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Measuring the economic impact of early bushfire detection

ANU Centre for Social Research and Methods

Professor Nicholas Biddle¹, Dr Colleen Bryant², Professor Matthew Gray¹ and Dinith Marasinghe¹

1 ANU Centre for Social Research and Methods

2 Research School of Earth Sciences

Australian National University

March 2020

Abstract

The fires that occurred over the 2019/20 Australian summer were unprecedented in scale and had a devastating impact on large parts of Australia. In this paper, we estimate the economic costs of bushfires between 2020 and 2049 and the potential reduction in these costs from investments in early fire detection systems. Under various plausible climate change related scenarios the costs of fires over the next 30 years will be considerable, up to \$2.2billion per year, or \$1.2billion per year in Net Present Value terms. Even with conservative estimates of the reduction in the number of economically damaging fires due to earlier fire detection, the reduction in the costs of fires over the next 30 years is considerable. Under plausible scenarios of change leading to a growth in large fires (which almost all scientists expect it will) and early detection leading a reduction in the probability of large fires, then we predict an economic benefit of around \$14.4billion, or \$8.2billion in Net Present Value terms.

Acknowledgements

This paper was funded by Fireball International, developers of real-time mapping and fire detection. While we take into account Fireball International's approach when constructing potential future scenarios, we are not modelling the cost effectiveness of their or other products or specific approaches. The authors would like to thank Christopher Tylor and Tim Ball from Fireball for comments on an earlier draft of the paper, as well as Dr Roslyn Prinsley for co-ordinating comments from colleagues at the ANU.

1 Introduction and overview

Australia is prone to frequent and severe bushfires (wildfires) that result in significant loss of human and animal life, mental and physical injury and illness, and substantial economic costs. The bushfires that occurred over the 2019/20 Australian spring and summer were unprecedented in scale both in Australia and arguably internationally, and had a devastating impact on large parts of Australia, but particularly the east and south-east of the content. As of March 2020, more than 11 million hectares (110,000 square kilometres) had been burnt.¹²

Boer, Resco de Dios et al. (2020) concluded that although the Australian continent is relatively fire prone, typically less than two per cent of the forest biome burns even in the most extreme fire seasons whereas the 2019/20 forest fires burnt 21 per cent. This is a globally unprecedented percentage of any continental forest biome burnt. According to the Australian Academy of Science, the country appears to have lost over a billion birds, mammals and reptiles, with additional loss of life of insects, amphibians and fish.³

The human costs of the 2019/20 fires are large with 34 people having lost their lives. Survey data reveals that 'the vast majority of Australians (78.6 per cent) were impacted either directly, through their family/friends, or through the physical effects of smoke' and that 'around 2.9 million adult Australians had their property damaged, their property threatened, or had to be evacuated' (Biddle, Edwards et al. 2020). More than half of the adult Australian population reported some form of anxiety or worry due to the fires. The Australian Government has allocated at least \$2 billion towards a National Bushfire Recovery Fund.

While the economic costs of the 2019/20 bush fires is still emerging, the insurance costs alone, as of mid-January, was \$1.4 billion (\$2019).⁴ Based on the experience of previous major fires, the total economic costs will be a multiple of the insurance costs. For example, the insurance costs of the 2009 Victorian Black Saturday fires were also \$1.4 billion (in \$2019) whereas the total economic costs are estimated to be \$7.4 billion (\$2019). For reasons discussed below, the costs of the 2019/20 fires are likely to therefore be at least as large, and potentially many times larger than the costs of previous fires.

The scientific consensus is that climate change or global warming/heating is making bushfires more likely, last longer and more intense (IPCC 2014). This is due to a combination of the direct effect of high temperatures on combustibility during the fire season, the difficulties of hazard reduction during hotter than average years and the decreased moisture due to more frequent and prolonged drought in part due to increases in drought associated with El Niño (Cai et al., 2014; Garnaut 2019; State of the Climate Report,⁵ 2018; Wang et al. 2017). The prediction is for 'An increase in the number of higher fire weather danger days and a longer fire season for southern and eastern Australia' (State of the Climate, 2018).

¹ https://www.bbc.com/news/world-australia-50951043 [accessed 29 March 2020]

² In a paper published since this report was finalised, Bowman et al. (2020) estimate using satellite imagery that the total area burned was 30.4 million hectares, about 24 per cent lower than estimates from compilations of official government sources. However, the authors also estimate that 'almost 20% of Australia's eucalyptus forest coverage burnt — a figure more than 7.5 times higher than the annual average percentage burnt for the past 18 years.'

³ <u>https://www.science.org.au/news-and-events/news-and-media-releases/australian-bushfires-why-they-are-unprecedented [accessed 29 March 2020]</u>

⁴ Data from the Insurance Council of Australia.

⁵ <u>http://www.bom.gov.au/state-of-the-climate/</u>

Even if the world is successful in climate change mitigation, under the most optimistic scenarios, it is likely that temperatures will still increase by 1.5-2°C over pre-industrial levels and that temperature increases, increased frequency of heatwaves, are likely to be greater in Australia than the global average (Cowan, Purich et al. 2014). Australia alone cannot control the future effects of climate change and is highly reliant on global efforts. It is important, therefore, for bushfire policy planning to reflect likely increases in average temperature.

According to the Productivity Commission (2014) governments overinvest in post-disaster reconstruction and underinvest in mitigation that would limit the impact of natural disasters in the first place. As such, natural disaster costs have become a growing, unfunded liability for governments. This statement applies equally to bushfires as it does to other types of natural disasters. Finding ways to reduce the incidence and severity of large bushfires are likely to have large economic returns.

A key determinant of whether a fire ignition turns into a large and costly fire is the size of the fire when fire suppression resources arrive. The more quickly fire suppression resources arrive at the fire ground (the initial attack delay) the smaller the fire will be at the time of first attack response and the better the chances of the fire being contained before it can do significant economic damage. One of the ways of responding more quickly to fires is to increase how quickly fires are detected through investments in early fire detection system.

This paper presents results of the modelling of the potential impact of earlier detection of fires which increases the effectiveness of initial fire suppression efforts on the economic costs of Australian bushfires over the period 2020 to 2049. Specifically, we combine a number of databases on the current distribution of bushfires within Australia and then relate these to known cost estimates. We then outline a number of potential future distributions of bushfires and related costs based on plausible climate change scenarios and population growth and changes in density. These are the counterfactual scenarios, in the absence of any policy change. For each of these future counterfactual scenarios, we then introduce a number of alternative (treatment) scenarios with more rapid detection of fires, with related decreases in either the number or scale of fires under extreme fire weather conditions. The Net Present Value of the difference between the estimated costs under the counterfactual and treatment scenarios are then taken to be an initial estimate of the economic impact of early bushfire detection.

The costs of developing and implementing early detection systems that can achieve the fire detection outcomes modelled under the different scenarios have not been taken into account and thus any investment decisions based on a cost or benefit or return on investment criteria would need to offset these costs against the projected benefits.

The remainder of the paper is structured as follows. First, we provide a brief contextual review of the literature on risk factors for bushfires, how these impact upon fire suppression and the success of fire suppression and the potential role for early fire detection in reducing fire probabilities (Section 2). This is followed in Section 3 by a discussion of the methods for estimating the costs of bushfires, including direct tangible costs, indirect tangible costs, and intangible costs. We then introduce the data and methods used to estimate the economic impacts of early detection, including the parameters for the counterfactual and treatment scenarios (Section 4), followed by our initial estimates and a discussion of their sensitivity to alternative assumptions (Section 5). In the final section of the paper (Section 6), we provide

some concluding comments, and outline what we think the data and research needs are for a more comprehensive analysis of the economic impacts of early detection of bushfires.

