Evaluating Wildfire Exposure: Using Wellbeing Data to Estimate and Value the Impacts of Wildfire

Johnston, David and Onder, Yasin Kursat and Rahman, Habibur and Ulubasoglu, Mehmet

Monash University, Ghent University, Curtin University, Deakin University

8 September 2021

Evaluating Wildfire Exposure: Using Wellbeing Data to Estimate and Value the Impacts of Wildfire

David Johnston[1] Yasin Kürşat Önder[2]

Muhammad Habibur Rahman[3] Mehmet Ulubaşoğlu[4]

Abstract

This paper estimates and quantifies the wellbeing effects of the 2009 Black Saturday Bushfires, the deadliest wildfire event in Australia's known history. Using subjective wellbeing data from a nationally representative longitudinal study and adopting an individual fixed-effects approach, our results identify a significant reduction in life satisfaction for individuals residing in close proximity of the wildfires. The negative wellbeing effect is valued at A$52,300 per annum; corresponding to 80% of the average annual income of a full-time employed adult. The satisfaction domain most negatively affected is how safe the person feels, and the group most affected are people with low social support. A delayed adverse mental health effect is also identified.

Keywords: Wildfires, georeferencing, life satisfaction
JEL Codes: O11, Q54

[1]Monash University, Centre for Health Economics, Building 75, Clayton, VIC 3800, Australia; Phone: +61 3 99058155, email: David.Johnston@monash.edu

[2]Ghent University, Department of Economics, Sint-Pietersplein 5, Ghent 9000, Belgium; email: kursat.onder@ugent.be

[3]Curtin University, School of Economics, Finance and Property, Perth, WA 6102, Australia; Phone: +61 8 9266 3805, email: habib.rahman@curtin.edu.au

[4]Deakin University, Department of Economics, Deakin Business School, 70 Elgar Road,. Burwood, VIC 3125, Australia; Phone: +61 3 924 46592, email: maulubas@deakin.edu.au. Mehmet Ulubaşoğlu gratefully acknowledges the financial support from the Bushfire and Natural Hazards Cooperative Research Centre.

Evaluating Wildfire Exposure: Using Wellbeing Data to Estimate and Value the Impacts of Wildfire

Abstract

This paper estimates and quantifies the wellbeing effects of the 2009 Black Saturday Bushfires, the deadliest wildfire event in Australia's known history. Using subjective wellbeing data from a nationally representative longitudinal study and adopting an individual fixed-effects approach, our results identify a significant reduction in life satisfaction for individuals residing in close proximity of the wildfires. The negative wellbeing effect is valued at A$52,300 per annum; corresponding to 80% of the average annual income of a full-time employed adult. The satisfaction domain most negatively affected is how safe the person feels, and the group most affected are people with low social support. A delayed adverse mental health effect is also identified.

Keywords: Wildfires, georeferencing, life satisfaction
JEL Codes: O11, Q54

1 Introduction

Extreme wildfires have substantial economic, social and environmental impacts. Lives are lost, homes and property are destroyed, smoke inhalation worsens health, and local economies suffer. For example, the 2018 Camp fire in Northern California that caused 88 deaths, destroyed almost 18,000 buildings, and burnt around 153,000 acres, has been reported as the world's costliest natural disaster in 2018 (Palinkas, 2020). Added to these direct losses of wildfire are fire suppression (i.e., firefighting) costs, which in recent years, exceeded $1.7B US dollars annually on US federal lands and $1B US dollars annually in Canada (Jolly et al., 2015).

Critically, the frequency of extremely destructive fires are increasing, with a trend towards more events in terms of geographic extent and duration, intensity, severity, and loss of life and property (Jolly et al., 2015; Westerling, 2016). In the western USA, Dennison et al. (2014) estimated that over the period 1984-2011 the number of large fires increased at a rate of seven fires per year, while total fire area increased at a rate of 355 km2 per year. Increased fire activity has likely been enabled by a number of factors, including the legacy of land use, the expansion of the wildland-urban interface, and increased temperatures and drought severity due to anthropogenic climate change (Schoennagel et al., 2017).[1] Abatzoglou and Williams (2016) estimated that anthropogenic climate change contributed to an additional 4.2 million hectares of forest fire area in the western United States during 1984-2015, nearly doubling the forest fire area expected in its absence.

Given the undoubtedly crucial importance of this issue, there are growing calls to better understand the full range of wildfire impacts. Recently, 57 of the world's most renowned scientists and research groups working in fire science, ecology, atmospheric chemistry, remote sensing and climate change modelling called for systematic quantifying of wildfire impacts in order to illustrate the significance of wildland fire management for sustainable development (Goldammer, 2015). Currently the social science literature that estimates and values the tangible and intangible impacts of wildfire is small, and so impacts of wildfires on human welfare are largely unquantified (Kountouris and Remoundou, 2011). This is

[1] The wildland-urban interface is the zone where houses meet or intermingle with undeveloped wildland vegetation (Schoennagel et al., 2017).

likely due to the fact that though it is relatively straightforward to calculate some of the short-term direct costs, such as property damage and health care costs, the intangible and potentially long-term wellbeing costs associated with physical injury, pain, psychological distress and behavioural change are much more difficult to evaluate.

The aim of this study is to help fill this research gap by estimating the subjective wellbeing effects of residing near deadly wildfires, and by subsequently estimating the dollar value of the reduction in wellbeing. These estimates will aid in the predictions of bushfire costs, including the intangible and non-market costs, for which there is relative paucity of research. The estimates will also shed light on whether levels of disaster assistance to victims are adequate to avert deleterious outcomes, and whether past humanitarian resources and public recovery projects are being efficiently targeted to those with the greatest need at the most beneficial stages of recovery. Moreover, they will provide insights into the suitable level of mitigation spending: the larger the effects and the longer they last, the larger the welfare losses, and thus the larger the benefit of mitigation spending (Deryugina et al., 2018).

Specifically, we estimate and value the wellbeing effects of Australia's deadliest wildfire event: the Black Saturday Bushfires (BSB) beginning on Saturday the 7th of February 2009. This event comprised a series of bushfires across the Australian state of Victoria, corresponding with record day and night-time temperatures (including three consecutive days above 43 °C / 109 °F), low humidity, and high wind speeds. These fires claimed 173 lives, destroyed 3,500 buildings, and burnt 450,000 hectares (National Museum Australia, 2020). The fires were completely unexpected, with the death of 112 people occurring in eight minutes (Önder et al., 2020). Correlational analyses in the aftermath of the BSB suggest that a significant proportion of people living in affected communities experienced PTSD, depression, and psychological distress for years after the fires (Bryant et al., 2014).

Our individual fixed-effects approach compares the changes over time in the wellbeing of people living close to the fires (measured by Euclidean distance), with changes over time in the wellbeing of people living further away. Subsequent analyses investigate how effect sizes vary with time since the fire, given the likelihood of eventual adaptation to baseline wellbeing (Frijters et al., 2011). A number of outcomes are explored, including overall life satisfaction, and satisfaction with your home, your neighbourhood, employment opportunities, financial situation, and how safe you feel. We additionally explore impacts on self-reported mental health. The estimated wellbeing effects of wildfire exposure are then costed using an empirical approach that estimates the amount of monetary compensation that is required to return the average person living close to a wildfire to his or her pre-fire level of wellbeing (Johnston et al., 2018). This "life satisfaction method" has been used widely in the literature to value the costs of various non-market goods (Luechinger and Raschky, 2009; Levinson, 2012). We extend the conventional approach by considering asymmetric effects of income on wellbeing, the endogeneity of income, and the adaptation to income and wildfire exposure (Johnston et al., 2018).

Subjective wellbeing measures have been increasingly used to evaluate the impacts of disasters, and environmental-related products and policies.[2] For example, studies have estimated the wellbeing effects of floods (Luechinger and Raschky, 2009; Sekulova et al., 2016; Kimball et al., 2006), droughts (Carroll et al., 2009), storms (von Möllendorff and Hirschfeld, 2016), tsunami (Rehdanz et al., 2015), earthquakes (Rehdanz et al., 2015; Wong, 2014), air pollution (Zhang et al., 2017; Levinson, 2012), airport noise (Van Praag and Baarsma, 2005), and wind turbines (Krekel and Zerrahn, 2017). The advantage of subjective wellbeing measures is that they can capture both tangible and intangible damages, such as those associated with pain, psychological distress, and a decrease in quality of life. However, few studies have used these measures to understand the impacts of wildfires. The most relevant for our study is Ambrey et al. (2017), who also use life satisfaction data to evaluate the costs of the Black Saturday Bushfires. Using variations in individuals' life satisfaction associated with percent burnt of respondents' residential location, they estimate that a 1% lower share of burnt area is equivalent to almost $3000 of annual

[2] A related, very large psychological literature has explored the mental wellbeing effects of disasters. However, many of these investigations include only people who were exposed to the disaster, and sometimes also people not exposed who were selected after the disaster. Such studies may be biased in their selection of exposed and unexposed groups, and use of retrospective information about health before the disaster. These biases generally lead to an overestimation of effects.

household income.[3] We differ from this work in several ways. First, we estimate the effects of the wildfires using a multi-ring approach that defines treatment status by distance from the closest fire. This approach recognizes that people can be negatively affected even if their residential location is not burnt (e.g., because of concerns about family and friends, and consequences for the local economy). It also recognises that control areas will be more similar to treated areas, and therefore identification assumptions more likely to be satisfied, if they are geographically close to one another. This is a distinctly different approach than the one used by Ambrey et al. (2017), who include control locations very far from the fires. A second difference is that we estimate wildfire treatment effects on overall life satisfaction, domains of life satisfaction, and mental health, and allow treatment effects to differ by individual-level and area-level factors, which have potentially important policy implications. Other important differences are that our study incorporates dynamic time effects - which we show to be statistically important - and in the evaluation exercise we identify income effects using large exogenous income shocks, which accounts for estimation bias related to the endogeneity of income. This combination of methodological differences means that our valuation is, in our view, more reasonable that those often generated. For instance, a 'traditional' life satisfaction valuation approach provides an estimated valuation roughly 15 times larger than our own. Furthermore, we consider effects of wellbeing and mental health in terms of individuals' locational mitigating factors, which are important for potential policy implications.[4]

There are also several economics studies on other wildfire impacts. The impact outcome most often explored in the literature is property prices. For example, Stetler et al. (2010)

[3]A public health study by Gibbs et al. (2016) investigates the mental health effects of the BSB by conducting interviews two and five years after the event. They report that being part of the local community reduces incidence of post-traumatic stress disorder and helps people to overcome mental health problems. Similarly, Bryant et al. (2014) conclude that a significant proportion of people living in affected communities experienced PTSD, depression, and psychological distress.

