2013) The poverty–vulnerability–resilience nexus: evidence from Bangladesh. *Ecol Econ* 96:114-124. <https://doi.org/10.1016/j.ecolecon.2013.10.008>
- Alexandra J (2020) Burning Bush and Disaster Justice in Victoria, Australia: Can Regional Planning Prevent Bushfires Becoming Disasters?. In: *Natural Hazards and Disaster Justice*, Palgrave Macmillan, Singapore, pp 73-92.
- Arriagada NB, Palmer AJ, Bowman DM, Morgan GG, Jalaludin BB, Johnston FH (2020) Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia. *Med. J. Aust* 213(6):282-283. <https://doi.org/10.5694/mja2.50545>
- Australian Bureau of Statistics (2016) Australian statistical geography standard (ASGS): volume 1 - main structure and greater capital city statistical areas, July 2016. Statistical Area Level 1 (SA1) ASGS Edition 2016 in .csv format. <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%202016?OpenDocument>. Accessed 5 July 2020.
- Australian Bureau of Statistics (2018a) Census of population and housing: socio-economic indexes for areas (SEIFA), Australia, 2016. <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/2033.0.55.0012016?OpenDocument>. Accessed 10 June 2020
- Australian Bureau of Statistics (2018b) Technical paper: socio-economic indexes for areas (SEIFA) 2016. Canberra. <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/2033.0.55.0012016?OpenDocument>. Accessed 30 June 2020.
- Australian Bureau of Statistics (2018c) Australian statistical geography standard (ASGS): volume 5 - remoteness structure, July 2016. <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.005July%202016?OpenDocument> Accessed 5 July 2020.
- Beale J, Jones W (2011) Preventing and reducing bushfire arson in Australia: a review of what is known. *Fire Technol* 47(2):507-518. <https://doi.org/10.1007/s10694-010-0179-4>
- Bell R, Doley R, Dawson D (2018) Developmental characteristics of firesetters: Are recidivist offenders distinctive?. *Legal Criminol Psychol* 23(2):163-175. <https://doi.org/10.1111/lcrp.12135>
- Boer MM, de Dios VR (2020) Unprecedented burn area of Australian mega forest fires. *Nat Clim Chang* 10(3): 171-172. <https://doi.org/10.1038/s41558-020-0716-1>
- Bowman D, Williamson G, Yebra M, Lizundia-Loiola J, Lucrecia Pettinari M, Shah S, Bradstock R, Chuvieco E (2020) Wildfires: Australia needs national monitoring agency. *Nature*. <https://www.nature.com/articles/d41586-020-02306-4>