2 The distribution of fires in Australia and the role of bushfire detection in bushfire risk

According to Geosciences Australia, 'Bushfires are an intrinsic part of Australia's environment. Natural ecosystems have evolved with fire, and the landscape, along with its biological diversity, has been shaped by both historic and recent fires.'⁶ Table 1 summarises data on the distribution of fires over the period 2008 to January 2020 for the three States in Australia that have experienced the greatest number of economic losses and fatalities – New South Wales, Victoria and South Australia.⁷ The dataset includes 13,790 bushfires ranging in size from less than 1 hectare to 1,346,813 hectares (hazard reduction fires that were lit and controlled by fire services are excluded).⁸

Table 1 divides bushfires fires into ten roughly equal size groups (deciles), with the average size, as well as the minimum and maximum size within each of the deciles. The majority of Australian fires are small with the median fire size being 5 hectares. The distribution of fire size being highly skewed. Decile 1 (smallest fires) entirely consists of fires of less than 1 hectare, and the fires in decile 10 (largest fires) range from a minimum fire size of 258 hectares to over one million hectares. The vast majority of total hectares burned in these three States come from a small number of fires.

⁶ <u>https://www.ga.gov.au/scientific-topics/community-safety/bushfire</u> [accessed 29 March 2020]

⁷ Fires in Queensland, Western Australia, and the Northern Territory tend to be less costly and to be much smaller in size

⁸ In the costs database used later in this paper, some of these fires are merged, as they commenced roughly concurrently or eventually merged.

Decile	Minimum	Mean	Maximum	
1 (smallest fires)	0	0	0	
2	0	0	1	
3	1	1	2	
4	2	2	3	
5	3	4	5	
6	5	7	9	
7	9	13	18	
8	18	30	47	
9	47	112	258	
) 10 (largest fires)	258	9 9/8	1 346 813	
TO Haigest mest	2.30		1,070,010	
Total	0	1,012	1,346,813	

Table 1Mean, minimum and maximum fire size (hectares) by fire size decile

Note: Hazard reduction fires that were controlled are excluded

Sources: 1) Department of Planning, Industry and Environment: NPWS Fire History - Wildfires and Prescribed Burns https://datasets.seed.nsw.gov.au/dataset/fire-history-wildfires-and-prescribed-burns-1e8b6

2) Department of Environment, Water and Natural Resources, Forestry SA and SA Water: Bushfires and Prescribed Burns History https://data.sa.gov.au/data/dataset/fire-history

3) Department of Environment, Land, Water and Planning (VIC) - Fire history overlay of most recent fires https://discover.data.vic.gov.au/dataset/fire-history-overlay-of-most-recent-fires

Twenty-three fires that met the minimum cost threshold to be included in the Insurance Council of Australia (ICA) database, with the vast majority not included in the fire cost database used in this paper. Only one of these (the Bunker Hill Bushfire in 2019) had a total area outside of the 10th decile in Table 1, with the average size of fires in the cost database over the 2008-2020 period being around 503,000 hectares. In other words, there is very little overlap between the bushfires database and the costs database discussed below.

The question then is, what factors influence the growth of a fire from a few hectares to the hundreds and thousands, and what role does early detection play in this potential growth.

2.1 The determinants of fire containment

The effectiveness of extinguishment measured in terms of the final area burned, the containment times, and the probability of containment within a given time frame or area, are a function of, or correlated with a number of environmental factors.

The fire-related weather at the time of ignition is associated with the probability of containment of forest fires in particular decreasing as fire weather severity increases (measured by the Forest Fire Danger Index (Arienti et al., 2006; Penman et al., 2013b; Plucinski, 2012; Collins et al., 2018).

The behaviour of grassfires and forest fires, however, differ. The behaviour of grass fires is highly influenced by weather (e.g., Cheney and Sullivan 2008), and can spread more rapidly than fires in other vegetation types (e.g., Luke and McArthur 1978; Cheney and Sullivan 2008; Sullivan 2010). However, most grassfires in Australia are contained quickly, with Collins et al. (2018) identifying that of the 4,618 grassfires included within their study (NSW, July 2005 to

June 2013), 95.2% were contained within 2 hours, and 98.9 percent were contained in less than 4 hours.

Forest fires take longer to contain than grassfires (762 minutes compared to 52 minutes). Although direct attack at the fires edge may be possible for some forest fires there is a greater probability that forest fires will require indirect attack, involving the construction of physical or chemical containment lines (e.g., back-burning, fire-retardant, grading), (e.g., Fried and Fried, 1996; Luke and McArthur, 1978). Not only is this process itself more time-consuming, there is often a need to wait for the arrival of the fire at the barrier. Fuel loads influencing flame dimensions, spread rates, spot-fire generation and accessibility are strongly correlated with the probability of containment of forest fires (McCarthy and Tolhurst 1998; McCarthy et al., 2012; Plucinski, 2012; Collins et al., 2018).

Fuel reduction burning can be effective in reducing the severity of fires. However, the analysis by Tolhurst & McCarthy (2016, p. 1) of the effects of previous fuel reduction burning on the severity of the 2003 Alpine Fire in eastern Victoria (of greater than one million hectares) highlighted that the reduction in fire severity and suppression assistance effects of previous fuel-reduction burning started to decline substantially when the Forest Fire Danger Index exceeded 50. Above a Forest Fire Danger Index of 50, landscape-scale fires became 'weather-dominated' and variation in fuel and topography became less important to continued fire spread.

The speed with which fire suppression resources arrive at the fire ground and the location, level and nature of fire suppression resources available have a substantial impact on the likelihood of a fire being contained quickly (Hirsch et al., 2004; McCarthy et al., 2012; Penman et al., 2013b; Podur and Martell, 2007). Importantly these are factors that can be influenced by fire policy and resourcing decisions. According to Gill, Stephens et al. (2013):

Minimizing adverse outcomes involves controlling fires and fire regimes, increasing the resistance of assets to fires, locating or relocating assets away from the path of fires, and, as a probability of adverse impacts often remains, assisting recovery in the short term while promoting the adaptation of societies in the long term.

To put this another way, once a fire has been ignited, the probability of that fire having devastating human, economic, and environmental costs is influenced by the speed of detection; the timing and scale of response; the effectiveness of extinguishment; and the post-recovery efforts.

2.2 The specific role of detection and response times

The time taken for fire suppression resources to reach a fire from time of ignition (initial attack delay) is a function of detection time and the response time. The detection time is the time taken for fire authorities to be notified of the fire, which depends upon the time taken for the fire to be observed plus the time taken for this information to be communicated to the fire authorities. The response time is the time taken from detection by the fire authorities to the arrival of suppression resources at the fire and depends upon how quickly resources are deployed (once information is communicated) and the time it takes for those resources to travel to the fire.

Minimising the time between fire ignition and first attack (initial attack delay) is a critical factor in determining how quickly a fire is contained and the final size of the fire. The larger the size (area and perimeter length), and intensity of a fire, the more difficult it becomes to suppress

and the greater the probability it will not be contained within a given time or area (Parks (1964), McCarthy and Tolhurst (1998), McCarthy (2003), Hirsch et al. (2004), Arienti et al. (2006) and Plucinski et al. (2007)). Fires that escape initial attack account for the bulk of the costs associated with bushfires.

While it is very difficult (impossible) to document the detection time of fires unless the actual ignition is observed, there is some data on response times. For NSW over the period July 2005 to June 2013, the response times for forest fires varied from 2 to 237 minutes with a median of 27 and a mean of 35 minutes. The response times for grassfires varied from 2 to 241 minutes with a median of 20 and a mean of 23 minutes (Collins et al. 2018).⁹

The existing evidence suggests that the relationship between response time (as a proxy for initial attack delay) and containment success is complex. What the research does suggest though is that initial attack delay becomes more critical as the fire danger increases (Plucinski et al. 2007). Specifically, on lower risk fire days (Forest Fire Danger Index less than 24) the probability of first attack success was 80 per cent if the time to first attack was less than 2 hours but 40 per cent if the time to first attack was greater than 2 hours (see Figure 1). Aerial attack makes relatively little difference to control likelihood on low fire risk days. On very high fire danger days (Forest Fire Danger Index of between 24 and 50) the probability of first attack was less than 30 minutes and 20 per cent if it was more than 30 minutes. On severe or above fire risk days (Forest Fire Danger Index above 50) the probability of first attack success (with aerial support) decreased to 40 per cent even when the time to first attack was 30 minutes or less.