[4]Other studies have more narrowly focussed on the effects of wildfire smoke. For example, Jones (2017) and Jones (2018) estimate the life satisfaction effects caused by wildfire smoke using individual cross-sectional data from the US Behavioral Risk Factor Surveillance System. Another example is Kountouris and Remoundou (2011), who use life satisfaction data from the cross-sectional Eurobarometer Survey Series matched to fire data at the broad region level (NUTS 2 level) in Spain, France, Italy and Portugal. Results from instrumental variable (IV) models, which assume that rainfall is a valid instrument for fire occurrence, suggest that the occurrence of one additional fire decreases life satisfaction by 0.00002 points (on a four-point scale).

examine the effects of 256 wildfires in northwest Montana over a 10 year period, and conclude that proximity to and view of wildfire burned areas has large and persistent negative effects on home values. More recently, McCoy and Walsh (2018) also find that proximity and visibility have negative effects on house prices in Colorado. The impact of wildfires on respiratory illness and other health conditions related to smoke inhalation has also received some attention. A particularly comprehensive study is Moeltner et al. (2013). They use Nevada hospital data from 2005-2008, and estimate that for every 100 acres burned there was $60-210$ in inpatient treatment costs for acute respiratory problems and $70-260$ for cardiovascular admissions, with the valuation depending upon fire distance and primary fuel type.[5] Few studies have explored the direct income effects of wildfires. An exception is Önder et al. (2020) which investigates the direct and spatial spillover income effects of the Black Saturday Bushfires using individual-level Census longitudinal data. They document significant income declines. Our analysis will complement these studies by evaluating the combined effect of these and other impacts of wildfire, including psychological distress.

The individual fixed-effects analysis provides estimated wellbeing effects of residing within 15km (9.4 miles) and residing 15-30km (9.4-18.8 miles) from the wildfire, relative to residing further away (either 30-50km or 30-100km from the wildfire). A number of key results stand out. First, we estimate that overall life satisfaction is significantly lower for people residing within 15km of the fire in the year after the disaster, relative to the pre-disaster period. The point estimates suggest that life satisfaction is reduced by 0.15 - 0.19 units, which is comparable in magnitude to the negative wellbeing effects of a serious illness or being the victim of physical violence (e.g., assault). These negative effects are relatively short-lived, with the estimate in the second year less than half the size of the year one estimate. Estimated wellbeing effects for residing within 15-30km from the fire are much smaller than the 0-15km effects in all years.

We also demonstrate that individuals experienced a significant reduction in mental health during the post-disaster period. The mental health of disaster-hit individuals

[5] For a review of the wider literature on the health impacts of wildfire smoke exposure, see Reid et al. (2016).

remained relatively unaffected in the year of the disaster, 2009, but a delayed onset of adverse mental health is observed within the 0-15km ring in 2010. Finally, our estimated valuation of the total wildfire effect across time corresponds to A$52,300, which equates roughly to 80% of the 2009 annual earnings of a full-time employed adult in Victoria, Australia. In other words, affected individuals required, on average, an income shock of A$52,300 to offset the negative wellbeing effects of the wildfire.

Importantly, all our results are robust to the construction of the treatment and control groups, and numerous checks related to satisfying the parallel trends assumption. We should note also that the estimates we present are likely to underestimate the true characterization of the wildfires because of the general equilibrium economic effects that jointly affected people living close and further away from the fires (see Önder et al., 2020).

Section 2 provides a brief overview of the Black Saturday Bushfires and describes the construction of the treatment and control groups as well as the indicators we use from the HILDA survey. Section 3 discusses the empirical framework, Section 4 presents the results, and Section 5 concludes.

2 The Black Saturday Bushfires and Data

2.1 Background

The Black Saturday Bushfires were a series of bushfires that ignited across the State of Victoria on 7 February 2009 following several successive weather anomalies. By far the most deadly bushfire incident ever to hit Australia, the disaster led to 173 deaths and 414 injuries, the highest ever loss of life from a bushfire in Australia. The far reaching damage also included 3,500 destroyed buildings (2,133 houses) and 450,000 hectares of burnt land. The total estimated tangible cost was about $4 billion, with environmental and agricultural losses estimated at around $366 million and $733 million respectively (Black Saturday Royal Commission, 2009; Australian Emergency Management Institute, 2010; Stephenson et al., 2012). [6] The McArthur Fire Danger Index (FDI) had traditionally described the index of 50 and above as "extreme", but the unprecedented 2009 bushfire prompted the need for the introduction of a new category – 'catastrophic' for FDI that exceeded 100. During black Saturday, the FDI forecast was 142 for forests and 186 for grasslands (Australian Wilderness Society, 2015).[7]

The mapping analysis reveals that approximately 43% of fire-affected land was state forest, 29% was private land, 23% was National Parks and 5% was plantation (Australian Wilderness Society, 2015). Figure A1 shows the distribution and location of the bushfires highlighting how dispersed they were.

We use two data sources for this study. The first is information on individuals from the Household Income and Labour Dynamics in Australia (HILDA) survey. The second is individuals' distance to the five fatal bushfire pockets, which enables the construction of the treatment and control groups.

2.2 HILDA Study

We use HILDA data from years 2002 to 2011. Of these, 2002-2008 constitute the pre-disaster years, and 2009-2011 are the post-disaster years. Surveys in each year are heavily concentrated in August to November, with the 2009 HILDA wave conducted from 20 August 2009 to 11 March 2010. The self-reported life satisfaction variable is available as the respondents' ordinal answers between 0 (totally dissatisfied with life) and 10 (totally satisfied with life) to the question, "All things considered, how satisfied are you with your life?" In order to delve into certain driving factors behind the life satisfaction effects, we also consider some important sub-components of life satisfaction, including "your

[6] The fires affected 78 townships and many of them were badly damaged. All houses in towns of Kinglake, Marysville, Narbethong, Strathewen, and Flowerdale were completely destroyed. Houses in the towns of Steels Creek, Humevale, Clonbinane, Wandong, St Andrews, Callignee, Taggerty, and Koornalla were also either destroyed or severely damaged. As a result, fatalities were registered and an estimated number of 7,562 people were displaced from their homes.

[7] The conditions recorded on Black Friday in 1939 effectively set the Forest Fire Danger Index benchmark of 100. But the fire danger levels by Black Saturday on 7 February 2009 are believed to have significantly exceeded the previous records set by Black Friday on 13 January 1939 and the Ash Wednesday on 16 February 1983 Australian Wilderness Society (2015).

employment opportunities", "your financial situation", "how safe you feel", "feeling part of your local community", "your health", and "the neighbourhood in which you live".

2.3 Treatment and Control Group Construction

Black Saturday Royal Commission (2009) provides the detailed mapping of 12 different pockets of fires in a raster data format, all of which constitute the BSB (see chapters 3 to 14 of their report).[8] Figure 1 depicts one of these pockets. Following the approach in Önder et al. (2020), location-based analysis is applied to these maps, using the ESRI shapefile formats provided by ABS: Australian Bureau of Statistics (2017), to identify the distance of each locality from the bushfire pockets. With these distances, we construct the treatment and control groups.

The main sample includes all individuals residing within a 100km radius of the outer borders of the bushfire areas that experienced fatalities (see Table 1). The two baseline treatment groups are defined as locations 0-15km and 15-30km from the fires, and the baseline control group is defined as locations 30-100km from the fires. Individuals residing within the burnt areas themselves (the red marked areas in Figure 2) are also assigned to the 0-15km treatment group. Most of the burnt area is state forest or national parkland (77% of the area), and the remainder has low population density, meaning that there are insufficient observations in the HILDA dataset from those areas with which to define a separate treatment group. For a robustness analysis we alter the groupings such that the control group is defined as locations 30-50km from the fires. In a second robustness analysis, we use only those locations within the 0-15km ring as the treatment group, and use 15-50km and 50-100km rings as control groups. Our key findings are generally robust across these different definitions.[9]

A potential caveat is that we cannot rule out the possibility that the control group, no matter how measured, may have been affected by the fires. Control group respondents may

[8] Rasters are digital pictures consisting of matrices of cells (or pixels) organized into rows and columns in which each cell contains a value representing the severity of bushfire intensity.

[9] The radius 100km comprises some of Melbourne's outer metropolitan suburbs. Our individual fixed effects approach controls for differences between urban and rural populations. Moreover, excluding these suburbs from the control group does not change our key results.

have friends that were directly affected by the fires, or shop, socialise or work in the fire affected communities. Moreover, the BSB may have increased control group respondents' perceived risk of future fires in their own localities, and negatively affected their house price expectations. Hence it is possible that the estimated effects we present in subsequent sections are biased towards zero (i.e., too small in magnitude).