- Brouwer R, Akter S, Brander L, Haque E (2007) Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Anal* 27(2):313-326. <https://doi.org/10.1111/j.1539-6924.2007.00884.x>
- Brunet A, DeBoer L, & McNamara KT (2001) Community choice between volunteer and professional fire departments. *Nonprofit Volunt Sect Q* 30(1):26-50. <https://doi.org/10.1177/0899764001301002>
- Bureau of Meteorology (BoM) and CSIRO (2018). State of the Climate 2018. <http://www.bom.gov.au/climate/current/annual/aus/>. Accessed 25 July 2020
- Cottrell A (2005) Communities and bushfire hazard in Australia: more questions than answers. *Global Environmental Change Part B: Environmental Hazards* 6(2):109-114. <https://doi.org/10.1016/j.hazards.2005.10.002>
- Cutter SL (1996) Vulnerability to environmental hazards. *Prog Hum Geogr* 20(4):529-539. <https://doi.org/10.1177/030913259602000407>
- Davies IP, Haugo RD, Robertson JC, Levin PS (2018) The unequal vulnerability of communities of colour to wildfire. *PLoS One* 13(11):e0205825. <https://doi.org/10.1371/journal.pone.0205825>
- Department of Agriculture, Water and the Environment (2019a) Fires in Australia's forests 2011–16 (2018). Australian Government. <https://www.agriculture.gov.au/abares/forestsaustralia/forest-data-maps-and-tools/spatial-data/forest-fire> Accessed 7 April 2020
- Department of Agriculture, Water and the Environment (2019b) Forests of Australia (2018) Australian Government. <https://www.agriculture.gov.au/abares/forestsaustralia/forest-data-maps-and-tools/spatial-data/forest-cover> Accessed 7 April 2020
- Department of Agriculture, Water and the Environment (2020) National indicative aggregated fire extent dataset v20200428. Australian Government. <http://www.environment.gov.au/fed/catalog/search/resource/downloadData.page?uuid=%7B9ACDCB09-0364-4FE8-9459-2A56C792C743%7D>. Accessed 8 April 2020
- Elliott JR, Pais J (2006) Race, class, and Hurricane Katrina: social differences in human responses to disaster. *Soc Sci Res* 35(2):295-321. <https://doi.org/10.1016/j.ssresearch.2006.02.003>
- Ellis-Smith T, Watt BD, Doley RM (2019) Australian arsonists: an analysis of trends between 1990 and 2015. *Psychiatr Psychol Law* 26(4):593-613. <https://doi.org/10.1080/13218719.2018.1556131>
- Filkov AI, Ngo T, Matthews S, Telfer S, Penman TD (2020) Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience* 1: 44-56. <https://doi.org/10.1016/j.jnlssr.2020.06.009>
- Foster H, Towers B, Whittaker J, Handmer J, Lowe T (2013) Peri-urban Melbourne in 2021: changes and implications for the Victorian emergency management sector. *The Australian Journal of Energy Management* 28(3):6-11.
- Geoscience Australia (2020) The Australian exposure information platform (AEIP), statistical areas level 1 (SA1) exposure information. Geoscience Australia, Canberra. <http://pid.geoscience.gov.au/dataset/ga/135593> Accessed 3 May 2020.
- Grose MR, Fox-Hughes P, Harris RM, Bindoff NL (2014) Changes to the drivers of fire weather with a warming climate—a case study of southeast Tasmania. *Clim Change* 124(1):255-269. <https://doi.org/10.1007/s10584-014-1070-y>
- Hallegatte S, Vogt-Schilb A, Rozenberg J, Bangalore M, Beaudet C (2020) From poverty to disaster and back: a review of the literature. *Econ Disaster Clim Chang* 4:223-247. <https://doi.org/10.1007/s41885-020-00060-5>
- Hawbaker TJ, Radeloff VC, Stewart SI, Hammer RB, Keuler NS, Clayton MK (2013) Human and biophysical influences on fire occurrence in the United States. *Ecol Appl* 23(3):565-582. <https://doi.org/10.1890/12-1816.1>
- Hazlett C, & Mildenerger M (2020). Wildfire exposure increases pro-environment voting within democratic but not republican areas. *Am Polit Sci Rev* 114(4):1359-1365. <https://doi.org/10.1017/S0003055420000441>
- IPCC 2014 Summary for policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, United Kingdom and New York, NY, USA, pp 1–32.
- Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DM (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat Commun* 6(1):1-11. <https://doi.org/10.1038/ncomms8537>

Koksal K, McLennan J, Every D, Bearman C (2019). Australian wildland-urban interface householders' wildfire safety preparations: 'everyday life' project priorities and perceptions of wildfire risk. *Int J Disaster Risk Reduct* 33:142-154. <https://doi.org/10.1016/j.ijdrr.2018.09.017>

Langford R (2019) Why do Australia's bushfire defences rely on tens of thousands of volunteers?. *The Feed*. <https://www.sbs.com.au/news/the-feed/why-do-australia-s-bushfire-defences-rely-on-tens-of-thousands-of-volunteers> Accessed 25 July 2020.

Leichenko R, Silva JA (2014) Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdiscip Rev Clim Change* 5(4):539-556. <https://doi.org/10.1002/wcc.287>

Lindenmayer DB, Taylor C (2020) New spatial analyses of Australian wildfires highlight the need for new fire, resource, and conservation policies. *Proc Natl Acad Sci USA* 117(22):12481-12485. <https://doi.org/10.1073/pnas.2002269117>

Lynn K, Gerlitz W (2005). Mapping the relationship between wildfire and poverty. URI: <http://hdl.handle.net/1794/2417>

McDougall HA (2007) Hurricane Katrina: A story of race, poverty, and environmental injustice. *Howard Law J* 51:533. SSRN: <https://ssrn.com/abstract=2562571>

McLennan BJ, Handmer J (2012) Reframing responsibility-sharing for bushfire risk management in Australia after Black Saturday. *Environmental Hazards* 11(1):1-15. <https://doi.org/10.1080/17477891.2011.608835>

McLennan J, Birch A (2005) A potential crisis in wildfire emergency response capability? Australia's volunteer firefighters. *Global Environmental Change Part B: Environmental Hazards* 6(2):101-107. <https://doi.org/10.1016/j.hazards.2005.10.003>

Nguyen K, Brunero T, Thomas S, Keane D, Mills N (2020) The truth about Australia's fires – arsonists aren't responsible for many this season. Australian Broadcasting Corporation. <https://www.abc.net.au/news/2020-01-11/australias-fires-reveal-arson-not-a-major-cause/11855022>. Accessed 10 June 2020.