That is, the window of opportunity for initial attack success decreases, and commensurately the probability of a large fire increases markedly as the fire danger increases. There is only a 40 per cent chance of initial attack success if aircraft reach the fire-ground within the first half hour of detection under conditions where the Forest Fire Danger Index exceeds 50.

⁹ The Collins et al. (2018) estimates are for over 2,200 forest fires and 4,600 grassfires attended by fires services in NSW from July 2005 to June 2013, for which suppression resources were deployed immediately upon notification.



Figure 1 Factors associated with probability of first attack success

Note: FFDI = Forest Fire Danger Index

Source: Plucinski et al. (2007: p4).

3 Measuring the costs of bushfires

While there have been a number of studies that attempt to quantify the costs of bushfires, only fires that have large economic costs have been the subject of the detailed study required to estimate their cost. According to Ambrey, Fleming et al. (2017):

In 2014, the total economic cost of bushfires in Australia was estimated to average approximately \$337 million per year ... In real terms, this total is forecast to grow by 2.2 per cent annually. This is primarily due to the impact of further population growth and concentrated infrastructure density. With this growth rate, the annual total economic cost of bushfires in Australia is expected to reach \$800 million by 2050.

Despite the efforts to construct a standardised estimate of bushfire costs, estimating the costs of bushfires remains a challenge, and as a result, the existing literature on cost estimates is patchy and disparate. Difference in cost estimates stem from the differences in methodology, which costs are included and whether some included components are treated as a loss or a benefit (Ladds, Keating et al. 2017). These differences result in a significant variation in cost estimates. There is widespread recognition amongst researchers of the lack of consistent and comparable data (Ladds, Keating et al. 2017). Estimates of the cost of the 2009 Black Saturday fires are a useful example, with estimates including (all in \$2013) \$6.72 billion (Deloitte Access Economics 2016), \$11.8 billion (Ladds, Keating et al. 2016 and Magee 2017), \$1.5 billion (Stephenson, Handmer et al. 2013), and \$4.8 billion (the Bushfires Royal Commission).

A useful framework for identifying and categorising the costs of bushfires was developed by the Productivity Commission (2014) and is reproduced in Figure 2. Under this framework, the costs of bushfires are broad and include direct market costs, indirect market costs and intangible or non-market cost.





Source: Productivity Commission (2014), Volume 2, Figure 1.1.

Estimating of many of the individual components of the economic costs of fires is often difficult, and as noted above have usually been only available for the largest and most catastrophic fires. For many of the smaller to medium fires only insured losses are available, and even then, the Insurance Council of Australia database only includes disasters where the insured costs (i.e., insurance payouts) exceed \$10 million. Insurance costs are usually an underestimate of the total economic costs of natural disasters as they do not include uninsured property or infrastructure, and very little of the intangible costs or indirect market costs.¹⁰

Within the Productivity Commission (2014) framework, intangible or non-market costs are the most difficult to measure, as they include damages that cannot easily be priced, based on goods and services not usually bought and sold on markets. The most tragic impact of bushfires is the loss of life. In the last half-century, 75 people were killed in the Ash Wednesday bushfires (February 1983); 173 in the Black Saturday bushfires (February to March 2009) and 34 people were killed in the 2019/20 bushfire season. Many other recent fires have resulted in deaths in the single digits. In order to estimate the dollar value of the costs of bushfires, it is necessary to place a monetary value on the loss of human life (Viscusi and Aldy 2003). Using the *Value of*

¹⁰ However in some cases can be an over-estimate, as they reflect the replacement costs, rather than the depreciated value of assets.

Statistical Life (VSL)¹¹a standard estimate recommended by the Department of Prime Minister and Cabinet of \$4.6 million costs of the 2019/20 bushfires purely attributable to deaths would, therefore, be in the order of \$156 million, though this might vary somewhat depending on the age distribution of victims and associated life expectancy.

The costs of serious injury also need to be estimated and this can be done either using estimates derived from the VSL, or a range of other methods that can be used for different types of injuries, including the direct health expenditure, and the opportunity cost of time in treatment and recovery. We do not yet have final estimates of the health impacts of the 2019/20 bushfires, though it is likely that they will be relatively high due to the health impacts of exposure to bushfire smoke.

Environmental and animal welfare costs are also challenging to calculate. One way to put a value on these costs is through willingness to pay (WTP) surveys, where individuals with a particular stake in the preservation of a particular area or aspect of an ecosystem are asked how much they would be prepared to pay (either with their own money or through general revenue) to preserve or repair damage to the environment (Levin and McEwan 2000). While these are sometimes validated against actual expenditure (Carlsson and Martinsson 2001), individuals often give much larger hypothetical values (stated preference) than they are actually prepared to make (revealed preference). There is a large and growing literature on the measurement of this 'hypothetical bias', with an important role for natural field experiments (Hensher 2010). At the moment though, there are such large differences in estimates based on variation in wording, framing, and context that it is difficult to consistently apply WTP estimates.

4 Methods for measuring the economic impact of early bushfire detection

The factors that predict size and intensity of fires (Section 2) can be categorised as: (i) environmental risk factors which impact upon the likelihood of fires starting and the characteristics of fires that do start (e.g., fuel load, vegetation type, topography, fire weather risk); and (ii) firefighting response factors (e.g., detection time, response time and level and nature of fire suppression resources).

While government policies can influence some of the environmental risk factors and factors that affect the economic costs of fires, many of these are not easily amenable to being modified by government policies in the short-term, although many can be influenced by government policies over the longer-term. For example, factors that policy can influence only over the longer-term include the location of urban areas with respect to vegetation type and topography via urban planning, zoning laws and other policies and long-term climate change. Furthermore, climate change cannot be addressed by Australian policy action alone and there is considerable warming that is already likely to occur, regardless of any future emissions reductions. Reductions in fuel loads can have a benefit and can be achieved more quickly, but as the discussion in Section 2 shows, this is only likely to be beneficial on days where the fire risk is comparatively lower.

¹¹ This is 'an estimate of the financial value society places on reducing the average number of deaths by one' (Office of Best Practice Regulation 2014)

In contrast, fire response factors are within control of short- to medium-term policy change, including fire detection and reporting systems, how quickly fires are responded to, the amount and types of firefighting resources and the location of these resources. As outlined in Section 2, an important influence on whether a fire can be controlled before it causes significant economic damage is the time from fire ignition to the arrival of effective fire suppression resources on the fire ground (initial fire attack delay).

One way of reducing the initial attack delay is via reducing the time from detection to the arrival of suppression resources at the fire ground. There, however, are limits to how fast existing suppression resources can arrive at a fire. It is thus necessary to find gains in temporal responses elsewhere. Substantially lowering the detection time, provides one efficient way of achieving that. This can be demonstrated through hypothetical scenarios. Ten minutes equates to a truck travelling about 16.6 km on a highway at 100 km/h, or 8.3 km on a road at 50 km/h. Therefore, reducing detection time by 10 minutes is broadly equivalent to reducing the distance between rural fires station by more than 8 km. In more populated regional areas, of eastern Australia, this may be equivalent to 0.5-1 times the travel distance between rural fire brigade brigades.

The basic approach we follow is to use the existing data to generate a synthetic dataset that has a simulated number of fires, size, location and cost for each year between 2020 and 2049 under different scenarios. This is achieved using the following steps:

- 1. Using existing data on the cost of fires, estimate the relationship between the economic cost of fire (for fires with an insured cost in excess of \$10 million) and fire characteristics including fire size, land use and proximity to urban areas;
- 2. Simulate the distribution of fires and associated costs for the period 2020 to 2049 under a continuation of the recent past number and size of fires and two plausible scenarios (based on the scientific literature) which relate to increases in the number of fires as a result of climate change;
- 3. Simulate the future distribution of fire sizes for each of the three scenarios described in Step 2, for four speed of fire detection scenarios. The first is no change in the speed of fire detection and the other three are for different reductions in response time related to early fire detection than currently is the case; and
- 4. Calculate the difference in costs of fires between the different scenarios.

