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Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends

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Abstract

2019/20 Australia's bushfire season (Black Summer fires) occurred during a period of record breaking temperatures and extremely low rainfall. To understand the impact of these climatic values we conducted a preliminary analysis of the 2019/20 bushfire season and compared it with the fire seasons between March 2000 and March 2020 in the states of New South Wales (NSW), Victoria, and South Australia (SA). Forest and fire management in Australia were asked to provide data on the number of fires, burned area, life and house loss, as well as weather conditions. By March 2020 Black Summer fires burnt almost 19 million hectares, destroyed over 3,000 houses, and killed 33 people. Data showed that they were unprecedented in terms of impact on all areas. A number of mega-fires occurred in NSW resulting in more burned area than in any fire season during the last 20 years. One of them was the largest recorded forest fire in Australian history. Victoria had a season with the highest number of fires, area burned, and second highest numbers of houses lost for the same period. SA had the highest number of houses lost in the last 20 years. Black Summer fires confirmed existing trends of impact categories during the last two decades for NSW and Victoria. It showed that the smoke from the bushfires may be a significant concern in the future for the global community, as it travels to other countries and continents. Based on preliminary data, it will take many years to restore the economy and infrastructure in impacted areas, and to recover animal and vegetation biodiversity.

Keywords: 2019/20 season, bushfires, impact, retrospective analysis

1. Introduction

In the last decade, there have been extreme wildfire events around the world resulting in substantial social, economic and environmental impacts (Table 1). Recently, extreme wildfire events shifted to countries where they were a rare or extraordinary event. They were observed in tropical and temperate rainforests of Brazil in 2019 [1], Chile in 2014 and 2017 [2,3], Bolivia in 2017 [4], close to the Arctic circle in Greenland in 2017 and 2019 [5,6], and Sweden in 2014 and 2018 [7,8]. In some countries, extreme fires may become a regular event.

Table 1. Examples of wildfires with large social, economic and environmental impacts from 2010 - 2020

Name	Region	Impact
2019 Black Summer fires	Australia	33 people killed and over 3,000 houses destroyed [9]
2018 Camp fire	USA	85 fatalities and nearly 19,000 structures destroyed [10]
2018 Attica fires	Greece	102 fatalities and approximately 3000 houses burned [11]
2017 Thomas fire	USA	1,300 structures lost and 2.2 billion USD in damages [12]
2017 British Columbia fires	Canada	1.2 million hectares burned and 65,000 people evacuated [13,14]
2017 Wildfires	Portugal	112 human lives lost with 424,000 hectares burned [15]
2016 Fort McMurray wildfire	Canada	2,400 houses lost and 6 billion CND in damages [13,14]
2016 Wildfires	Portugal	4 people killed and more than 1,000 evacuated [16],
2015 Wildfires	Russia	33 people killed and 1,300 houses burned [17]
2015 South Australia fires	Australia	2 lives lost and 88 houses burned [18]
2013 Red October fire	Australia	224 structures destroyed and 1 person died [19,20]
2012 Chios fire	Greece	9 villages evacuated and 7,000 hectares burned [21]
2011 Slave Lake fire	Canada	374 properties destroyed and 700 million CND in damages [22]
2011 Bastrop County Complex fire	USA	2 deaths and 1,645 homes lost [23]
2010 Wildfires	Russia	53 fatalities and 2,500 houses lost [24,25]

Climate change is already influencing fire seasons around the world [26-29]. Wildfire seasons are extending as the number of dry and hot days increases. A longer fire season is expected to result in more frequent and severe fires [30,31]. Australia's bushfire season 2019/20 (Black Summer hereafter) appears to have supported these conclusions in terms of the ecological consequences and impacts on human populations. However, behind the mass

media “noise” and subjective information, the real magnitude of Black Summer’s events has not been compiled.

The aim of this study was to conduct a preliminary analysis of the 2019/20 bushfire season in Australia and to compare it with the last two decades of fires for the states of New South Wales, Victoria, and South Australia. Specifically, we asked:

- Was there a trend or precondition for the 2019/20 catastrophic bushfire season?
- How abnormal or unusual was the 2019/20 bushfire season?
- Did the 2019/20 bushfire season change current trends?