Ojerio R, Moseley C, Lynn K, Bania N (2011) Limited involvement of socially vulnerable populations in federal programs to mitigate wildfire risk in Arizona. *Nat Hazards Rev* 12(1):28-36. [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000027](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000027)

Paveglio TB, Prato T, Edgeley C, Nalle D (2016) Evaluating the characteristics of social vulnerability to wildfire: demographics, perceptions, and parcel characteristics. *Environ Manage* 58(3):534-548. <https://doi.org/10.1007/s00267-016-0719-x>

Paveglio TB, Edgeley CM, Stasiewicz AM (2018) Assessing influences on social vulnerability to wildfire using surveys, spatial data and wildfire simulations. *J Environ Manage* 213:425-439. <https://doi.org/10.1016/j.jenvman.2018.02.068>

Richards L, Brew N, Smith L (2020) 2019–20 Australian bushfires—frequently asked questions: a quick guide. Research Paper Series, 2019–20, Department of Parliamentary Services, Parliament of Australia. https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/rp/rp1920/Quick_Guides/AustralianBushfires. Accessed 20 July 2020.

Royal Commission into National Natural Disaster Arrangements (2020) Royal Commission into National Natural Disaster Arrangements Report. Canberra, Australia. <https://naturaldisaster.royalcommission.gov.au/> Accessed January 20 2021.

Sharples JJ, Geoffrey JC, Fox-Hughes P, Mooney S, Evans JP, Michael-Shawn F, Fromm M, Grierson PF, McRae R, Baker P (2016) Natural hazards in Australia: extreme bushfire. *Clim Change* 139(1): 85-99. <https://doi.org/10.1007/s10584-016-1811-1>

Syphard AD, Massada AB, Butsic V, Keeley JE (2013) Land use planning and wildfire: development policies influence future probability of housing loss. *PloS One* 8(8): e71708. <https://doi.org/10.1371/journal.pone.0071708>

United Nations (2015) Sendai Framework for Disaster Risk Reduction 2015–2030. http://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf Accessed 3 July 2020.

Volunteering Australia (2020) Submission to the Royal Commission into national natural disaster arrangements, 1 May 2020. Canberra. <https://www.volunteeringaustralia.org/wp-content/uploads/VA-Submission-to-Commission-into-National-Natural-Disaster-Arrangements-FINAL.pdf>. Accessed 1 August 2020.

Whittaker J, Handmer J, Mercer D (2012) Vulnerability to bushfires in rural Australia: a case study from East Gippsland. Victoria. *J Rural Stud* 28(2):161-173. <https://doi.org/10.1016/j.jrurstud.2011.11.002>

Wigtill G, Hammer RB, Kline JD, Mockrin MH, Stewart SI, Roper D, Radeloff VC (2016) Places where wildfire potential and social vulnerability coincide in the coterminous United States. *Int J Wildland Fire* 25(8): 896-908. <https://doi.org/10.1071/WF15109>

Tables

Table 1 Descriptive statistics of the key variables

Variables	N	Mean	Std. Dev.	Minimum	Maximum
Wildfire hazard exposure	1,655	115.393	210.947	0	800
IRSED_r decile 1	1,655	0.026	0.161	0	1
IRSED_r decile 2	1,655	0.053	0.224	0	1
IRSED_r decile 3	1,655	0.079	0.270	0	1
IRSED_r decile 4	1,655	0.114	0.319	0	1
IRSED_r decile 5	1,655	0.141	0.348	0	1
IRSED_r decile 6	1,655	0.161	0.367	0	1
IRSED_r decile 7	1,655	0.147	0.354	0	1
IRSED_r decile 8	1,655	0.133	0.340	0	1
IRSED_r decile 9	1,655	0.088	0.284	0	1
IRSED_r decile 10	1,655	0.056	0.230	0	1
Population density (per sq km)	1,655	152.785	430.495	0.001	4240.310
Population density squared	1,655	208557.7	1028668	1.18E-06	1.80E+07
Forest area (%)	1,655	43.994	28.040	0	99.659
Distance from the coast (km)	1655	69.769	90.892	0.048	765.588
Average percentage of area burnt from 2011–2016 (%)	1,655	1.329	2.359	0	17.080
Fire stations	16,55	0.685	0.985	0	6
Total number of business	1,655	80.541	56.924	0	855
Major cities	1,655	0.116	0.320	0	1
Inner regional Australia	1,655	0.467	0.499	0	1
Outer regional Australia	1,655	0.346	0.476	0	1
Remote Australia	1,655	0.051	0.220	0	1
Very remote Australia	1,655	0.015	0.122	0	1