To locate where each individual in the HILDA dataset resides, we use their location identifier at the Statistical Area-1 (SA1) level,[10] which is a relatively precise location in terms of Australia's regional geography. Overall, we compute the distance of 12,800 SA1s to the five fatal fire hotspots.[11] The right panel of Figure 3 shows the histogram with distance to the fires.

Individuals move into or out of treatment and control areas over the years. We account for such migration by fixing our sample to individuals who were present in a particular SA1 in the year prior to the disaster (i.e., 2008). In other words, our sample includes only those individuals who were in a particular treatment or control SA1 as of 2008, whom we track in the years prior to and following the disaster year (irrespective of their residential SA1).

Summary statistics for the key variables used in our analysis are presented in Table 2. The means and standard deviations are presented for the most inner ring (i.e., distance less than 15km) and the control ring (i.e., distance greater than 30km) for our benchmark 0-100km sample for the years immediately before and immediately after the BSB. For the inner ring, we observe a 0.19 reduction in the unconditional mean of life satisfaction, which is a 0.15 larger drop than observed for the outer ring. The largest simple difference-in-difference occurred for satisfaction with financial situation and satisfaction with employment opportunities, equalling 0.26 and 0.21 satisfaction units, respectively.

[10]On average, SA1s comprise around 400 individuals. There are 57,523 spatial SA1 regions covering the whole of Australia, of which 13,335 are within the state of Victoria.

[11]Note that we compute our distance measure using ArcGIS as the distance between the centre of respondent's SA1 and the outer boundary of nearest deadliest fires. Drawing radii from the outer bound of deadliest fire zones is necessary to ensure that we do not have treatment and control rings overlapping with each other. This provides us with cleaner rings, as shown in Figure 2.

3 Empirical Specification

Our main empirical approach is a linear panel event-study design. This is operationalized by interacting the treatment and control rings with indicator variables representing the years 2008, 2009, 2010 and 2011. These interaction terms are expected to capture the year-specific life satisfaction effect of the BSB during 2009-2011, compared to their life satisfaction average during the 2003-2007 period, with the 2008 interaction testing for the presence of pre-event trends. Formally, we estimate:

$$log(y_{i,s,t}) = \sum_{y=2008}^{2011} \sum_{k=1}^{2} \beta^{ky} \mathcal{R}_{i,t}^{ky} + \alpha_i + \nu_t + \epsilon_{i,s,t}. \tag{1}$$

In this model, $y_{i,s,t}$ is our outcome of interest for individual i in period t residing in SA1 geographic area s; $\mathcal{R}$ denotes a dummy variable that equals one if an individual i lives in the radius ring k, and zero otherwise. α_i denotes the individual fixed effects, which control for time invariant individual determinants of residing in areas with higher wildfire risk, while ν_t denotes the year fixed effects, which capture broad changes over time affecting wellbeing. Note that residential proximity to the wildfires is measured in 2008, a few months preceding the BSB event, and so is a fixed individual characteristic. We fix one distance category K as the control group and omit the corresponding interaction term. As indicated, we explore using different omitted radius rings (15-50km, 30-50km, 15-100km, and 30-100km rings) depending on the specification. Thus, the vector of coefficients β_{kt} measures the treatment effect in radius ring k in year t with respect to the omitted distance category. If our intuition is correct, we should observe stronger life satisfaction reductions within the inner rings compared to the outer rings of the bushfire pockets. Standard errors are clustered at the SA1 area level.

The causal identification of the BSB's impact relies partly on the assumption that important differences between those residing close (<15km, 15-30km) and further away (30-100km) from the fires are time invariant. Wildfires typically occur in wildfire-prone areas (i.e., forests and grasslands), which suggests that their location within a state is not randomly determined. However, their occurrence over time within wildfire prone areas is likely to be as good as randomly determined, and not associated with time-varying individual characteristics. Supporting this supposition is the fact that the BSB fires were sporadically located across Victoria, affecting 12 non-contiguous areas. Moreover, the spread of the BSB fires were partly caused by unusual weather patterns, including the strength and direction of winds.

We assess the credibility of our identification by exploring whether there are systematic differences in life satisfaction across the treatment and control groups prior to the BSB. Specifically, we estimate the effects of BSB exposure (0-15km and 15-30km) on wellbeing in years 2005, 2006, and 2007 to determine whether there were significant pre-BSB wellbeing differences between those residing close and far away (30-50km and 30-100km) from the wildfires (relative to 2008). We find that the estimated wellbeing differences in each pre-BSB year were individually and jointly statistically insignificant (p-values all greater than 0.10). To visualize, the coefficient plots from this analysis for the 0-15km ring are presented in Figure A2.

Furthermore, in Appendix Table A1 we present estimated effects for differently defined treatment groups: 0-10km, 0-15km, 0-20km and 0-25km. As expected, the estimates indicate that the BSB effects are larger for individuals who resided closer to the BSB fires, with the estimates monotonically decreasing in magnitude as the treatment group increases in size. Our main specification uses 0-15km, because it balances the need to have a treatment group that is spatially close to the fires, while ensuring that the sample size of treated people is not too small.

Finally, we conduct an analysis using a year 2006 placebo treatment. The results in Appendix Table A2 show that differences in life satisfaction between high and low exposure areas in the years before the placebo treatment (2004, 2005) and after the placebo treatment (2007, 2008) are all smaller than our main effect in Table 3, and are statistically insignificant. These results suggest that wellbeing was not trending differently across areas in the years preceding the BSB event, lending credibility to our identification strategy.

4 Results

4.1 Baseline Results

Table 3 presents the main estimation results. Columns (1) and (2) report the estimates using the sample of individuals residing within 100km, while columns (3) and (4) present the results based on individuals residing within 50km. For each sample, we alternate the treatment group to be, first, both the 0-15km and 15-30km rings, and second, only the 0-15km ring. All the models control for individual fixed effects and year fixed effects. Coefficient estimates in columns (1) to (4) demonstrably show that life satisfaction is reduced within the 0-15km ring in 2009, the BSB year, relative to the 2003-2007 period. Estimates of the treatment effects in all four columns are relatively similar, generally significant at the 5% level, and suggest that life satisfaction is reduced within this ring by 0.15 - 0.19 units in 2009. There also seems to be no drastic difference in life satisfaction levels in 2010 and 2011 relative to the 2003-2007 period, meaning that individuals had mostly reverted back to their pre-disaster wellbeing trajectories.[12]

In order to place the negative effects for the 0-15km ring into context, we estimate using an individual fixed-effects regression the life satisfaction effects of different major life events (see Appendix Table A3). The estimated coefficients document that the wildfire effect in 2009 is similar in magnitude to other significant adverse events, such as having a serious personal injury or illness, and being the victim of physical violence (i.e., being assaulted). The wildfire effect is also similar in size, but opposite in sign, to happy life events such as getting married, falling pregnant, and experiencing a major financial improvement. Interestingly, the wildfire effect is much larger than the effect of common labour market changes, including retirement, being fired, receiving a promotion, and changing jobs.

In contrast to the large 2009 effects for the 0-15km ring, the estimates are small and statistically insignificant across all four columns for the 15-30km ring. This finding is not

[12] An alternative approach to using the 0-10 life satisfaction variable, is to estimate the effects of the BSB on the likelihood of having very low life satisfaction (4 or lower). Using the covariate set from Column 1 of Table 3, we find that living within 15km of the fire is estimated to significantly increase the likelihood of very low life satisfaction in 2009 by 1.9 percentage points.

entirely unexpected, because the outer rings are anticipated to have been less affected by the fires.

Notably, the estimate for 2008 is estimated to be insignificant for both 0-15km and 15-30km rings, suggesting that the treatment groups exhibited no significant difference in life satisfaction levels relative to those of the control groups in the year preceding the disaster, which supports the parallel trends assumption. Estimating the models with SA1-fixed effects instead of individual fixed effects does not change the key results, and it even mildly increases the significance levels.

Table 4 reports the results for the sub-components of life satisfaction, focussing on the sample of respondents residing within the 100km radius and considering, as the treatment group, those within the 0-15km and 15-30km rings. The most important result is that "how safe you feel" (column 3) is estimated to be negative and significant for both the 0-15km and 15-30km rings in the year 2009. The coefficient sizes, both significant at 10% level, are -0.17 and -0.11, respectively. Importantly, the 0-15km ring also exhibits a stronger and continued reduction in satisfaction in the year 2010, with the estimate equalling -0.23 and significant at at the 5% level.

An additional finding in Table 4 is the increased satisfaction with 'feeling part of your local community' in the wake of the disaster (column 4). For the year 2009 the estimate is positive and significant at the 5% level for the 0-15km ring and positive with a t-statistic of 1.45 for the 15-30km ring. No other sub-component of life satisfaction was found to be significant in Table 4 (columns 1, 2, 5 and 6).

Our estimates so far suggest that the BSB was a major adverse event that reduced individuals' well being in 2009, and that reduced feelings of safety drive these results. Next we explore whether these wellbeing effects had correspondingly negative impacts on people's mental health. HILDA includes five mental health questions as part of the 36-Item Short Form Health Survey (SF-36): "have you been a nervous person?", "have you felt so down in the dumps nothing could cheer you up?", "have you felt calm and peaceful?", "have you felt down?", and "have you been a happy person?". Responses to these questions range from (1) "All of the time" to (6) "None of the time". Columns (1) to (5) in Table 5 demonstrates that the responses to four of these five questions are significantly related to residing within the 0-15km ring in the year 2010, demonstrating adverse mental health effects.