2. Methods

We collected all available information about weather and bushfires impact to understand the novelty of the Black Summer in the history of Australian bushfires during last 20 years. Forest and fire management in Australia is predominantly undertaken at a state level and each state has its own fire service that defines the beginning of a fire season. Agencies were asked to provide data on the number of fires, burned area, life and house loss, as well as weather conditions between March 2000 and March 2020. Responses were received from New South Wales Rural Fire Service (NSW), Department of Environment, Land, Water and Planning and Country Fire Authority of Victoria (Vic), and Department of Environment and Water and Country Fire Service of South Australia (SA) (Figure 1). Data for the 2019/20 bushfire season for other states were taken from a combination of news reports and media releases by the fire service agencies, as annual reports are not yet available. Additional weather data has been obtained from the Australian Government Bureau of Meteorology [32,33]; data about impact of bushfires were obtained from the annual reports of the fire service agencies responsible for firefighting in the state.

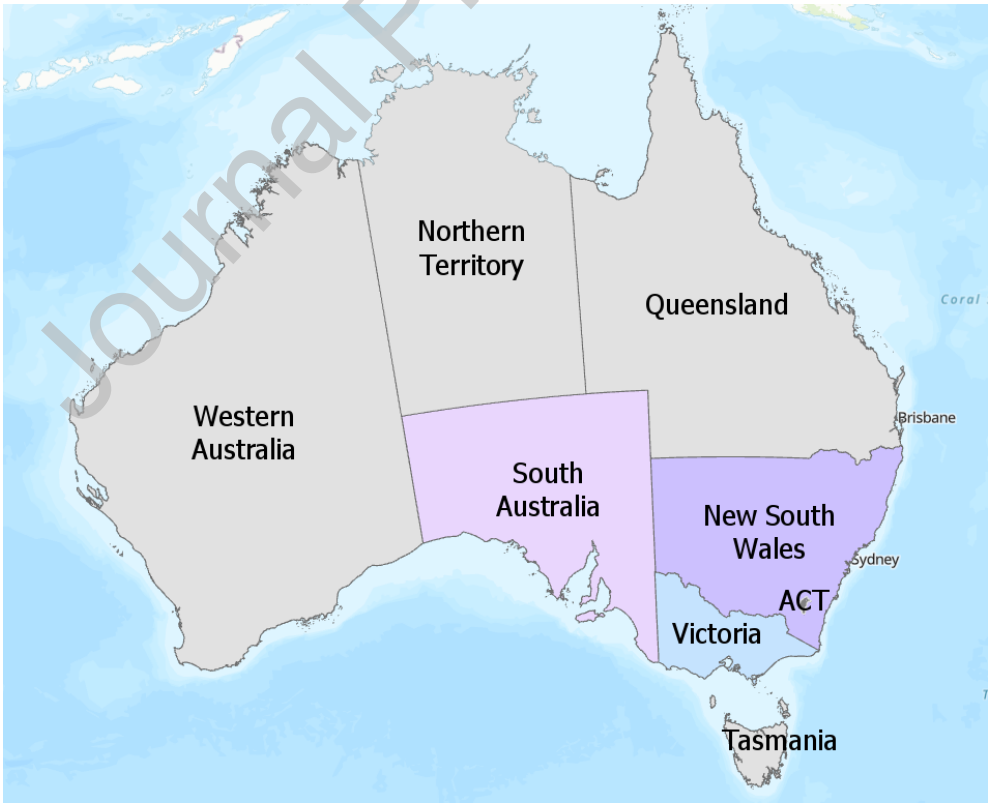


Figure 1. Study area

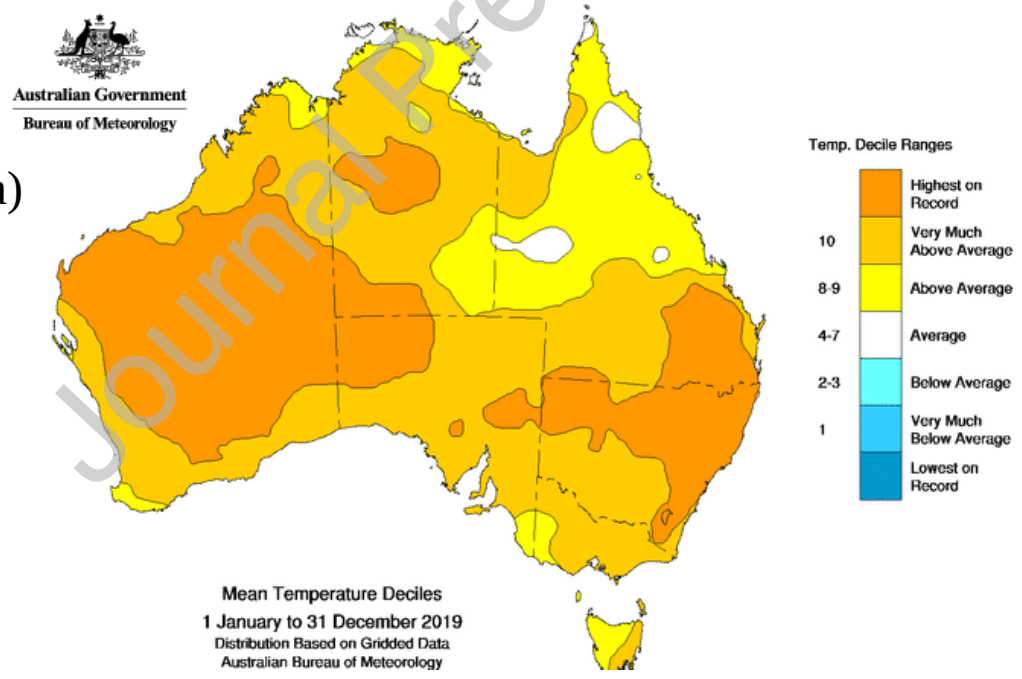