Table 2 Tobit regression results of the correlation between the Index of Relative Socio-economic Disadvantage (IRSED) and wildfire hazard exposure in Australia in 2019–2020

	Wildfire hazard exposure index ^a	
	(1)	(2)
IRSED_r decile 2 ^b	59.760***	50.960
	(20.810)	(35.050)
IRSED_r decile 3 ^b	49.880***	77.300**
	(18.600)	(32.880)
IRSED_r decile 4 ^b	63.390***	72.160**
	(17.980)	(33.080)
IRSED_r decile 5 ^b	81.890***	77.150**
	(17.910)	(32.600)
IRSED_r decile 6 ^b	87.110***	94.430***
	(17.890)	(32.660)
IRSED_r decile 7 ^b	72.610***	68.090**
	(16.980)	(32.820)
IRSED_r decile 8 ^b	120.500***	106.500***
	(20.360)	(34.110)
IRSED_r decile 9 ^b	130.600***	96.220***
	(24.250)	(35.680)
IRSED_r decile 10 ^b	169.300***	144.400***
	(31.450)	(39.320)
Population density (per sq km)	...	0.055*
		(0.030)
Population density square	...	-6.78e-06
		(9.67e-06)
Forest area (%)	...	1.767***
		(0.263)
Distance from the coast (km)	...	-0.288**
		(0.114)
Average percentage of area burnt from 2011–2016 (%)	...	11.610***
		(3.369)
Number of fire stations	...	5.733
		(5.045)
Number of business	...	-0.202***
		(0.078)
Inner regional Australia ^c	...	54.810**
		(25.380)
Outer regional Australia ^c	...	89.600***
		(30.850)
Remote Australia ^c	...	130.300***

		(36.750)
Very remote Australia ^c	...	148.300***
		(43.570)
SA3 fixed-effects	N	Y
Constant	29.340**	-19.710
	(11.590)	(50.660)
Observations	1655	1655

Notes:

^aThe interaction of fire extent (i.e., total burnt area as a percentage of the total size of a Statistical Area (SA)1) and proximity of fire to settlements.
^bBase level=IRSED decile 1 (least disadvantaged). ^cBase level=Major cities. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.
 Analysis is conducted at SA1 level. Analysis sample contains only fire affected SA1s. Excluded areas are all SA1s of Northern Territory, SA4 Outback (North) of Western Australia, SA3 Gascoyne, Goldfields and Mid-West of Western Australia, SA3 Outback (North and East) of South Australia, and SA3 Far North and Outback (North and South) of Queensland.

Table 3 Correlations among remoteness area, categories of socio-economic disadvantage and wildfire hazard exposure during the 2019–2020 bushfires in New South Wales and Victoria

	Wildfire hazard exposure categories ^a	
	NSW	Victoria
Major cities*Disadvantaged ^b	-0.086	...
	(0.092)	
Major cities*Most disadvantaged ^b	0.104	...
	(0.153)	
Inner regional Australia*Least disadvantaged ^b	0.326***	-0.143
	(0.101)	(0.136)
Inner regional Australia*Disadvantaged ^b	0.609***	-0.143
	(0.099)	(0.136)
Inner regional Australia*Most disadvantaged ^b	0.593***	-0.143
	(0.112)	(0.136)
Outer regional Australia*Least disadvantaged ^b	0.142	-0.095
	(0.132)	(0.144)
Outer regional Australia*Disadvantaged ^b	0.339***	0.275
	(0.108)	(0.173)
Outer regional Australia*Most disadvantaged ^b	0.826***	0.607**
	(0.113)	(0.252)
Remote Australia*Least disadvantaged ^b	...	-0.143
		(0.136)
Remote Australia*Disadvantaged ^b	...	0.857
		(0.739)
Remote Australia*Most disadvantaged ^b	...	1.857***
		(0.136)
Constant	1.174***	1.143***
	(0.078)	(0.136)
Observations	840	195
R-squared	0.089	0.346