In the remainder of this section, we expand to describe the methodology in detail.

4.1 Modelling the costs of fires

The first step in our approach involves estimating a model of the relationship between fire characteristics and insured fire costs. This enables estimates of the economic costs of different counterfactual distributions of future fires to be calculated. As discussed above, only fires with an insurance cost in excess of \$10 million are included in the modelling (the list of fires and costs used in the modelling are provided in Appendix A).¹² The costs of fires are adjusted for inflation to be in 2019 dollars. The explanatory variables included in the model are the size of the fire (area in hectares), the distance between the fire and closest significant urban area, the population density of the closest urban area, and the primary land use of the area in which the fire is located.

¹² Given the focus of the paper we **do not do any additional cost estimation for individual fires.**

Several specifications of the cost of fires model related to including log and higher order powers of area burned, and interactions between the main variables of interest were estimated. The final specification is the one which best trades-off maximising the R-Squared (amount of variation explained by the model) and minimises the root mean square error (difference between actual and predicted values) whilst also maintaining plausible predicted values over the observed distribution of fires in the database. Our final model includes linear and non-linear terms for area burned, as well as linear and quadratic term for density of closest urban area.¹³ The parameter estimates are shown in Equation 1.

$insuredcost = 200.7128 * size - 6.60x10^{-6} * size^{2} + 1.05x10^{7} * density + 2.80x10^{6} * landuse2 + 1.56x10^{7} * landuse3 + 1.32x10^{8} * landuse5$ (Equation 1)

Table 2 shows the predicted insured cost for different points on the distribution of fire size (fixing population density at the median value of 2.09 person per hectare) and Table 3 shows the predicted insured costs across the distribution of population density (fixing size of fire at the median of 62,575 hectares). For both distributions, we fix land use at 'Conservation and natural environments', which is the most common category across the fires in the database.

Table 2 shows that the model predicts a positive, but reasonably flat relationship between fire size and insured cost at for fires at the smaller end of the fire size distribution. This reflects the observed data (Figure 3) which shows that for fires under 150,000 hectares, there is a positive relationship, but a significant amount of error around any linear or non-linear model. Variation in costs of fires, therefore, is influenced more by whether a fire is very large or not, rather than by differences at the lower part of the distribution.

¹³ The constant term, higher order values for area burnt (cubic), and a quadratic term for population density drop out of the model as they generate implausible values for certain points on the distribution, whereas minimum distance to an urban area drops out of the model as being insignificant and not improving model fit. The R-Squared for this model is 0.6252 from a sample size of 32 fires from the year 1990 onwards. Extending the model to fires from before 1990 and including normalised rather than insured costs both reduce the fit of the model.

(+)		
Percentile of the fire size distribution	Fire size (hectare)	Predicted insured cost
1%	150	\$21,960,900
5%	650	\$22,061,254
10%	3,000	\$22,532,873
25%	11,050	\$24,147,864
50%	62,575	\$34,464,554
75%	145,500	\$50,994,782
90%	753,314	\$169,385,175
95%	1,200,000	\$253,282,154
99%	9,890,000	\$1,361,420,526

Table 2Predicted distribution of insured costs, across observed distribution of fire size
(\$2019)

Source: Modelling of ICA Database.

Table 3Predicted distribution of insured costs, across observed distribution of
population density (\$2019)

Percentile of the population density distribution	Population density (persons per hectare)	Predicted insured cost
1%	0.253	\$15,191,216
5%	0.273	\$15,405,042
10%	0.969	\$22,708,077
25%	1.796	\$31,386,657
50%	2.089	\$34,464,554
75%	5.720	\$72,590,600
90%	9.163	\$108,748,169
99%	11.523	\$133,521,060

Notes: The 95th and 99th percentiles have the same values, as they are both closest to the Sydney Significant Urban Area

Source: Modelling of ICA Database and Australian Census of Population and Housing.



Figure 3 Observed relationship between fire size and insured cost for fires under 150,000 hectares

Source: ICA Database.

In total, there is data for 52 fires since 1967 for which information on cost is available. Of these fires, 42 fires have data on insured costs and the cost is over \$10 million, 23 fires have reported costs and 13 fires have both insured and reported costs (see Appendix Table A1). As noted in Section 3, reported costs are closer to the full costs of fires as defined in the Productivity Commission framework than are insured costs.

The approach taken in this paper is to use data from the fires with both insured and estimated reported costs to estimate the relationship between insured and reported costs. For this model data on fires since 1967 is used in order to maximise the number of fires included in the model. This is done using a regression model with reported costs as the dependent variable and insured costs as the only independent variable, we estimate a multiplier of 4.08, with an R-Squared of 0.8414.¹⁴ This multiplier is used is to create a synthetic estimate for total costs for fires for which only insured costs are available. For those fires for which we have a reported cost, we use the actual reported data for synthetic costs. For those fires without a reported cost of the fire but an insured cost, we use the predicted value based on the insured cost and multiplier above to create the synthetic costs estimate.

¹⁴ We estimated models with and without a constant term. The model with the constant term had a lower R-squared (0.8182) and the constant itself was not statistically significant. We also estimated a model with area, and distance to/density of urban area as additional explanatory variables. None of these were statistically significant.

While we are unable to individually itemise all costs associated with fires, the multiplier that we estimate incorporates many of the components in the Productivity Commission framework (Figure 2). Thus, our estimate of the total costs of fires includes direct market costs (primarily through the insurance costs) including infrastructure, commercial buildings, residential buildings, and agriculture, but also indirect market costs and non-market costs. The mark-up for the latter is likely to be conservative given the difficulty in measurement, but would include environmental costs, death/injury, psychological costs and animal welfare. In the concluding section, we call for additional investments in monitoring these costs, but we should note that they are incorporated albeit imperfectly in our model.

Setting the costs of fires that have an insured value of less than \$10 million to a cost of zero dollars (a conservative assumption that likely reduces the estimated cost savings), we can then obtain an estimate of the total costs of fires over a given time window. Figure 4 gives the estimated costs of bushfires by year of commencement of fire for the period 2009 to 2019, adjusted for inflation. The total estimated cost over the 11-year period is around \$16.0 billion, or around \$1.5 billion per year.



Figure 4 Estimated costs of bushfires – 2009 to 2019 (\$2019)

Source: ICA Database.

4.2 Simulated distributions of fires and costs in the absence of policy change

It is impossible to accurately predict the specific bushfires that will occur in the future or their costs. We can, however, make predictions of the size distribution of fires in future years and their associated economic costs using:

- the observed fire size distribution over recent years (1990 to 2019);
- the parameter estimates from the models of the relationship between fire size and cost and population density and cost; and

• likely changes in the distribution of fires due to climate change (obtained from the existing literature).

The first step is to model the likely growth through time in the number of fires that occur under adverse fire conditions, which is done using a Poisson distribution.¹⁵ The second step is to apply a distribution to the size and location of each of the fires. Based on observed data, the distribution of both fire size and population density are estimated to follow independent, log-normal distributions. The observed density functions are summarised in Figure 5 and 6 respectively, with fire size appearing to more closely approximate a normal distribution.¹⁶



Figure 5 Observed distribution of natural log of fire size

$$Pr(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

where $\lambda = \exp(-1.307988 + 0.0837808 * t)$ and t = 0 in 1990 and is fixed initially at the 2019 value. For fire size, we estimate (via maximum likelihood estimation) a mean value for the distribution of 10.76381 and a sigma of 2.202706. For density, the equivalent values are 0.9421025 and 0.923861 respectively.