Finally, we estimate wildfire effects on an overall mental health index (with mean zero and standard deviation one). The index is constructed by conducting a principal component-factor analysis on the eight health dimensions contained in the SF-36 health questionnaire. Results reported in column (6) are for the mental health index, and indicate a negative mental health effect in 2010 for the inner ring of about 8% of a standard deviation. The fact that this effect pertains to 2010, and not to 2009, suggests that there is delayed onset of mental health problems. This is not unexpected, because disaster-induced adverse life events, such as changes in income or relationship status, typically occur with a lag. Also, extensive support from the government and community agencies in the wake of the catastrophe may have suppressed the onset of mental health problems initially. Moreover, it is expected that mental health effects will be transitory for the average person, because most people eventually experience posttraumatic growth, which refers to positive experiences after trauma, such as appreciating life, new ways of life, personal strength, spiritual change, community engagement, relating to others, and even moving out of the disaster area. See Gibbs et al. (2016) for a similar result.

4.2 Valuation of the Wildfire Impacts

We use the life satisfaction approach to estimate the dollar cost of residing near deadly wildfires. Under the assumption that subjective wellbeing provides an approximation to individual welfare, this approach involves estimating the marginal disutility of wildfires and the marginal utility of income, and calculating the trade-off ratio between them (Frey et al., 2010). Following Johnston et al. (2018), we extend the conventional approach by considering the endogeneity of income, and the dynamic nature of the wellbeing effects (adaptation profiles). Essentially, the extended approach involves a comparison of the total time-discounted wellbeing effects caused by wildfires with the total time-discounted wellbeing effects caused by the receipt of a positive income shock. This provides the amount of monetary compensation required by wildfire victims to offset their total loss of welfare across time.

We identify income shocks by reports in the HILDA survey of a "major financial improvement, e.g. won a lottery, received an inheritance". Further analysis of HILDA data demonstrates that this income shock variable reflects lottery wins and inheritances, but not other sources of windfall income, such as income from annuities, pension funds, insurance, severance package, gifts, company shares, managed funds, or property trusts (Au and Johnston, 2015). Furthermore, we demonstrate that the occurrence of an income shock is not predicted by within-individual changes over time in demographic or socioeconomic characteristics, nor is it predicted by residing in close proximity to a wildfire.[13]

The valuation estimate is obtained in several steps. First, we estimate individual-level fixed-effects life satisfaction regressions with (i) indicators for residing in close proximity to a wildfire (with coefficients δ_j); and (ii) indicators of receipt of an income shock (with coefficients π_k). Lags are included to capture the complete life satisfaction profiles, with effect magnitudes largest immediately after the event, and then becoming smaller over time, as life satisfaction returns to baseline (pre-event) levels (i.e., a typical adaptation profile).

Second, we estimate the average dollar value of the income shock by regressing past year's total household irregular income on an income shock indicator, controlling for other life events or shocks, and individual and time fixed-effects.[14] For our estimation sample, the average estimated increase in income for people who received an income shock equals A$41,954.

In the final step, we calculate the dollar amount that exactly equates the negative discounted sum of the wildfire effects with the positive discounted sum of the income

[13] All demographic characteristics (e.g. age, number of children, marital status, health status) and socioeconomic characteristics (e.g. employment status, income) are statistically insignificant (at the 10% level) in a fixed-effects regression of the occurrence of an income shock in the next 12 months. A test of their joint significance has a p-value equal to 0.48. Residing near the deadly wildfires and life satisfaction are also insignificant predictors of income shock receipt: p-values equal 0.28 and 0.27, respectively.

[14] The other life events that are controlled for in the fixed-effect regression include: victim of physical violence, victim of property crime, major financial worsening, death of spouse/child, death of other close relative, death of a close friend, fired/made redundant, personal injury/illness, injury/illness to a close relative, promoted at work, retired from the workforce, changed jobs.

shock effects. In other words, we calculate the amount of compensation a victim of wildfire events would need to return them to their pre-wildfire level of well-being. The following equation represents this calculation:

$$-\frac{\sum_{j=0}^{J}\delta_j(1+d)^{-j}}{\sum_{k=0}^{K}\pi_k(1+d)^{-k}}\overline{\Delta income}, \tag{2}$$

where δ_j are the estimated parameters on the wildfire exposure indicators (up to J lags) and π_k are the estimated parameters on the income shock indicators (up to K lags) from the fixed-effects life satisfaction regressions. d is the discount rate (which we set at 5%), and $\overline{\Delta income}$ is the estimated value of the income shock ($41,954).

Results from each step of the valuation exercise are presented in Table 6. The numerator of equation (2) – the discounted sum of the wildfire effects – equals -0.310 life satisfaction units (column 1). The denominator of equation (2) – the discounted sum of the income shock effects – equals 0.269 units. These values indicate that living in close proximity to a wildfire reduces life satisfaction by more than the income shock increases it. Column (4) of Table 6 presents the estimated valuation figure: residing near deadly wildfires has a wellbeing cost equivalent to A$52,300. This equates to approximately 80% of the 2009 annual earnings of a full-time employed adult in Victoria, Australia.[15] So we estimate that the average individual requires approximately 80% of average annual full-time earnings to offset all of the negative wellbeing effects of wildfire exposure, such as respiratory illness, psychological distress, and loss of earnings.[16]

Our back-of-the-envelope calculations indicate that the total monetary cost of the wellbeing reductions is quite large. The total population of the 0-15km ring equals about 144,000 people. Conservatively assuming that the negative wellbeing effects are concentrated solely among the adult population, equalling about 80% of the population, this implies 115,200 affected people. The total value of the aggregated wellbeing effects there-

[15]The total average weekly earnings of full-time employed Adults in Victoria Australia in November 2009 equalled $1232 (see ABS: Australian Bureau of Statistics, 2019).

[16]It is possible that the death of a family member or relative is correlated with both windfall income and life satisfaction. However, given that the BSB treatment is residing close to someone who died in the BSB fires, wellbeing losses arising from the death of relatives is a potentially important pathway for our effects. Nevertheless, when we include controls for death of relatives and death of friends, the estimated evaluation is only reduced from AUD 52,300 to AUD 45,100.

fore equal about A$6 billion. This substantial cost once again points to the importance of investments into mitigation mechanisms prior to disasters, such as new technologies of early warning and community training programs for timely evacuation of disaster areas to minimize the death toll and subsequent psychological impacts.

The presented valuation estimate is calculated with consideration for the endogeneity of income (through the use of an exogenous income shock), and the adaptation profiles associated with wildfire exposure and the income shock (through the inclusion of lagged indicators). The common life satisfaction valuation approach ignores these issues, and more simply divides the coefficient on an indicator of wildfire exposure with the coefficient on contemporaneous household income from a fixed-effects life satisfaction regression. Using this approach, the estimated valuation equals approximately A$755,000. Finding a very large valuation estimate such as this one is common with this alternative method, and is often due to the income coefficient being very small; partly due to attenuation bias caused by year-to-year measurement error in income. We believe our estimated valuation is more reasonable.

Finally, note that our estimated valuation figure is contingent on the recovery and relief funds and insurance pay-outs received by some people in our treatment group. It is impossible to estimate what the negative BSB wellbeing impacts would have been if the funds and pay-outs had not been made. However, it is reasonable to assume that they will have mitigated some of the adverse effects, and so that without these payments the magnitude of the wellbeing effects, and consequently the estimated valuation figure, would have been significantly larger.

4.3 Heterogeneity Analysis

We now turn to a policy question: what could have been done, or what should be done in the future, to mitigate the negative effects of catastrophic natural disasters? We seek to answer this question by exploring whether there were observable characteristics of individuals or communities that were important for buffering the wellbeing effects. These heterogeneity results are presented in Table 7. Panel A presents estimated effects from life satisfaction regressions estimated separately for subsamples defined by age, gender and marital status. The results indicate that older people (aged > 45 years) and women experienced greater reductions in life satisfaction from the fires, than did younger people and men; however, the differences between groups are not statistically significant. Interestingly, single people appear most negatively affected. This might be due to heightened loneliness during the post-disaster phase, and also due to having lower (pre-disaster) psychological and financial resources to draw upon.

Panel B presents estimates based on sub-samples defined by socioeconomic characteristics. Our estimates indicate that individuals who completed at least 12 years of education experienced greater life satisfaction losses due to the BSB. We find a similar result when using an index of neighbourhood socioeconomic advantage based upon people's education and occupation levels reported in the 2011 Census. Those residing in neighbourhoods with above median socioeconomic advantage experienced more negative effects than those residing in neighbourhoods below the median. In contrast to these results, we find that the BSB effect is more negative for people from lower income households. This will partly reflect heterogeneity by age, with older retired populations tending to have lower annual incomes.

To explore the role of social capital, we constructed a social support index through a factor analysis of ten HILDA variables measured pre-BSB.[17] Panel C presents estimated effects for subsamples defined by having above or below median values of this index. They show that individuals with low levels of social support experienced much larger drops in wellbeing following the fire than those with high levels of social support. In addition to this individual-level measure of social support, we constructed two neighbourhood-level measures. An index of neighbourhood bondage is constructed by the area-level (SA2) mean of pre-BSB responses regarding the level to which neighbours help each other out and neighbours do things together. Similarly, an index of neighbourhood hostility is

[17] These HILDA variables include: people don't come to visit me as often as I would like; I often need help from other people but can't get it; I seem to have a lot of friends; I don't have anyone that I can confide in; I have no one to lean on in times of trouble; there is someone who can always cheer me up when I'm down; I often feel very lonely; I enjoy the time I spend with the people who are important to me; when something is on my mind, just talking with the people I know can make me happy; and when I need someone to help me out, I can usually find someone.

constructed from responses regarding the level to which people in your neighbourhood are hostile and aggressive, there is vandalism and property damage, and there is burglary and theft. The estimates for subgroups defined by having above or below median values of these area-level indices, are not significantly different from one another. The neighbourhood 'hostility' results indicate that neighbourhoods with low values may have experienced larger negative BSB effects; but the estimate imprecision does not allow us to make any strong conclusions. [18]

5 Conclusion

The increasing frequency and severity of natural disasters, arguably ushered in by well-documented changes in climatic and weather regimes, result in growing costs for the economies and public health systems of various countries. These costs also include intangible and long-term well-being losses associated with physical injury, pain, psychological distress and behavioural change. The literature presents several attempts to evaluate the intangible and wellbeing costs of various types of natural shocks, such as floods, droughts, storms, tsunami, earthquakes, and air pollution, however, relatively little attention has been paid to the wellbeing effects of wildfires. At this juncture, an increased scrutiny on wildfires is critical, because on-average approximately 4% of the global land surface is affected by bushfires per annum. Most recently, the 2019-20 Australian bushfires, the 2018 Californian fires (reported to be the largest in the state's history), and the 2018 Greek fires (considered one of the deadliest in the country's history), raised significant alarm bells in this vein (see Önder et al., 2020).