Notes:

Base level=Major cities*Least disadvantaged

^aBushfire hazard exposure has three levels: low (bushfire hazard index \leq 100), medium (100<bushfire hazard index \leq 300) and high (bushfire hazard index>300). ^bIRSED_r deciles 1–4=least disadvantaged; deciles 4–6=disadvantaged; deciles 7–10=most disadvantaged. Base level=Major cities*Least disadvantaged.

... means insufficient data. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Figures

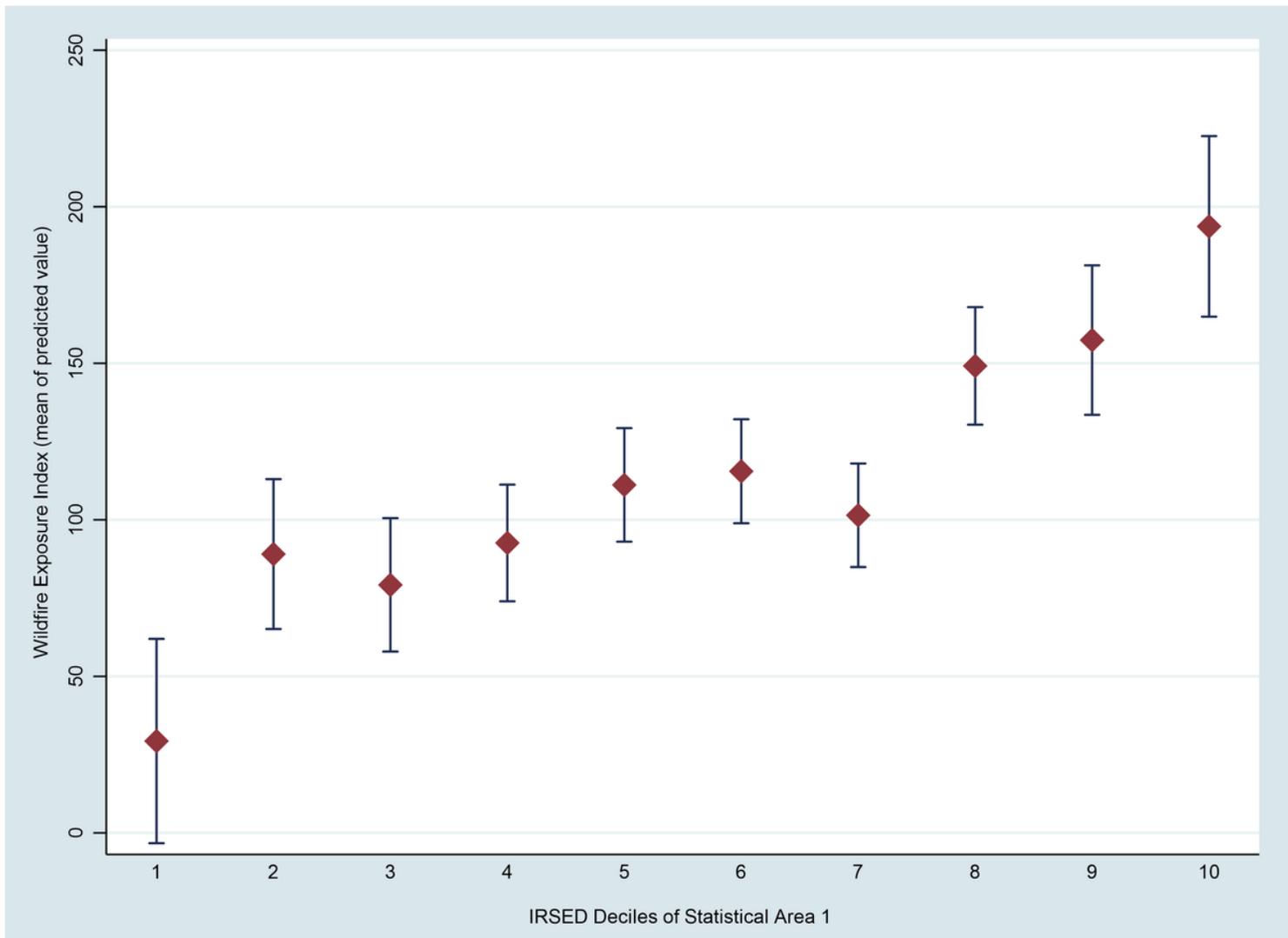


Figure 1