¹⁵ We also tested for and rejected overdispersion using the negative binomial model, though it should be pointed out this was primarily due to quite wide confidence intervals due to the relatively small sample. We assume the time trend observed between 1990 and 2019 is fixed at the end of the period, giving a model for the Poisson distribution of the probability of the number of fires (X) in a given year (t) being equal to k as:





The third step is to estimate the land use of the area in which the fire is located. Here, we assume a generalised Bernoulli distribution, where the probability of being in each of the four potential land use categories is assumed to follow the same distribution as in the observed database.¹⁷

With the above set of assumptions, we create a synthetic dataset that has a simulated number of fires for each year between 2020 and 2049, with a simulated size and location for each fire.¹⁸ We then apply our model for insured costs, as well as the multiplier for total costs, which gives us an estimate of the cost of each fire.

It is standard in cost-effectiveness/cost-benefit analysis to assume that a cost or benefit incurred or received in the future is worth less than one incurred or received in the present year. The intuition for this is that, in terms of benefits, if that money was available now, then it could be invested with a reasonably consistent return over the long-run. In terms of costs, a person can invest less than the future costs now and have the funds available to cover those costs in the future. The difference between a dollar amount now and in the future is known as the discount rate, which we set to 4 per cent, following a House of Representatives Standing Committee on Infrastructure, Transport and Cities recommendation.

¹⁷ Specifically, 33.3 per cent of fires are assumed to be in 'Conservation and Natural Environments', 8.3 per cent in 'Production from Relatively Natural Environments', 27.8 per cent in 'Production from Dryland Agriculture and Plantations', and 30.6 per cent in 'Intensive Uses.'

¹⁸ In order to avoid extremes in the distributions, we restrict the number of fires to 6 in a given year (one more than the maximum in the observed dataset) and the fire size to 12 million hectares (roughly 20 per cent larger than the largest fire in the observed dataset).

The process described above gives us the Net Present Value for simulated bushfire costs under the scenario of the predicted level of bushfires continuing into the future. We set up two additional counterfactual scenarios, which factor in future additional increases in the number of fires due to climate change (we make the conservative assumption that the size distribution of fires is unchanged). Following Sharples, Cary et al. (2016) we assume a 30 per cent increase in fires by 2050 as our 'high climate change' scenario (or a 0.88 per cent increase per year, compounded) and a 15 per cent increase in fires by 2050 as our moderate climate change scenario (a 0.44 per cent increase per year, compounded).

4.3 Simulated distributions of fires under early fire detection scenarios and calculation of cost savings from early fire detection

The counterfactual fire size and cost distributions (Section 4.2) describe the projected costs of large bushfires (i.e. those that are present in the costs database) in the absence of any major policy change related to fire detection or suppression, but taking into account future growth due to climate change. The aim of this paper, and the final part of the methodology, is to identify a set of potential treatment distributions under the scenario of reduced detection times of fires.

We incorporate the introduction of such an early fire detection by assuming that the main effect will be to reduce the probability of a fire entering the insurance database in the first place due to a cost of at least \$10 million (that is, the number of large fires each year), rather than the size or costs of fires that have an insured cost of over \$10 million. The intuition is that early detection will have little impact on fire size and costs if the first attack is not successful, but rather increase the chance of there being a successful first attack.

The main challenge in estimating the potential effect of an early detection system is that we do not know the current distribution of fire detection times, as fire ignitions are generally not observed. We do, however, have data from Plucinski (2012) which showed that in periods of extreme fire danger, if the time taken between detection and arrival of first attack is less than 30 minutes, then the chance of successful suppression is estimated to be 40 per cent. We can conceptualise a reduced detection time as being equivalent to an increased chance of arriving at the fire within 30 minutes of ignition (what ultimately matters is time between ignition and arrival).

Furthermore, we have information on 34 forest fires between 2005 and 2007 where the Forest Fire Danger Index was greater than or equal to 50. On those days, the mean time between detection and first attack is 1.45 hours, with a standard deviation of 2.80. We once again estimate a log-normal distribution for this data.¹⁹

Using the observed distribution, 55.9 per cent of fires are responded to within 30 minutes, which means 22.4 per cent are assumed to be successfully dealt with at first attack (based on the success rate identified above). Under scenario one, we assume that detection time is improved by 30 minutes. This means, using the observed distribution that 70.6 per cent are responded to within the first 30 minutes, leading to 28.2 per cent being dealt with, or a reduction in the number of fires that are not dealt with of 7.5 per cent.²⁰ Under scenario two, we assume detection time is reduced by a further 30 minutes, which based on the observed

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^{20} \left(1 - \left(\frac{1 - 0.282}{1 - 0.224}\right)\right)
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¹⁹ mean = -0.5622704 and sigma = 1.283504)

distribution means that 88.2 per cent of fires are responded to within 30 minutes, leading to 35.3 per cent being dealt with, or a reduction in the number of fires that are not dealt with of 16.6 per cent.²¹ The final scenario is where early detection leads to all fires being responded to within 30 minutes, resulting in a 40.0 success rate, or a 22.7 per cent reduction in the number of fires compared to the counterfactual scenario.

In the treatment scenarios, we therefore, reduce the probability of each given fire occurring by 7.47 per cent (Scenario 1), 16.6 per cent (Scenario 2) and 22.7 per cent (Scenario 3). We do not make any assessment as to the feasibility of early detection systems achieving these outcomes.

5 Results

Bushfires are expected to result in significant economic costs over the next thirty years (2020 to 2049) and these costs are projected to grow under the scenarios in which climate change increases the number of fires. The modelling also shows, for a range of scenarios, that earlier fire detection which reduces bushfire risk would have significant economic benefits. This section first presents the results of the simulation of the number of high cost fires (over \$10 million insurance cost) under the various climate change and fire detection speed scenarios. It then presents the estimates of the costs of the economic costs of fires under the various scenarios and the economic benefits that may result from the different scenarios related to early fire detection.

The discussion of results begins with the simulated number of large fires per year. (Table 4).²² In the absence of any change in the speed of fire detection or changes in the frequency of fires due to climate change, we estimate that there will be an average of 3.06 large fires per year over the 2020 to 2049 period. Under the moderate climate change scenario (fire frequency increases by 15 per cent) we estimate that there will be an average of 3.30 fires per year, and under the high climate change scenario (fire frequency increase by 30 per cent) we estimate that on average there will be 3.53 large fires per year.

Early detection of fires is estimated to reduce the number of fires per year, but not eliminate them. Even under our most optimistic scenario that there will be no increase in fires from climate change and that all fires will be detected in such a way as to lead to responses within 30 minutes, we are still estimating 2.39 large fires per year over the period. An example of such fires is the 2020 Australian Capital Territory (ACT) Orroral Valley which was detected almost instantaneously, with professional fire crews within very close proximity. However, it still led to over 80,000 hectares being burned, an ACT State of Emergency, and has been described as 'the territory's worst ever environmental disaster.'²³

One comparison that is worth making is between the average number of large fires in our middle Scenario 2 (a one-hour reduction in response time) under the projected increase in

²¹ $\left(1 - \left(\frac{1 - 0.353}{1 - 0.224}\right)\right)$

Results presented in Table 4 are based on 1,000 replications, pseudo-randomly drawing from the estimated distribution of fires as discussed in the previous section. A pseudo-random number generator uses an initial seed value (in this paper, we use 15) and an algorithm for generating a sequence of numbers whose properties approximate the properties of sequences of random numbers. (L'ecuyer P. Pseudorandom number generators. Encyclopedia of Quantitative Finance. 2010 May 15.)

²³ <u>https://www.abc.net.au/news/2020-02-16/namadgi-national-park-recovery-after-orroral-valley-fire/11968950</u>

fires due to climate change (2.96 fires per year) and the average number of fires with no policy change in the absence of any climate change effects (3.06 fires per year). A very significant increase in early detection is only likely to bring the distribution of fires back to roughly what it would have been in the absence of climate change-related increases.