The principal objective of this study is to help bridge this research gap by quantifying the wellbeing effects of Australia's deadliest wildfire event: the Black Saturday Bushfires beginning on Saturday the 7th of February 2009. This event comprised 12 pockets of non-contiguous bushfires across the Australian state of Victoria, corresponding with record

[18] We also explored whether fire severity was an important moderating factor. All fires analysed in the study could be considered severe, given each was associated with fatalities. But even so, some survey respondents resided in areas (SA2s) with higher burnt-area percentages, than other respondents. Our results indicate that the negative wellbeing effects in year 2009 did not significantly differ between people with different magnitudes of burnt area.

day and night-time temperatures (including three consecutive days above 43 °C / 109 °F), low humidity, and high wind speeds. These fires claimed 173 lives, destroyed 3,500 buildings, and burnt 450,000 hectares. The fires constituted a major traumatic shock to the community, with the death of 112 people occurring in only eight minutes. Valuation of the wellbeing costs of wildfires will assist with the prediction of market and non-market costs of wildfires. It will also illuminate whether disaster relief and recovery spending reach the neediest segments of society, including socio-economically and psychologically vulnerable groups. Moreover, the valuation cost estimates will inform on the appropriate levels of mitigation spending, which must consider the fact that welfare losses due to wildfires are driven by both the size and the duration of the deleterious effects.

Using the Household, Income and Labour Dynamics in Australia (HILDA) Survey, we estimate causal effects through a difference-in-differences approach. Specifically, we identify HILDA respondents within a 100km radius of the outer borders of the five deadly bushfire pockets, and classify individuals residing within the 0-15km and 15-30km rings as the treatment groups, and those within the 30-50km and 30-100km rings as alternative control groups.

Our results document several important findings. First, life satisfaction is significantly reduced in the disaster year (2009) within the 0-15km ring, relative to the pre-disaster period. Our estimated valuation of the wildfire effect corresponds to A$52,300 per person. That is, affected individuals required, on average, a compensation of A$52,300 in order to mute the negative wellbeing effects they experienced due to the bushfire exposure. This amount is not trivial as it corresponds to roughly 80% of the 2009 annual earnings of a full-time employed adult in Victoria, Australia. Second, the wellbeing effects for the outer ring of 15-30km are estimated to be negligible, suggesting that wellbeing effects are substantially reduced in zones farther from the bushfire pockets. Third, we identify the safety domain of wellbeing (i.e. "feeling safe") as being the principal factor driving the reduced wellbeing effects. Fourth, we document a delayed onset of mental health decline, whereby individuals within the 0-15 ring experienced mental health problems one year after the disaster. Our results are robust to a range of considerations regarding the construction of the treatment and control groups, and a battery of checks related to satisfying the parallel trends assumption.

Despite the significant shock to individuals' wellbeing, the effect was concentrated in the first-year post-disaster. It is possible that government relief and recovery programs, assisted in the wellbeing rebound. For instance, governments implemented various disaster recovery programs in the aftermath of the BSB, including, among others, rehousing and recovery projects for destroyed and damaged properties, state-wide community projects, psychological support, scholarships, school holiday programs, and primary producer repair and restoration. An important policy question that we are unable to answer in this study, is whether more could be done in the first several months to reduce the initial significant decline in wellbeing. This is especially important for people who are socially isolated, as it is for this group that we find particularly large negative effects.

6 References

Abatzoglou, John T. and A. Park Williams, "Impact of anthropogenic climate change on wildfire across western US forests," *Proceedings of the National Academy of Sciences*, 2016, *113* (42), 11770–11775.

ABS: Australian Bureau of Statistics, 2017. Australian Statistical Geography Standard (ASGS): Volume 1 - Main Structure and Greater Capital City Statistical Areas, July 2016.

, 2019. Average Weekly Earnings Australia, Cat No. 6302.0.

Ambrey, Christopher L, Christopher M Fleming, and Matthew Manning, "The social cost of the Black Saturday bushfires," *Australian Journal of Social Issues*, 2017, *52* (4), 298–312.

Au, Nicole and David W Johnston, "Too much of a good thing? Exploring the impact of wealth on weight," *Health economics*, 2015, *24* (11), 1403–1421.

Australian Emergency Management Institute, "Event – Bushfire – Black Saturday, Victoria," 2010. http://www.disasters.ema.gov.au/Browse%20Details/DisasterEventDetails.aspx?DisasterEventID=2894.

Australian Wilderness Society, "Summary and implications of Report: Victorian 2009 February Fires," 2015. https://www.wilderness.org.au/articles/

summary-and-implications-report-victorian-2009-february-fires#sthash.R0rgIWhJ.dpuf.

Black Saturday Royal Commission, "The 2009 Victorian Bushfires Royal Commission final report," 2009. http://www.royalcommission.vic.gov.au/Commission-Reports/Final-Report.html.

Bryant, Richard A, Elizabeth Waters, Lisa Gibbs, H Colin Gallagher, Philippa Pattison, Dean Lusher, Colin MacDougall, Louise Harms, Karen Block, Elyse Snowdon et al., "Psychological outcomes following the Victorian Black Saturday bushfires," *Australian & New Zealand Journal of Psychiatry*, 2014, *48* (7), 634–643.

Carroll, Nick, Paul Frijters, and Michael A. Shields, "Quantifying the costs of drought: new evidence from life satisfaction data," *Journal of Population Economics*, 2009, *22 (2)*, 445–461.

Dennison, Philip E, Simon C Brewer, James D Arnold, and Max A Moritz, "Large wildfire trends in the western United States, 1984–2011," *Geophysical Research Letters*, 2014, *41* (8), 2928–2933.

Deryugina, T., L. Kawano, and S. Levitt, "The economic impact of Hurricane Katrina on its victims: Evidence from individual tax returns," *American Economic Journal: Applied Economics*, 2018, *10(2)*, 202–33.

Frey, Bruno S, Simon Luechinger, and Alois Stutzer, "The life satisfaction approach to environmental valuation," *Annu. Rev. Resour. Econ.*, 2010, *2* (1), 139–160.

Frijters, Paul, David W Johnston, and Michael A Shields, "Life satisfaction dynamics with quarterly life event data," *Scandinavian Journal of Economics*, 2011, *113* (1), 190–211.

Gibbs, L., R. Bryant, L. Harms, D. Forbes, K. Block, HC. Gallagher, G. Ireton, J. Richardson, P. Pattison, C. MacDougall, and D. Lusher, "Beyond Bushfires: Community Resilience and Recovery Final Report," 2016. University of Melbourne, Victoria, Australia.

Goldammer, Johann Georg, "Vegetation fires and global change-challenges for concerted international action: a white paper directed to the United Nations and International Organizations," *Planet@ risk*, 2015, *3* (1).

Johnston, David W., Michael A. Shields, and Agne Suziedelyte, "Victimisation, Wellbeing and Compensation: Using Panel Data to Estimate the Costs of Violent Crime," *The*

Economic Journal, 2018, *128* (611), 1545–1569.

Jolly, W Matt, Mark A Cochrane, Patrick H Freeborn, Zachary A Holden, Timothy J Brown, Grant J Williamson, and David MJS Bowman, "Climate-induced variations in global wildfire danger from 1979 to 2013," *Nature communications*, 2015, *6* (1), 1–11.

Jones, Benjamin A, "Are we underestimating the economic costs of wildfire smoke? An investigation using the life satisfaction approach," *Journal of Forest Economics*, 2017, *27*, 80–90.

, "Willingness to pay estimates for wildfire smoke health impacts in the US using the life satisfaction approach," *Journal of Environmental Economics and Policy*, 2018, *7* (4), 403–419.

Kimball, Miles, Helen Levy, Fumio Ohtake, and Yoshiro Tsutsui, "Unhappiness after Hurricane Katrina," 2006. NBER Working Paper No. 12062.

Kountouris, Yiannis and Kyriaki Remoundou, "Valuing the Welfare Cost of Forest Fires: a Life Satisfaction Approach," *Kyklos*, 2011, *64* (4), 556–578.

Krekel, Christian and Alexander Zerrahn, "Does the presence of wind turbines have negative externalities for people in their surroundings? Evidence from well-being data," *Journal of Environmental Economics and Management*, 2017, *82*, 221–238.

Levinson, Arik, "Valuing public goods using happiness data: the case of air quality," *Journal of Public Economics*, 2012, *96*, 869–880.

Luechinger, Simon and Paul A. Raschky, "Valuing flood disasters using the life satisfaction approach," *Journal of Public Economics*, 2009, *93*, 620–633.

McCoy, Shawn J and Randall P Walsh, "Wildfire risk, salience & housing demand," *Journal of Environmental Economics and Management*, 2018, *91*, 203–228.

Moeltner, Klaus, M-K Kim, E Zhu, and W Yang, "Wildfire smoke and health impacts: A closer look at fire attributes and their marginal effects," *Journal of Environmental Economics and Management*, 2013, *66* (3), 476–496.