Wildfire exposure index across IRSED deciles of Statistical Areas (SA) 1. Notes: Decile 1=least disadvantaged SA1s and Deciles 10=most disadvantaged SA1s. Analysis sample contains only fire affected SA1s. Excluded regions are all SA1s of Northern Territory, SA4 Outback (North) of Western Australia, SA3 Gascoyne and Mid West of Western Australia, and SA3 Far North and Outback (North) of Queensland.

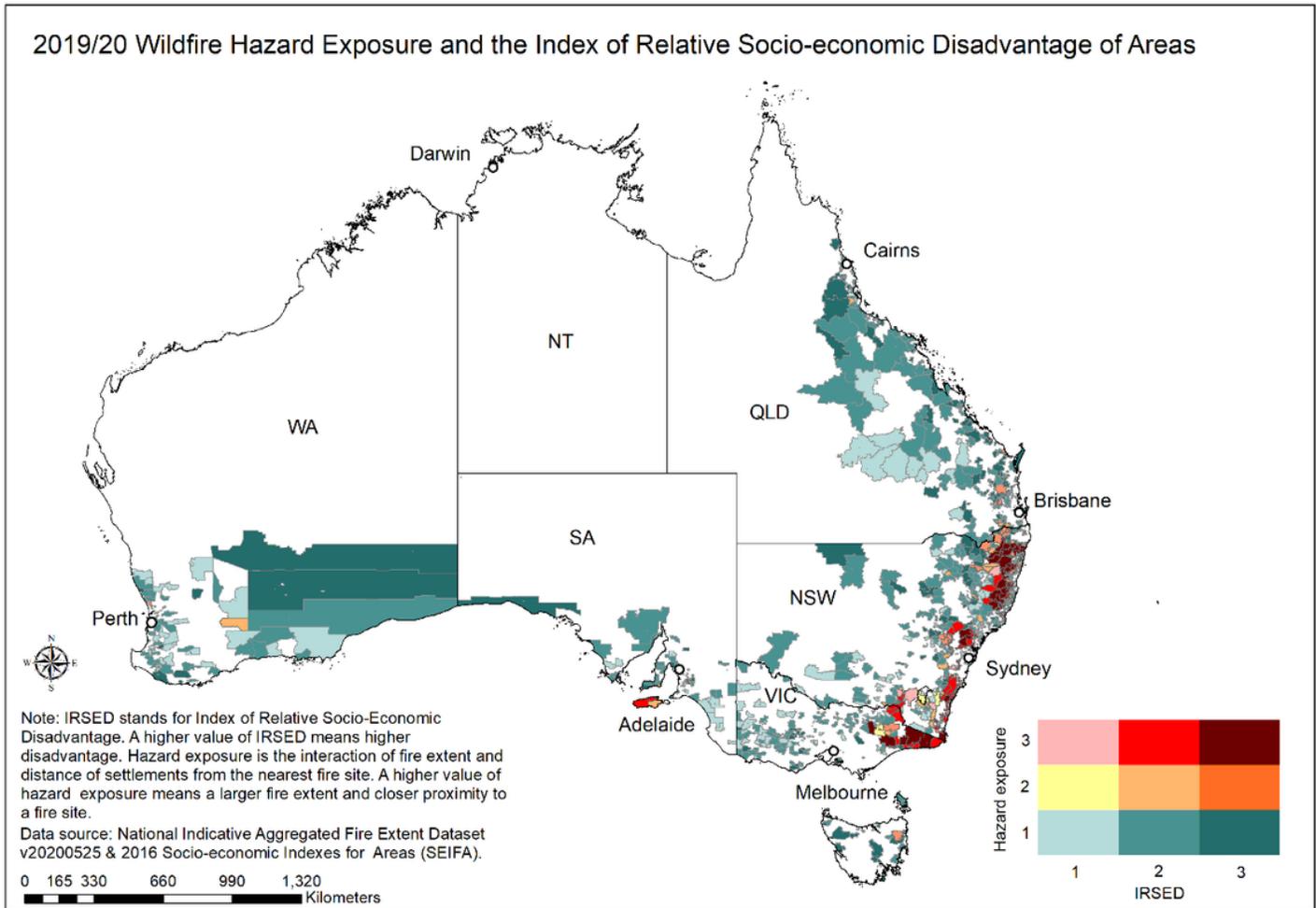


Figure 2
 The spatial distribution of the interlinkage between the Index of Relative Socio-Economic Disadvantage (IRSED) and the 2019–2020 wildfire exposure in Australia