The intention of this study was not to develop the best predictive model but to understand high-level trends in NSW, Vic, and SA. Therefore, data were analysed using linear regression analysis. Specifically, we calculated the slope of the regression line *m*, standard error of the regression *SE*, significance *p*, Pearson's correlation coefficient *r*, coefficient of determination R^2. Response variables were burned area, number of fires, houses and lives lost, and the predictor variable was fire season. Negative and positive relationships were indicated as decreasing and increasing trends (slopes) respectively. To analyse the effect of the 2019/20 season on trends we undertook regression analysis with and without the last year data. Burned area includes all types of vegetation. House loss data do not include major damage to houses or damage or loss of structures other than primary dwellings. Fatalities are directly related to fires.

3. Results and discussion

3.1 Preconditions of Black Summer fires

The Bureau of Meteorology has determined 2019 was Australia's warmest year on record (Figure 2) [32]. It broke records of area-averaged mean temperature (+1.33 °C) and mean maximum temperatures (+1.59 °C, Figure 2b). All the years since 2013 are included in the ten warmest on record for Australia. An extended period of heatwaves over much of Australia began in early December 2018 and continued into January 2019. January 2019 was the warmest month on record, with the monthly mean temperature 2.90 °C above average. Spring was Australia's driest spring on record and the fifth-warmest on record. Heat continued to affect Australia until the end of the year, bringing repeated periods of severe fire weather to the south-eastern States.

a)