	Detection scenarios				
Climate change scenarios	No change in detection times	Scenario 1 (30-min reduction)	Scenario 2 (60-min reduction)	Scenario 3 (all fires responded to within 30-min)	
No growth	3.06	2.84	2.57	2.39	
Moderate climate change (15% growth)	3.30	3.07	2.77	2.57	
High climate change (30% growth)	3.53	3.29	2.96	2.76	

Table 4Simulated average number of large fires per year (2020-2049)

Based on the modelling of economic costs we estimate that bushfires will cost, in Net Present Value terms, between \$1.1 billion per year in the absence of climate change increasing the number of fires and \$1.2 billion per year under the high climate change scenario (top panel of Table 5). The undiscounted economic cost of fires averaged over the period 2020 to 2049 is between \$1.9 billion per year in the absence of climate change increasing the number of fires and \$2.2 billion per year under the high climate change increasing the number of fires and \$2.2 billion per year under the high climate change scenario (bottom panel of Table 5).

	Detection scenarios			
Climate change scenarios	No change in detection times	Scenario 1 (30-min reduction)	Scenario 2 (60-min reduction)	Scenario 3 (all fires responded to within 30-min)
		Net Presei	nt Value	
No growth	\$1,103,880,576	\$1,017,468,160	\$913,638,080	\$853,655,168
Moderate climate change (15% growth)	\$1,159,702,784	\$1,068,843,456	\$959,046,464	\$887,380,800
High climate change (30% growth)	\$1,211,963,648	\$1,125,198,976	\$1,012,863,360	\$937,132,224
	Undiscounted values			
No growth	\$1,911,119,488	\$1,754,565,504	\$1,588,569,088	\$1,477,930,496
Moderate climate change (15% growth)	\$2,038,681,472	\$1,875,301,760	\$1,683,185,664	\$1,559,620,224
High climate change (30% growth)	\$2,156,314,112	\$1,995,298,560	\$1,791,100,672	\$1,664,713,856

Table 5Simulated average cost of large fires per year (2020-2049)

The estimated costs per year between 2020 and 2049 expressed in Net Present Value terms are less than the estimated costs for 2009 to 2019, presented in the previous section. The reason for this is the discounting of the costs of future fires, which is a common approach used in studies of value for money. However, an alternative, not unreasonable assumption is that we value the future in exactly the same way as we value the present, and the only discounting

that should occur is for inflation (which is held constant in our model). The effect of this is shown across the two panels in Table 5, as well as more explicitly in Figure 7, which gives the simulated costs of fires per year in their original value, and after discounting to Net Present Value terms, under the scenario of 30 per cent growth of fires due to climate change and no policy intervention. Costs increase without discounting, but decrease under discounting (because the discount rate used by the government is far greater than the annual growth in fires under the scenario we model).

In deciding whether to invest in early detection technology, we still recommend the use of a discount rate as best practice, but do also recognise that different assumptions may lead to somewhat different conclusions and provide both discounted and non-discounted values.



Figure 7 Costs of fires per year with and without discounting – 30 per cent growth over period/no change in detection scenario

So, what does that yearly reduction in costs translate to over a thirty-year period? Quite a lot. Table 6 gives the difference in costs between the detection scenarios and the baseline counterfactual distribution, summed over all 30 years of the simulation period. In the absence of any increase in fires due to climate change, we estimate a reduction in the economic costs of fires by \$2.6billion, even with improvements in response times by 30 minutes. Under the Sharples et al. (2016) climate change scenario, and with the very strong assumption of all fires being able to be responded to within 30 minutes, we estimate a total benefit of \$8.2billion, in 2019 dollars and in Net Present Value terms, or \$14.8 billion in non-discounted terms.

	Detection scenarios			
Climate change scenarios	Scenario 1	Scenario 2	Scenario 3	
	(30-min reduction)	(60-min reduction)	(all fires responded to within 30-min)	
	N	et Present Value	-	
No growth	\$2,592,372,480	\$5,707,274,880	\$7,506,762,240	
Moderate climate change (15% growth)	\$2,725,779,840	\$6,019,689,600	\$8,169,659,520	
High climate change (30% growth)	\$2,602,940,160	\$5,973,008,640	\$8,244,942,720	
	Undiscounted values			
No growth	\$4,696,619,520	\$9,676,512,000	\$12,995,669,760	
Moderate climate change (15% growth)	\$4,901,391,360	\$10,664,874,240	\$14,371,837,440	
High climate change (30% growth)	\$4,830,466,560	\$10,956,403,200	\$14,748,007,680	

Table 6Simulated total benefit over 30 years of earlier fire detection (2020-2049)

It is impossible to know what the level and costs of fire activity are likely to be in a given year into the future. Our method relies on estimating parameters for a set of observed distributions and then randomly drawing from those distributions for each year and for each scenario. We do this a thousand times, and then take the average across those replications as an estimate of the likely number of fires and associated costs. However, while the average value is in many ways the most likely outcome, it is not the only plausible outcome and any one of our replications represents a plausible value. The distribution of those plausible values is a useful measure of the uncertainty around the estimates of the costs of bushfires, and the benefits in response times due to early detection.

Based on the largest increase in fires due to climate change, Figure 8 shows the estimated distribution of costs under the counterfactual scenario, as well as under the three treatment scenarios for early detection. Not surprisingly given the results presented in Table 5, the greater the reduction in fire probability due to the assumed effect of early detection, the lower the average economic cost per year from bushfires. This is represented by a shift to the left in the distributions. However, there is also a noticeable narrowing of the distribution in Scenario 3 compared to the other three scenarios, representing a smaller standard deviation.

Figure 8 Distribution of costs of fires per year by scenario – assuming 30 per cent increase in fires due to climate change



Despite this narrowing of the standard deviation for Scenario 3 as shown in Figure 8, there is still a large range around the mean in terms of plausible values in the costs of fires under Scenario 3. The 10th percentile, which represents the lowest average economic costs of fires that we think has a 1 in 10 chance of occurring over the next 30 years is around \$730 million in Net Present Value terms. The 90th percentile, which represents the highest average economic costs of fires that we think has a 1 in 10 chance of occurring over the next 30 years is around \$730 million in Net Present Value terms. The 90th percentile, which represents the highest average economic costs of fires that we think has a 1 in 10 chance of occurring is \$1.17 billion. Clearly, there is a large range of potential costs from fires, with that variation due to characteristics not well captures in our models.

6 Concluding comments and potential extensions

As a country, Australia is prone to frequent and severe bushfires (wildfires) that can and do result in significant loss of human and animal life, mental and physical injury and illness, and significant economic costs. The fires that occurred over the 2019/20 Australian summer (what are beginning to be called the Black Summer Fires) were unprecedented in scale both in Australia and arguably internationally, and had a devastating impact on large parts of Australia, but particularly the east and south-east of the continent.

Efforts to rebuild from the fires are only just beginning and, if previous large fires are any guide, will take many years and billions of dollars. Discussion has also turned to the potential policy responses, and steps that can be taken to reduce the chance and severity of such fires in the future. Contributing to the reduction of growth and eventually levels of greenhouse gases in the atmosphere are an important component of the Australian policy response. Discussion

earlier in this paper highlighted that one of the key predictors of large fires is the Forest Fire Danger Index (which is in turn driven by moisture, temperature and wind velocity), with most scientists who have looked at the issue predicting that the number of days with extreme and catastrophic ratings is likely to increase into the future.

Despite the importance of climate change to the current and future distribution of fires in Australia, alone Australia can only make a small contribution, and policy returns are likely to be far into the future. Other strategies are also needed.

The available literature suggests that one of the key predictors of whether a fire turns into a large and costly fire is the time between ignition and first attack response. This is particularly the case during days of extreme and catastrophic fire danger. The two components of initial attack delay are time to detection, and time from detection to response. In a country as large and sparsely populated as Australia, there are physical limits to how quickly resources can be deployed to a fire once it has been detected. This is particularly the case when fires start in remote areas, even if those remote fires end up threatening homes and other infrastructure. The sparse geographic distribution of populations in Australia also mean that fires may not be detected in a sufficient time to deploy resources before they reach a size that makes them uncontrollable, particularly without significant investment in remote detection resources. The results presented in this paper, however, show that the economic returns to such investment have the potential to be very high.