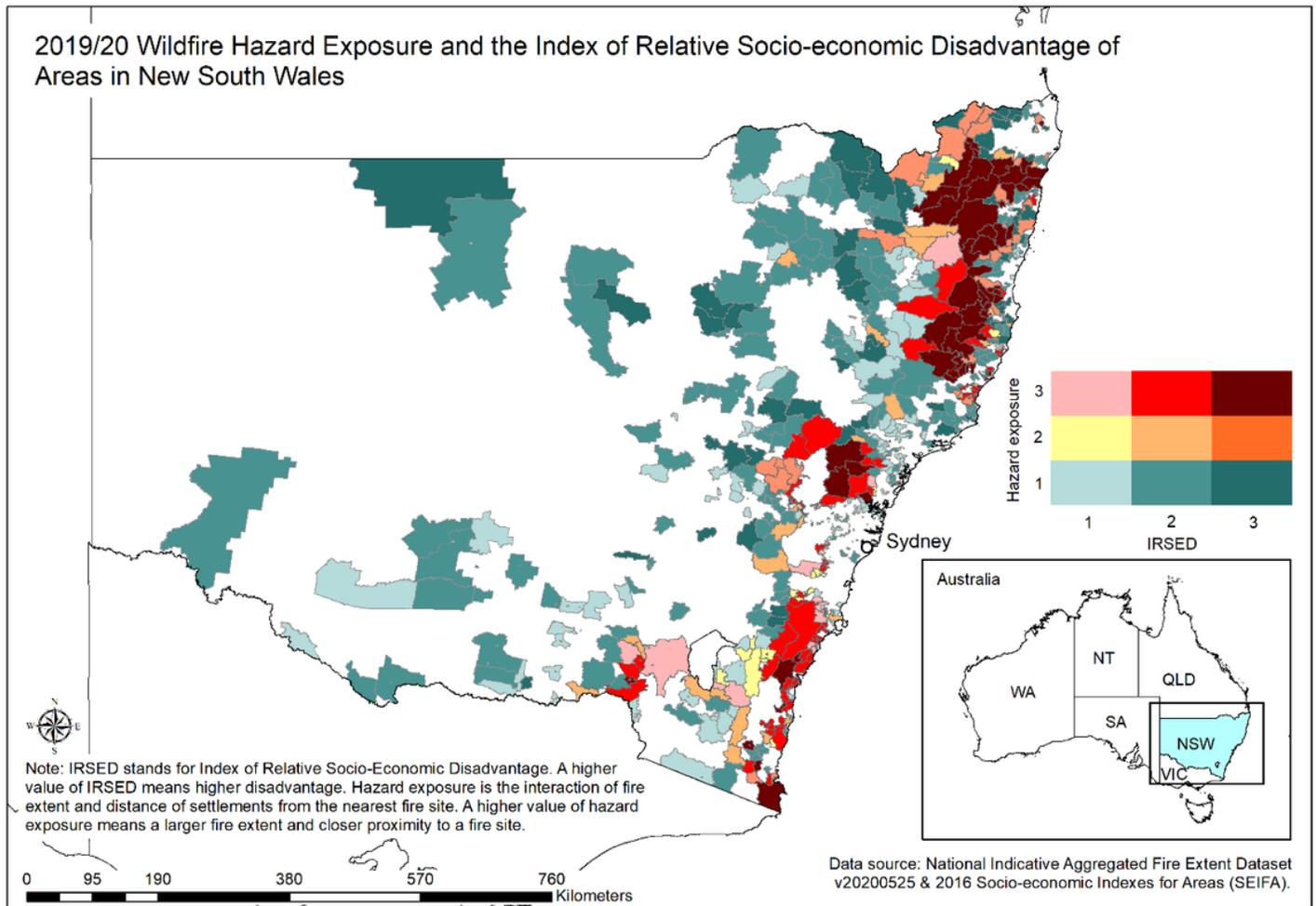


Figure 3
 The spatial distribution of the interlinkage between the Index of Relative Socio-Economic Disadvantage (IRSED) and the 2019–2020 wildfire exposure in New South Wales, Australia