National Museum Australia, "Defining Moments: Black Saturday bushfires," 2020. https://www.nma.gov.au/defining-moments/resources/black-saturday-bushfires.

Önder, Yasin Kürşat, Muhammad Habibur Rahman, and Mehmet Ulubaşoğlu, "Spatial Transmission of the Black Saturday Bushfires in Australia," 2020. Unpublished Manuscript.

Palinkas, Lawrence A, *Global Climate Change, Population Displacement, and Public Health: The Next Wave of Migration*, Springer Nature, 2020.

Praag, Bernard MS Van and Barbara E Baarsma, "Using happiness surveys to value intangibles: The case of airport noise," *The Economic Journal*, 2005, *115* (500), 224–246.

Rehdanz, Katrin, Heinz Welsch, Daiju Narita, and Toshihiro Okubo, "Well-being effects of a major natural disaster: The case of Fukushima," *Journal of Economic Behavior & Organization*, 2015, *116*, 500–517.

Reid, Colleen E, Michael Brauer, Fay H Johnston, Michael Jerrett, John R Balmes, and Catherine T Elliott, "Critical review of health impacts of wildfire smoke exposure," *Environmental health perspectives*, 2016, *124* (9), 1334–1343.

Schoennagel, Tania, Jennifer K Balch, Hannah Brenkert-Smith, Philip E Dennison, Brian J Harvey, Meg A Krawchuk, Nathan Mietkiewicz, Penelope Morgan, Max A Moritz, Ray Rasker et al., "Adapt to more wildfire in western North American forests as climate changes," *Proceedings of the National Academy of Sciences*, 2017, *114* (18), 4582–4590.

Sekulova, Filka, JCJM Van den Bergh et al., "Floods and happiness: Empirical evidence from Bulgaria," *Ecological Economics*, 2016, *126* (C), 51–57.

Stephenson, Catherine, John Handmer, and Aimee Haywood, "Estimating the Net Cost of the 2009 Black Saturday Fires to the Affected Regions," 2012. Tech report. RMIT, Bushfire CRC, Victorian DSE.

Stetler, Kyle M, Tyron J Venn, and David E Calkin, "The effects of wildfire and environmental amenities on property values in northwest Montana, USA," *Ecological Economics*, 2010, *69* (11), 2233–2243.

von Möllendorff, Charlotte and Jesko Hirschfeld, "Measuring impacts of extreme weather events using the life satisfaction approach," *Ecological Economics*, 2016, *121*, 108–116.

Westerling, Anthony LeRoy, "Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring," *Philosophical Transactions of the Royal Society B: Biological Sciences*, 2016, *371* (1696).

Wong, Yunong Huang Hung, "Impacts of Sense of Community and Satisfaction with Governmental Recovery on Psychological Status of the Wenchuan Earthquake Survivors," *Social Indicators Research*, 2014, *117 (2)*, 421–436.

Zhang, Xin, Xiaobo Zhang, and Xi Chen, “Happiness in the air: How does a dirty sky affect mental health and subjective well-being?,” *Journal of environmental economics and management*, 2017, *85*, 81–94.

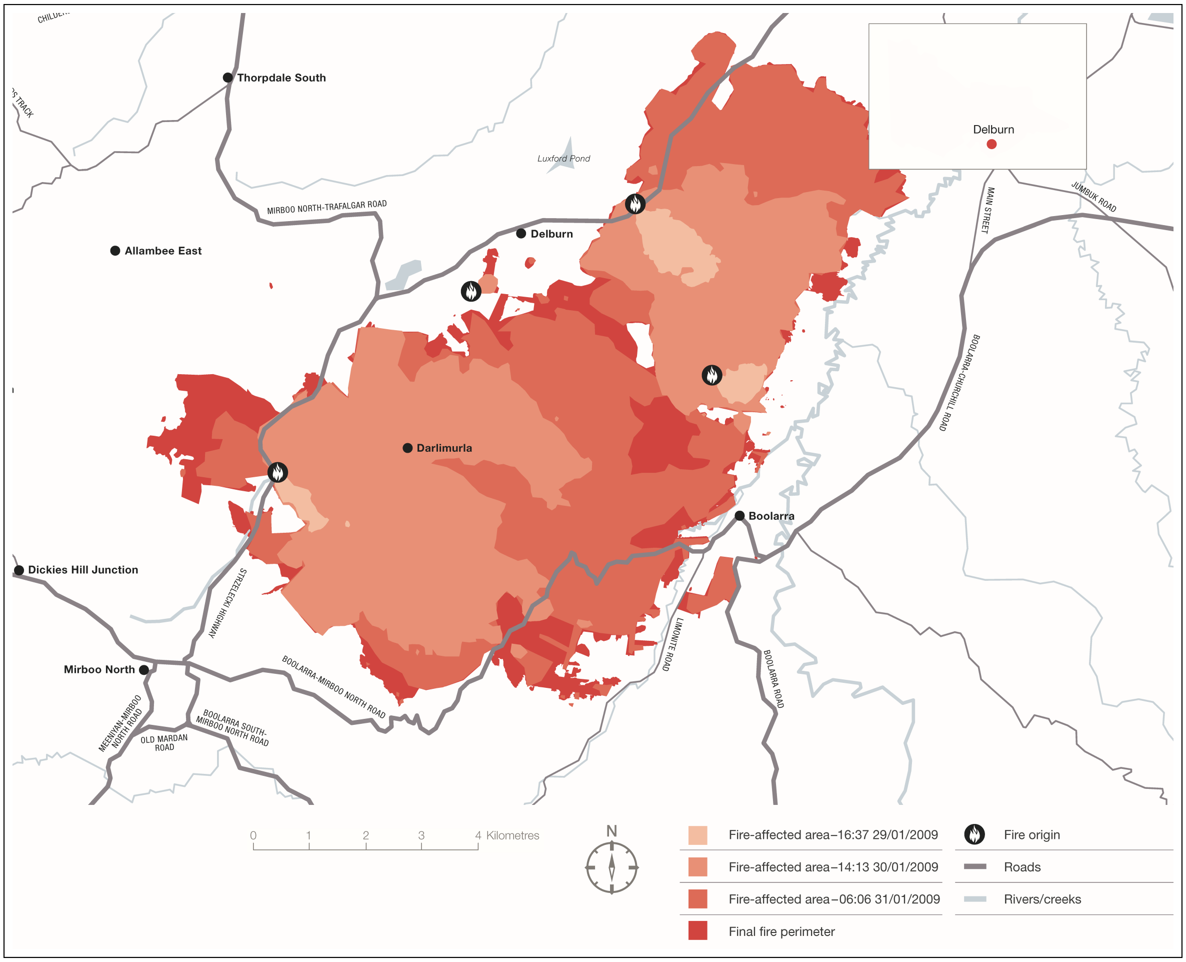

Figure 1: The figure shows the extent of fires in Delburn hotspot. Source: Black Saturday Royal Commission (2009).

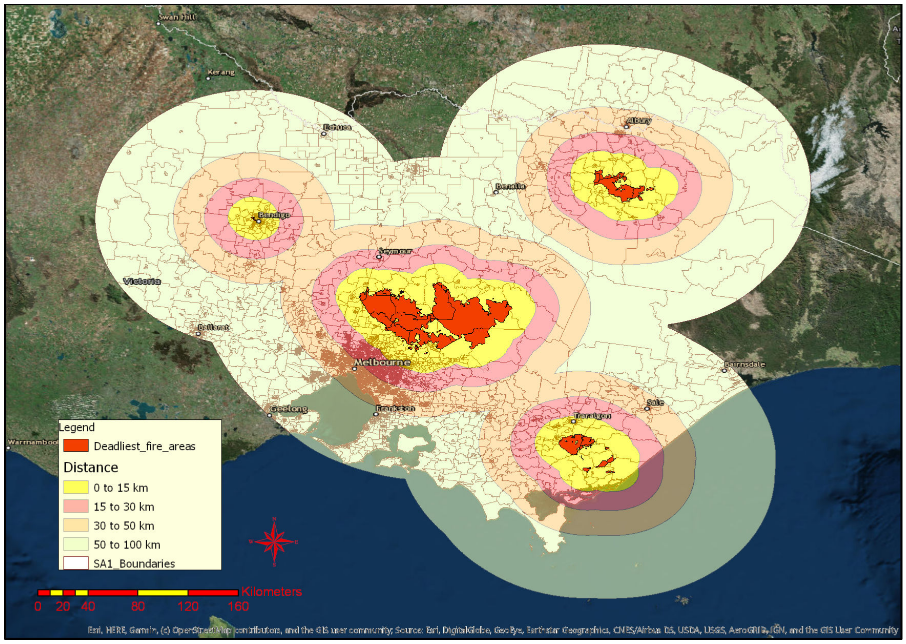

Figure 2: Distribution and location of deadliest fire zones. The red zones (epicenter of the rings) represent the locations of the deadliest fires. The yellow zones overlap the deadliest fire zones and extend to its neighbouring areas within a 15km radius. Outer rings are distances from the yellow zones with 30km, 50 km and 100km radii.