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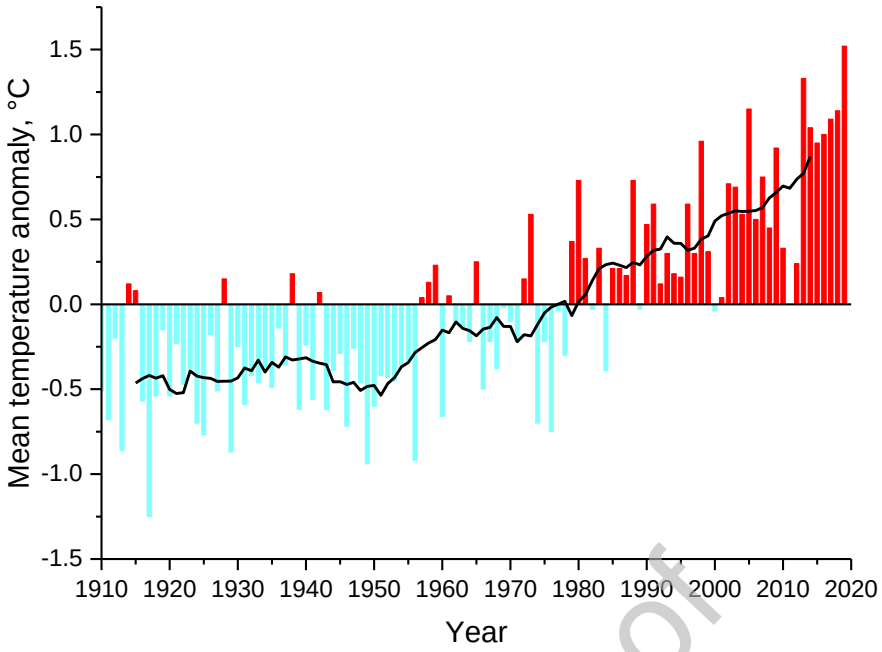


Figure 2. Air temperature [32]: a) Annual mean temperatures compared to historical temperature observations, b) Mean temperature anomalies averaged over Australia. Deciles show whether temperature is above average, average or below average for the time period and area chosen. The black line shows the 11-year moving average. Pictures and data were published in the Bureau of Meteorology's annual statement [32] under Creative Commons licensing arrangements.

2019 was also the driest year on record for Australia at 277.6 mm (annual mean) [32], although parts of Queensland's northwest and northern tropics were wetter than average (Figure 3a). Rainfall was 40 % below the 1961–1990 average (Figure 3b). The extraordinarily low rainfall experienced in 2019 is only comparable to the driest periods in Australia's recorded history. Annual rainfall totals were in the lowest 10% of historical observations for almost 70% of Australia. Each month from July through December was amongst the ten driest on record for their respective month nationally. Starting in early 2017, rainfall has been near or below previous record low values over much of New South Wales and southern Queensland. The impact of low rainfall over the period has been exacerbated by record high temperatures, which in turn drive higher rates of evaporation where water is available. Low rainfall also led to very low soil moisture across large areas of Australia during 2019. Additionally, a very strong positive Indian Ocean Dipole (IOD, sustained changes in the difference between sea surface temperatures of the tropical western and eastern Indian Ocean [34]) was one of the main influences on Australia's climate during 2019, and contributed to very low rainfall and low humidity across Australia.