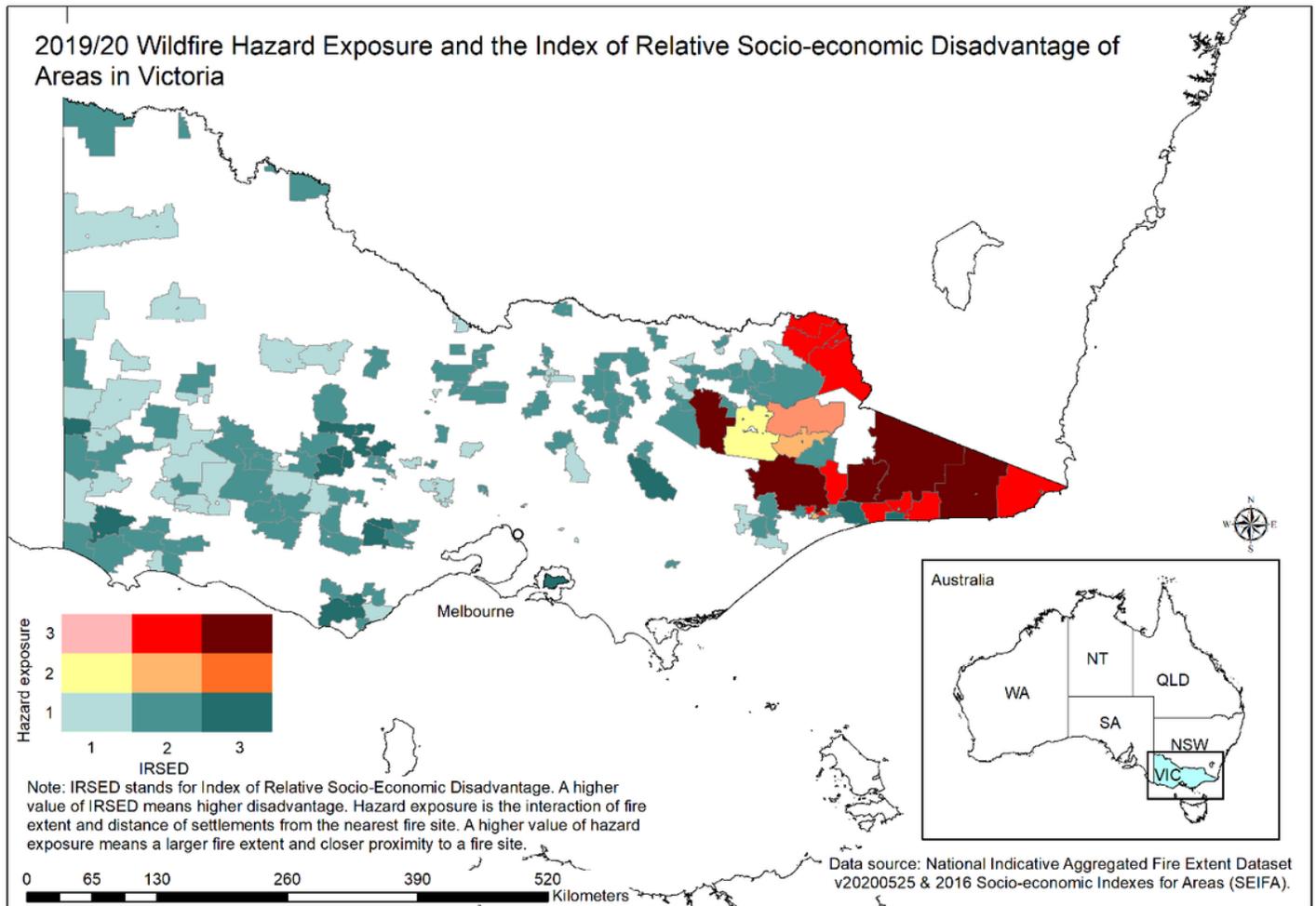


Figure 4

The spatial distribution of the interlinkage between the Index of Relative Socio-Economic Disadvantage (IRSED) and the 2019–2020 wildfire exposure in Victoria, Australia

Supplementary Files

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