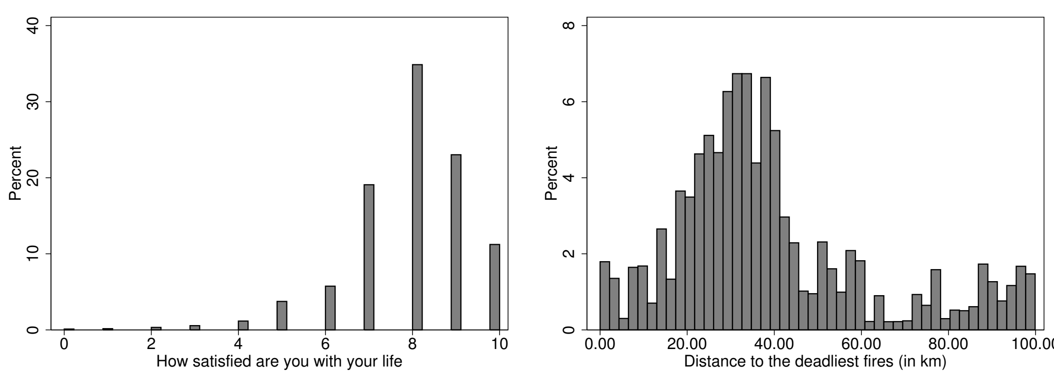

Figure 3: Left panel displays the distribution of well-being scores of respondents. Right panel shows the distance distribution of respondents to the deadliest BSB fires.

Table 1: Details of the Black Saturday Bushfires used in the analysis

Fires	Fatalities	Casualties	Houses Destroyed	Burnt area Hectares
Killmore-East	119	232	1,242	125,383
Churchill	11	35	145	25,861
Murrindindi	40	73	538	168,542
Bendigo	1	41	58	341
Beechworth-Mudgegonga	2	12	38	33,577

Note: This table summarizes the fire toll in each of the 12 non-contiguous bushfire area. Source: Önder et al. (2020).

Table 2: Sample characteristics

	Year before the BSB				Diff.	Year after the BSB			
	distance < 15km		distance > 30km			distance < 15km		distance > 30km	
	mean	**sd**	**mean**	**sd**	***P*-val.**	**mean**	**sd**	**mean**	**sd**
Wellbeing	8.12	1.38	7.92	1.39	0.987	7.93	1.44	7.88	1.41
Your employment opportunities	7.53	1.99	7.27	2.13	0.946	7.18	2.13	7.13	2.25
Your financial situation	6.78	1.98	6.46	2.18	0.990	6.52	2.05	6.46	2.19
How safe you feel	8.44	1.44	8.20	1.52	0.992	8.37	1.46	8.24	1.49
Feeling part of your local community	7.25	2.12	6.75	2.18	0.999	7.28	2.04	6.69	2.17
Your health	7.55	1.94	7.34	1.81	0.954	7.47	1.96	7.33	1.89
The neighbourhood in which you live	8.19	1.65	7.84	1.69	0.999	8.23	1.51	7.85	1.67

Note: The means and standard deviations (sd) are presented for the most inner ring (i.e., distance less than 15km) and the control ring (i.e., distance greater than 30km) for our benchmark 0-100km sample for the years immediately before (2008) and immediately after (2009) the BSB. For balancedness, Column 5 shows the *p*-values whether there is a positive difference between the unconditional means of the inner (i.e., treatment) and control rings before the BSB.

Table 3: The Impact of the BSB on Life Satisfaction: A Ring Approach

	(1)	(2)	(3)	(4)
0-15 km × 2008	-0.0264	-0.0229	-0.0658	-0.0449
	(0.0904)	(0.0890)	(0.0919)	(0.0895)
0-15 km × 2009	-0.1771**	-0.1881***	-0.1450*	-0.1737**
	(0.0720)	(0.0706)	(0.0745)	(0.0717)
0-15 km × 2010	-0.0417	-0.0715	-0.0513	-0.0880
	(0.0815)	(0.0799)	(0.0843)	(0.0809)
0-15 km × 2011	-0.0550	-0.0798	-0.0533	-0.0878
	(0.0784)	(0.0762)	(0.0803)	(0.0768)
15-30 km × 2008	-0.0110		-0.0497	
	(0.0498)		(0.0532)	
15-30 km × 2009	0.0361		0.0690	
	(0.0501)		(0.0542)	
15-30 km × 2010	0.0972*		0.0882	
	(0.0509)		(0.0556)	
15-30 km × 2011	0.0801		0.0825	
	(0.0494)		(0.0525)	
Observations	25611	25611	19555	19555
R^2	0.004	0.004	0.006	0.006
Indiv. Fixed Effects	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y
Within 100km	Y	Y	N	N
Within 50km	N	N	Y	Y

Standard errors in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: The estimation method is OLS. The reference period is 2003-2007. 2008 is the year prior to the BSB, 2009 is the BSB year, and 2010 and 2011 are the post-BSB years. Standard errors are clustered at the SA1 level.

Table 4: The Impact of the BSB on Life Satisfaction: Subcomponents of Life Satisfaction

	(1)	(2)	(3)	(4)	(5)	(6)
0-15 km × 2008	0.1245	0.1560	-0.0662	0.1098	0.1433*	0.0652
	(0.1600)	(0.1229)	(0.0672)	(0.1251)	(0.0848)	(0.1050)
0-15 km × 2009	-0.1289	-0.0483	-0.1695*	0.2522**	0.1131	0.1097
	(0.1410)	(0.1618)	(0.0864)	(0.1277)	(0.0918)	(0.1016)
0-15 km × 2010	-0.2039	-0.0213	-0.2267**	0.0327	0.1048	0.0762
	(0.1617)	(0.1732)	(0.0939)	(0.1304)	(0.1008)	(0.1004)
0-15 km × 2011	-0.2920	0.1587	-0.1337	-0.1464	0.0015	0.0242
	(0.1812)	(0.1526)	(0.0859)	(0.1427)	(0.1138)	(0.1193)
15-30 km × 2008	0.0191	0.0910	-0.0342	0.1178	0.0278	-0.0152
	(0.0827)	(0.0844)	(0.0602)	(0.0777)	(0.0584)	(0.0623)
15-30 km × 2009	-0.0512	0.0274	-0.1058*	0.1240	-0.0117	0.0585
	(0.0891)	(0.0796)	(0.0630)	(0.0854)	(0.0651)	(0.0700)
15-30 km × 2010	0.0066	0.0566	0.0207	0.2022**	0.1083	0.0607
	(0.0998)	(0.0838)	(0.0599)	(0.0895)	(0.0678)	(0.0728)
15-30 km × 2011	0.0179	-0.0516	-0.0764	0.0718	-0.0258	-0.0535
	(0.1060)	(0.0850)	(0.0676)	(0.0890)	(0.0659)	(0.0797)
Observations	20384	25611	25612	25597	25615	25610
R^2	0.007	0.011	0.003	0.002	0.017	0.003
Indiv. Fixed Effects	Y	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y	Y

Standard errors in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: The estimation method is OLS. The reference period is 2003-2007. 2008 is the year prior to the BSB, 2009 is the BSB year, and 2010 and 2011 are the post-BSB years. Standard errors are clustered at the SA1 level. The dependent variables are as follows: column (1): "your employment opportunities"; column (2) "Your financial situation"; column (3) "How safe you feel"; column (4): "Feeling part of your local community"; Column (5): "your health"; column (6) " The neighbourhood in which you live". For brevity we do not present the results using the sample within the 50km radius or the results with only the 15km ring as the treatment group. Estimates are highly similar to the presented here.

Table 5: The Impact of the BSB on Mental Health

	(1)	(2)	(3)	(4)	(5)	(6)
0-15 km × 2008	0.0055	-0.0029	0.1294*	-0.0093	0.0348	-0.0117
	(0.0630)	(0.0472)	(0.0669)	(0.0541)	(0.0588)	(0.0266)
0-15 km × 2009	-0.0503	-0.0039	0.0179	-0.0116	0.0429	0.0123
	(0.0627)	(0.0671)	(0.0634)	(0.0656)	(0.0645)	(0.0281)
0-15 km × 2010	-0.2588***	-0.0947*	0.1621**	-0.0871	0.2718***	-0.0788***
	(0.0726)	(0.0561)	(0.0702)	(0.0579)	(0.0715)	(0.0273)
0-15 km × 2011	-0.1462**	-0.0981	-0.0012	-0.1068	0.1554**	0.0091
	(0.0677)	(0.0655)	(0.0944)	(0.0656)	(0.0655)	(0.0345)
15-30 km × 2008	-0.0140	0.0115	0.0197	-0.0454	0.0024	0.0118
	(0.0380)	(0.0366)	(0.0433)	(0.0391)	(0.0408)	(0.0213)
15-30 km × 2009	-0.0019	0.0171	-0.0407	-0.0030	-0.0158	-0.0252
	(0.0406)	(0.0404)	(0.0424)	(0.0422)	(0.0423)	(0.0180)
15-30 km × 2010	-0.0488	0.0332	-0.0478	0.0203	-0.0346	0.0044
	(0.0410)	(0.0374)	(0.0484)	(0.0444)	(0.0440)	(0.0206)
15-30 km × 2011	0.0107	0.0521	-0.0624	0.0023	-0.0144	0.0392**
	(0.0420)	(0.0407)	(0.0513)	(0.0445)	(0.0460)	(0.0197)
Observations	23146	23095	23137	23100	23124	13538
R^2	0.002	0.002	0.001	0.001	0.005	0.002
Indiv. Fixed Effects	Y	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y	Y
Within 100km	Y	Y	Y	Y	Y	Y

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: The dependent variable in each columns is as follows: column (1) 'have you been a nervous person?", column (2) "have you felt so down in the dumps nothing could cheer you up?", column (3) "have you felt calm and peaceful?", column (4) "have you felt down?", and column (5) "have you been a happy person?" The responses to these questions are measured in a reverse order, whereby the answer "All of the time" takes the value 1 and "None of the time" takes the value 6. The dependent variable in column (6) in a summary health indicator whereby HILDA A9 questions are aggregated with principal-component factor model. The estimation method is OLS. The reference period is 2003-2007. 2008 is the year prior to the BSB, 2009 is the BSB year, and 2010 and 2011 are the post-BSB years. Standard errors are clustered at the SA1 level.