Our aim in this paper is a modest, but a difficult one – to predict what the reductions in the economic costs of bushfires would be if it was possible to detect fires at a far earlier stage in their growth. Our task is made difficult by two major data limitations – we have close to zero information on the costs of small-medium fires in Australia and only slightly more information on the costs of large fires; and we do not currently know what the time between ignition and detection is for the vast majority of fires in Australia.

We do, however, have three sources of information that can help us answer our research question. We have reasonable information on the costs and incidence of large fires in Australia, as well as their size and location. From this, we can set up a data-driven model for the factors associated with cost differences in fires, albeit a model that relies on far fewer observations than we would otherwise hope for. With this information we can simulate the distribution of large fires over the next 30 years, building in some assumptions around growth in large fires due to climate change. The second bit of information we have is a model of the success of first attack for fires on extreme fire danger days, conditional on time between detection and arrival. A key threshold appears to be about 30 minutes. When combined with our third source of information, the distribution of times between detection and arrival for a subset of fires in 2005-2007, we are able to construct some scenarios of improvements in fire suppression based on reductions in detection time acting as de facto reductions in response times.

We regard the scenarios and assumptions that we build from the data as being conservative and thus our estimates of the economic benefits of early detection are likely to be a lower bound. If early detection leads to a reduction in the number and costs of small-medium fires, which we expect it will, then the estimates of the benefits of early detection would be larger. If early detection leads to a larger reduction in the probability of large fires occurring than the 22.7 per cent reduction that we take as our most optimistic scenario, then the benefits would also be larger.

Even with our conservative estimates though, the reduction in the costs of fires over the next 30 years is considerable. With no growth in fires due to climate change, no reduction in the costs of small-medium fires, and only a small reduction in the probability of large fires occurring, we estimate a reduction in the Net Present Value of the economic costs of large fires equal to \$2.6billion over thirty years from an improvement in early detection. If climate change does lead to a growth in large fires (which almost all scientists expect it will) and early detection leads to a larger but still plausible reduction in the probability of large fires, then we predict an economic benefit of \$8.2billion.

In our view, the large sums that result from our conservative estimates make investments and improvements in early detection financially very viable. The costs of developing and implementing early detection systems that can achieve the outcomes modelled under the different scenarios have not been taken into account and thus any investment decisions based on a cost or benefit or return on investment criteria would need to offset these costs against the projected benefits. However, we would also note that detection systems also operate as monitoring tools. That may result in additional benefits, as management of fires even beyond the initial detection is based on more up-to-date and reliable information.

However, we also think that other even smaller investments are worthwhile. In particular, there is very sparse data on the costs of fires in Australia, with the data that is available skewed towards the largest and most catastrophic fires. While the data from the Insurance Council of Australia has been very useful for this project, we recommend consideration of a more comprehensive bushfire costs database, including a greater disaggregation of the fires in the insurance database into individual events. There is also more that could be done with the cost data that is available. In particular, with more information on the distribution of fire detection (and potential reductions), our model estimates and scenarios could be even more precise.

Ultimately, based on conservative, plausible estimates of the size, distribution and costs of future fires, we estimate significant reductions in the economic costs of fires from improvements in detection time.

References

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

Arienti, M., Cumming, S. and Boutin, S. (2006). "Empirical models of forest fire initial attack success probabilities: the effects of fuels, anthropogenic linear features, fire weather, and management." *Canadian Journal of Forest Research*, 36(12): 3155-3166.

Beale, J. and Jones, W. (2011). "Preventing and reducing bushfire arson in Australia: A review of what is known." *Fire Technology* 47(2): 507-518.

Biddle, N., Edwards, B., Herz, D., Makkai, T., McAllister, I. (2020). "Bushfires, the environment, and optimism for the future." ANU Centre for Social Research and Methods, Australian National University, Canberra.

Boer, M.M., Resco de Dios, V. and Bradstock, R.A. (2020). "Unprecedented burn area of Australian mega forest fires." *Nature Climate Change* 10: 171-172

Bowman, D., Williamson, G., Yebra, M., Lizundia-Loiola, J., Pettinari, M.L., Shah, S., Bradstock, R. and Chuvieco, E., 2020. Wildfires: Australia needs national monitoring agency. *Nature* 584, 188-191

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M., Wu, L., England, M., Wang, G., Guilyardi, E. and Jin, F. (2014). "Increasing frequency of extreme El Niño events due to greenhouse warming." *Nature Climate Change* 4: 111-116.

Cai, W., Wang, G., Gan, B., Wu, L., Santoso, A., Lin, X., Chen, Z., Jia, F. and Yamagata, T. (2018). "Stabilised frequency of extreme positive Indian Ocean Dipole under 1.5 °C warming." *Nature Communications* 9(1).DOI: 10.1038/s41467-018-03789-6

Carlsson, F. and Martinsson, P. (2001). "Do hypothetical and actual marginal willingness to pay differ in choice experiments?: Application to the valuation of the environment." *Journal of Environmental Economics and Management* 41(2): 179-192.

Cary, G. J., I. D. Davies, R. A. Bradstock, R. E. Keane and Flannigan, M.D. (2017). "Importance of fuel treatment for limiting moderate-to-high intensity fire: findings from comparative fire modelling." *Landscape Ecology* 32(7): 1473-1483.

Cheney, P. and Sullivan, A. (2008). "Grassfires: Fuel, Weather and Fire Behaviour." DOI: 10.1071/9780643096493.

Collins, K., Price, O. and Penman, T. (2018). "Suppression resource decisions are the dominant influence on containment of Australian forest and grass fires." *Journal of Environmental Management* 228: 373-382.

Cook, G. D., S. Jackson and Williams, R.J. (2012). "A revolution in northern Australian fire management: recognition of Indigenous knowledge, practice and management." *Flammable Australia* CSIRO Publishing, Collingwood.

Cowan, T., Purich, A., Perkins, S., Pezza, A., Boschat, G. and Sadler, K. (2014). "More frequent, longer, and hotter heat waves for Australia in the twenty-first century." *Journal of Climate* 27(15): 5851-5871.

CSIRO-BOM and Domingues, C. (2019). CSIRO-BOM Australian State of the climate-2018.

Deloitte Access Economics (2016). The economic cost of the social impact of natural disasters, Australian Business Roundtable for Disaster Resilience & Safer Communities.

Fried, J.S. and Fried. B.D. (1996). "Simulating Wildfire Containment with Realistic Tactics." *Forest Science* 42: 267-281.

Garnaut, R. (2019). *Superpower: Australia's Low-Carbon Opportunity*, Schwartz Books, Carlton, Victoria.

Gill, A. M., S. L. Stephens and Cary, G.J. (2013). "The worldwide "wildfire" problem." *Ecological Applications* 23(2): 438-454.

Gott, B. (2005). "Aboriginal fire management in south-eastern Australia: aims and frequency." *Journal of Biogeography* 32(7): 1203-1208.

Gould, J.S., McCaw, W.L., Cheney, N.P., Ellis, P.F., and Matthews, S. (2007). Field guide – fuel assessment and fire behaviour prediction in dry eucalypt forest, Ensis-CSIRO, Canberra, ACT & Department of Environment and Conservation, Perth, WA.

Hensher, D.A. (2010). "Hypothetical bias, choice experiments and willingness to pay." *Transportation Research Part B: Methodological* 44(6): 735-752.

Hirsch, K.G., Podur, J.J., Janser, R.F., McAlpine, R.S. and Martell, D.L. (2004). "Productivity of Ontario initial-attack fire crews: results of an expert-judgement elicitation study." *Canadian Journal of Forestry Research* 34(3):705-715.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva.

Ladds, M., A. Keating, J., Handmer and Magee, L. (2017). "How much do disasters cost? A comparison of disaster cost estimates in Australia." *International Journal of Disaster Risk Reduction* 21: 419-429.

Levin, H.M. and McEwan, P.J. (2000). Cost-effectiveness analysis: Methods and Applications. Sage, Thousand Oaks, California.

Luke, R. and McArthur, A. (1978). *Bushfires in Australia*. Australian Government Publishing Service, Canberra.