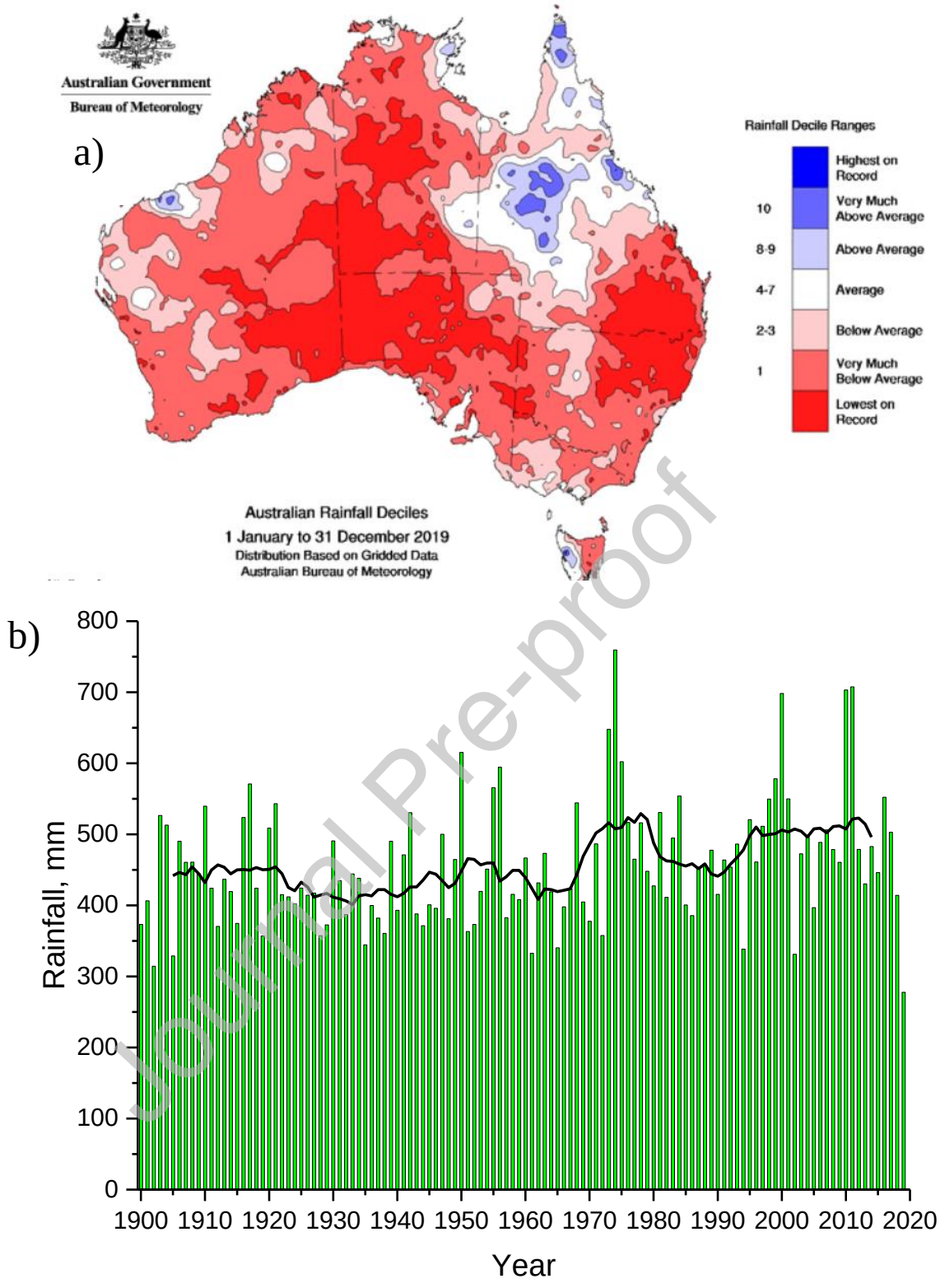
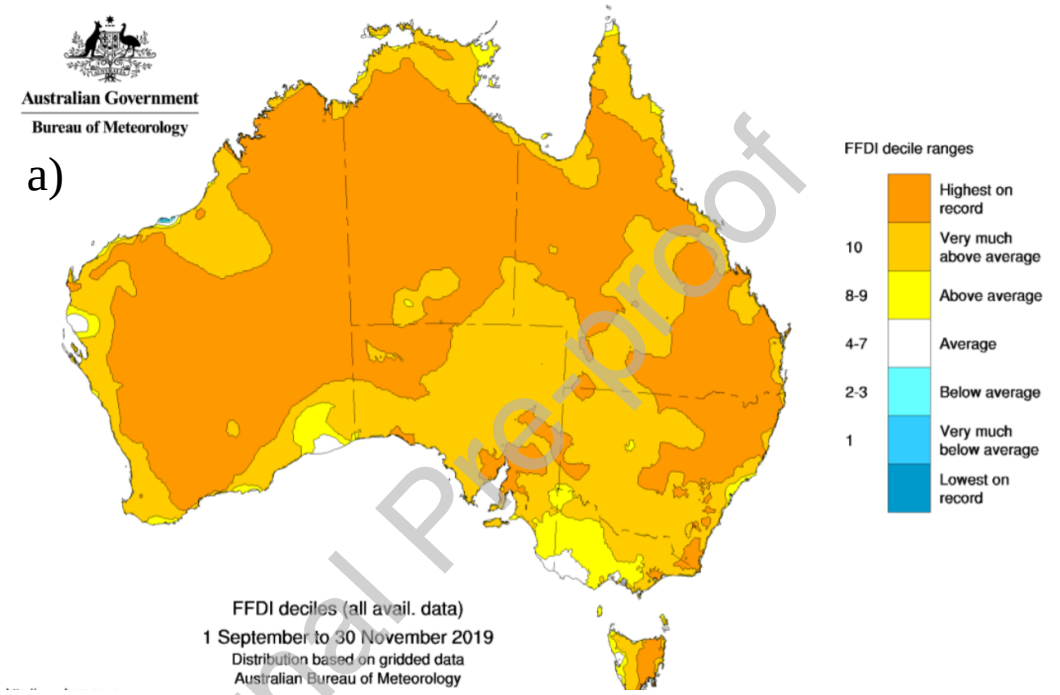