Table 6: Estimated valuation of the wellbeing loss

Income shock comparison approach				Simple approach
Discounted wildfire effect	Disc. income shock effect	Average income shock value	Valuation estimate	With indiv fixed-effects
(1)	(2)	(3)	(4)	(5)
-0.310	0.269	0.419	0.523	-7.551
(-0.635, 0.002)	(0.140, 0.403)	(0.315,0.544)	(-0.003,1.332)	(-19.219, 4.116)

Note: Income and compensation are measured in A$100,000. Allowing for clustering, the confidence interval estimates shown in parentheses in columns (1)–(4) span from the 2.5th percentile to the 97.5th percentile of the 1,000 bootstrapped coefficients. Conventional 95% confidence interval is shown in column (5).

Table 7: Impacts of the BSB on life satisfaction estimated separately for subsamples

Dependent Variable: Life Satisfaction	0-15 km ×2009	Standard Error	Obs.
Panel A: Demographics			
Age: Below 45 years	-0.181	(0.115)	13503
Age: 45 years or above	-0.237**	(0.114)	12108
Female	-0.219*	(0.118)	13504
Male	-0.137	(0.096)	12107
Married	-0.071	(0.102)	13135
Unmarried	-0.287**	(0.144)	12476
Panel B: Socioeconomic Status			
Education: 12 years or below	-0.118	(0.109)	12629
Education: 12 years above	-0.219*	(0.120)	12982
SEIFA index of education & occupation: Below median	-0.118	(0.093)	13025
SEIFA index of education & occupation: Above median	-0.278*	(0.147)	12586
Income: Below median	-0.250**	(0.121)	12806
Income: Above median	-0.142	(0.104)	12805
Panel C: Social Capital			
Social support index < 0	-0.803**	(0.320)	16610
Social support index > 0	-0.104	(0.091)	17340
Neighbors' bondage: Below median	-0.15	(0.109)	12763
Neighbors' bondage: Above median	-0.172*	(0.094)	12848
Neighbors' hostility: Below median	-0.269	(0.166)	12646
Neighbors' hostility: Above median	-0.094	(0.086)	12965

Note: The dependent variable in each columns is life satisfaction. The estimation method is OLS. We use same specification as in Table 3. An index of education and occupation is sourced from the Socioeconomic Indexes for Areas (SEIFA) dataset of the Australian Bureau of Statistics (ABS).We constructed social support index using a factor analysis on 10 HILDA variables (i.e., lssuppv, lssupnh, lssuplf, lssupac, lssuplt, lssupcd, lssupvl, lssuppi, lssuptp, and lssupsh). Similarly, using a set of HILDA variables we calculated neighbors' bondage (i.e., lslanh and lsland) and neighbors' hostility (i.e., lslaha, lslavd, and lslabt).

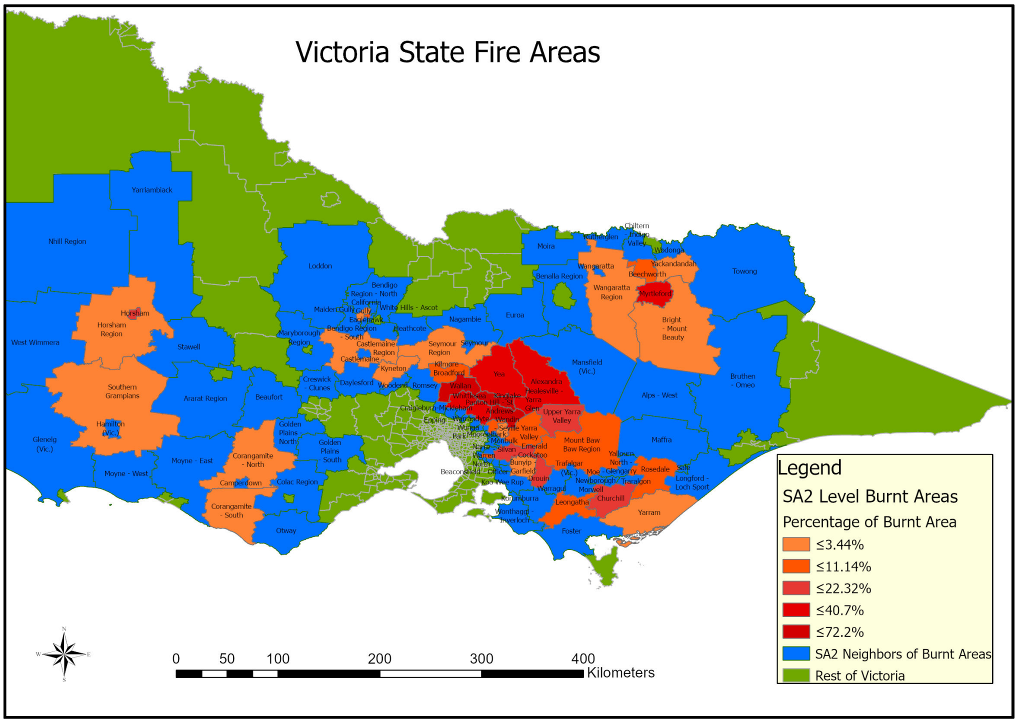

Figure A1: The figure displays the percentage burnt of a particular SA2 at the time of BSB. Blue colored part of the map represents the SA2 areas that has a border to a burnt area but was not directly impacted by the fires. Green colored parts represent the SA2s that do not have any borders to the direct hit area.

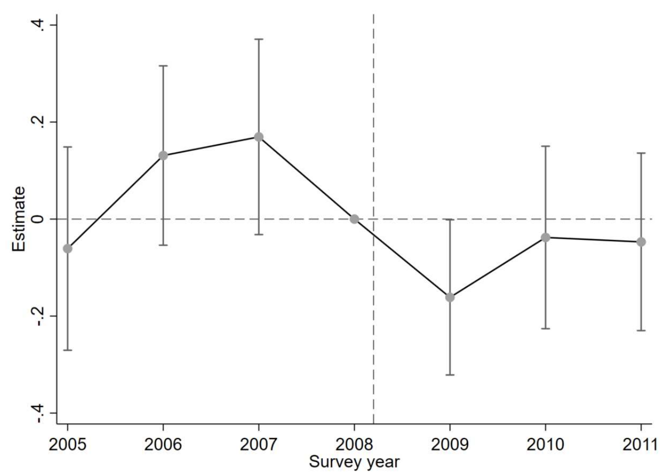

Figure A2: Event study analysis.

Table A1: The Estimated Effects of the BSB on Life Satisfaction in 2009 using alternative treatment groups

Treatment group	No. of people in treatment group	Estimate	Std. Error
0-10km	216	-0.201	-0.108
0-15km	340	-0.161	-0.084
0-20km	554	-0.089	-0.065
0-25km	916	0.008	-0.056

Note: The individual fixed-effects regression specification corresponds to Figure 4, and allows for BSB effects in 2005, 2006, 2007, 2009, 2010 and 2011, with 2008 being the reference year. All estimates other than those for 2009 are individually and jointly statistically insignificant. Standard errors clustered at the SA1 area level in parentheses.

Table A2: Parallel Trend Assumption: Using Placebo Years of Wildfires

	(1)	(2)
0-15 km × 2004	-0.11	-0.15
	(0.104)	(0.105)
0-15 km × 2005	-0.11	-0.087
	(0.090)	(0.092)
0-15 km × 2007	0.093	0.10
	(0.081)	(0.085)
0-15 km × 2008	-0.055	-0.093
	(0.105)	(0.108)
15-30 km × 2004	0.090	0.049
	(0.059)	(0.062)
15-30 km × 2005	-0.028	-0.0075
	(0.053)	(0.057)
15-30 km × 2007	-0.062	-0.051
	(0.053)	(0.058)
15-30 km × 2008	-0.018	-0.055
	(0.059)	(0.063)
Observations	17300	13240
R^2	0.0033	0.0046
Indiv. Fixed Effects	Y	Y
Year Fixed Effects	Y	Y
Within 100km	Y	N
Within 50km	N	Y

Note: The estimation method is OLS. Standard errors are clustered at the SA1 level. Standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A3: Life Time Events on Life Satisfaction

	Well-being
Life events in past year: Got married	0.193***
	(0.044)
Life events in past year: Separated from spouse	-0.292***
	(0.062)
Life events in past year: Got back together with spouse	0.010
	(0.131)
Life events in past year: Pregnancy	0.176***
	(0.042)
Life events in past year: Birth/adoption of new child	0.067
	(0.049)
Life events in past year: Serious personal injury/illness	-0.171***
	(0.035)
Life events in past year: Serious injury/illness to family member	-0.0549**
	(0.0214)
Life events in past year: Death of spouse or child	-0.287**
	(0.129)
Life events in past year: Death of close relative/family member	-0.002
	(0.025)
Life events in past year: Death of a close friend	-0.065**
	(0.028)
Life events in past year: Victim of physical violence	-0.199**
	(0.092)
Life events in past year: Victim of a property crime	-0.095**
	(0.038)
Life events in past year: Detained in jail	0.532***
	(0.200)
Life events in past year: Close family member detained in jail	-0.087
	(0.111)
Life events in past year: Retired from the workforce	0.091
	(0.060)
Life events in past year: Fired or made redundant	0.027
	(0.052)
Life events in past year: Changed jobs	-0.0002
	(0.024)
Life events in past year: Promoted at work	-0.017
	(0.030)
Life events in past year: Major improvement in finances	0.198***
	(0.040)
Life events in past year: Major worsening in finances	-0.546***
	(0.062)
Life events in past year: Changed residence	0.030
	(0.024)
Observations	22363
R^2	0.024
Indiv. Fixed Effects	Y

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: Standard errors are clustered at the SA1 level.