McAneney, J., Sandercock, B., Crompton, R., Mortlock, T., Musulin, R., Pielke Jr, R. and Gissing, A. (2019). "Normalised insurance losses from Australian natural disasters: 1966–2017." *Environmental Hazards* 18(5): 414-433.

McCarthy, G.J. and Tolhurst, K.G. (1998). "Effectiveness of firefighting first attack operations by the Department of Natural Resources and Environment from 1991/92 – 1994/95." *Research Report No.45*, Dept. Natural Resources and Environment, Victoria.

McCArthy, G.J. (2003). "Effectiveness of aircraft operations by the Department of Natural Resources and Environment and the Country Fire Authority 1997–1998." Research. Report No. 52. Department of Natural Resources and Environment, Victoria.

Office of Best Practice Regulation (2014). "Best practice regulation guidance note: value of statistical life." Department of the Prime Minister and Cabinet, Canberra.

Parks, G. (1964). "Development and Application of a Model for Suppression of Forest Fires." *Management Science* 10(4): 760-766.

Penman, T., Collins, L., Price, O., Bradstock, R., Metcalf, S. and Chong, D. (2013). "Examining the relative effects of fire weather, suppression and fuel treatment on fire behaviour – A simulation study." *Journal of Environmental Management* 131: 325-333.

Plucinski, M. (2012). "Factors Affecting Containment Area and Time of Australian Forest Fires Featuring Aerial Suppression." *Forest Science*, 58(4): 390-398.

Plucinski, M., J. Gould, G. McCarthy, and J. Hollis. (2007). "The effectiveness and efficiency of aerial firefighting in Australia, part 1." *Technical Report A0701*, Bushfire Cooperative Research Centre, Melbourne.

Podur, J. and Martell, D. (2007). "A simulation model of the growth and suppression of large forest fires in Ontario." *International Journal of Wildland Fire* 16(3): 285-294.

Preston, B. L., R. M. Westaway and E. J. Yuen (2011). "Climate adaptation planning in practice: an evaluation of adaptation plans from three developed nations." *Mitigation and Adaptation Strategies for Global Change* 16(4): 407-438.

Productivity Commission (2014). "Natural disaster funding arrangements." *Inquiry Report No.* 74, Productivity Commission, Canberra.

Sharples, J.J., Cary, G.J., Fox-Hughes, P., Mooney, S., Evans, J.P., Fletcher, M.S., Fromm, M., Grierson, P.F., McRae, R. and Baker, P. (2016). "Natural hazards in Australia: extreme bushfire." *Climatic Change* 139(1): 85-99.

Stephenson, C., J. Handmer and Betts, R. (2013). "Estimating the economic, social and environmental impacts of wildfires in Australia." *Environmental Hazards* 12(2): 93-111.

Sullivan A.L. (2010). "Grassland fire management in future climate." Advances in *Agronomy* 106: 173-208.

Tolhurst, K. and McCarthy, G. (2016). "Effect of prescribed burning on wildfire severity: A landscape-scale case study from the 2003 fires in Victoria." *Australian Forestry* 79: 1-14.

Viscusi, W. K. and J. E. Aldy (2003). "The value of a statistical life: a critical review of market estimates throughout the world." *Journal of Risk and Uncertainty* 27(1): 5-76.

Appendix A.	Bushfires for which cost estimates are available
Table A1	Cost of Bushfires

Start Date	End Date	State	Insured Cost (A\$)	Reported Cost (A\$)	Normalized cost (2017 A\$)
7/02/1967	7/02/1967	Tasmania	14,000,000		610,000,000
15/09/1968	30/01/1969	New South Wales	1,500,000	2,000,000	94,878,693
8/01/1969	9/01/1969	Victoria	7,845,000	15,000,000	477,785,077
1/12/1974	1/02/1975	New South Wales		5,060,000	
10/12/1977	29/12/1977	New South Wales	3,500,000	5,000,000	
12/02/1977	12/02/1977	Victoria	9,000,000	30,000,000	105,999,123
13/02/1979	28/02/1979	New South Wales		5,500,000	
20/02/1980	20/02/1980	South Australia	13,000,000	34,000,000	175,627,673
1/12/1979	1/02/1980	New South Wales	10,000,000	4,695,320	
15/01/1982	15/02/1982	Tasmania		5,350,000	
16/02/1983	18/02/1983	Victoria	176,000,000	503,843,524	1,761,595,800
1/01/1983	31/01/1983	New South Wales	5,350,000	12,000,000	
3/03/1985	6/03/1985	Australian Capital Territory		4,000,000	
5/09/1984	15/02/1985	New South Wales	25,000,000	40,000,000	255,418,097
14/01/1985	28/01/1985	Victoria		5,500,000	
17/01/1987	20/01/1987	New South Wales		2,000,000	
20/12/1990	30/12/1990	New South Wales	6,000,000		
27/12/1990	10/01/1991	Victoria		1,100,000	
27/12/1993	16/01/1994	New South Wales	59.000.000	152.668.161	332.842.129
8/01/1997	8/01/1997	Western Australia		12,000,000	,- , -
19/01/1997	21/01/1997	Victoria	9.000.000	,,	45.335.733
16/10/2002	29/10/2002	Queensland		6.500.000	-,,
9/10/2002	9/10/2002	New South Wales	25.000.000	-,,	54,957,304
24/12/2001	11/01/2002	New South Wales	69.000.000		166.968.846
8/01/2003	19/03/2003	Victoria	24.000.000	2.009.400.000	62.880.000
18/01/2003	19/01/2003	Australian Capital Territory	350.000.000	_,,,	839,446,512
10/01/2005	12/01/2005	South Australia	27.700.000		57,418,905
31/12/2005	31/01/2006	Victoria	22,400,000		33.602.225
1/12/2006	7/02/2007	Victoria		14.000.000	,,
29/12/2009	29/12/2009	Western Australia	7.400.000	50.000.000	7,286,998
7/02/2009	8/02/2009	Victoria	1.070.000.000	4.369.000.000	1.757.793.316
23/11/2011	6/12/2011	Western Australia	53.450.000	,,,	63,996,314
5/02/2011	7/02/2011	Western Australia	35.128.000		43.015.277
17/10/2013	27/10/2013	New South Wales	183,400,000		217,413,271
7/01/2013	20/01/2013	New South Wales	35,000,000		39,169,402
3/01/2013	14/01/2013	Tasmania	89,000,000		103 947 348
15/01/2014	15/01/2014	Victoria	18,500,000		20,753,550
12/01/2014	14/01/2014	Western Australia	87,812,300		97,900,802
26/11/2015	28/11/2015	South Australia	171,589,230		185,205,642
19/12/2015	20/12/2015	Victoria	5.000.000		5.621.781
24/12/2015	27/12/2015	Victoria	109 833 512		120 988 423
2/01/2015	8/01/2015	South Australia	62,133,554		69,616,414
20/11/2015	24/11/2015	Western Australia	16 800 000		17 197 514
6/11/2016	8/11/2016	New South Wales	1 000 000		1 040 599
15/01/2016	15/02/2016	Tasmania	2 200 200		2 349 389
6/01/2016	23/01/2016	Western Australia	71 250 666		70 579 607
12/02/2017	18/02/2017	New South Wales	33 500 000		34 243 907
17/03/2019	19/03/2018	New South Wales	82 489 235		82 489 235
8/11/2019	13/01/2020	NSW. OLD. SA_VIC	1.344 000 000		1 900 094 403
29/03/2019	30/02/2010	Victoria	750 000		±,500,05-,405 750 000
3/03/2019	12/03/2019	Victoria	35 429 104		25 429 104
5/09/2019	11/09/2010	NSW. OLD	13 500 000		55,725,107

Sources:

1. Ladds,, Keating, Magee, L, Handmer, J (2017) AUS:DIS - Database of losses from disasters in Australia 1967-2013

2. Insurance Council of Australia (ICA) Catastrophe Database.

3. Australian Disaster Resilience Knowledge Hub.