Figure 3. Rainfall [32]: a) Rainfall deciles for January to December 2019, b) Annual mean rain. The black line shows the 11-year moving average. Pictures are taken from the Bureau of Meteorology's annual statement [32]. Deciles show whether rainfall is above average, average or below average for the time period and area chosen. Pictures and data were published in the Bureau of Meteorology's annual statement [32] under Creative Commons licensing arrangements.

Forest Fire Danger Index (FFDI) is used in Australia to measure the degree of fire danger in Australian forests [35]. It combines a record of dryness, based on rainfall and evaporation, with meteorological variables for wind speed, temperature and humidity. Daily FFDI values can be accumulated (summed) over time. The accumulated FFDI values for spring 2019 were highest on record over large areas of Australia (Figure 4a) [33]. More than 95% of Australia by spring had accumulated FFDI values that were very much above average, including almost 60% of the country that was highest on record (Figure 4a). New South Wales, Queensland, Northern Territory, Western Australia and Tasmania all experienced record-high spring FFDI. Victoria was the only state with an area-averaged accumulated FFDI value for spring below its previous record high. South Australia experienced its second-highest accumulated FFDI on record. The accumulated FFDI for Australia in spring 2019 was significantly higher than any other season on record (Figure 4b).



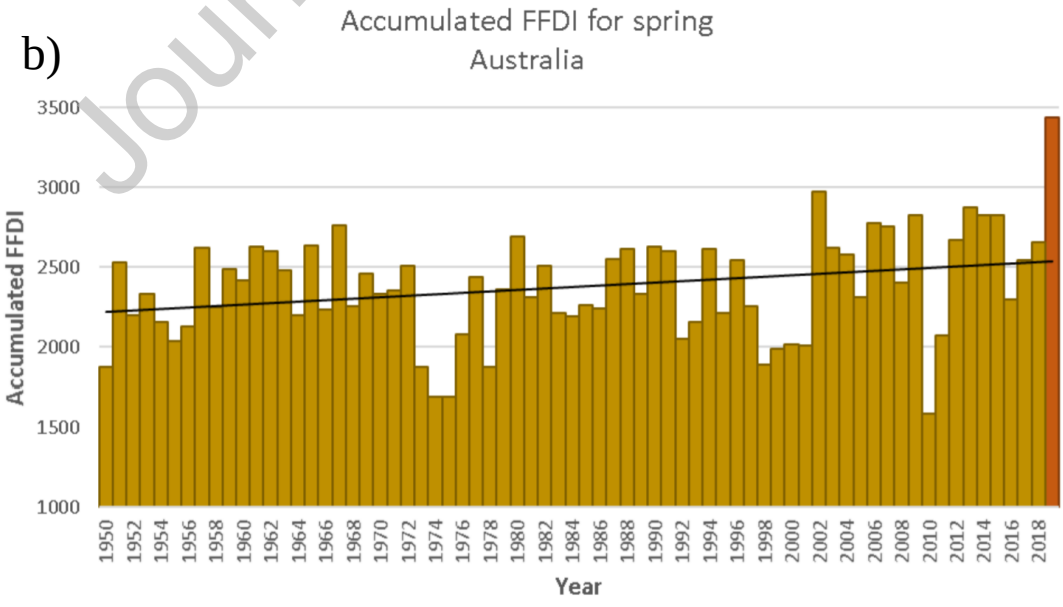


Figure 4. Forest Fire Danger Index [33]: a) Accumulated-FFDI deciles for spring 2019 (based on all years since 1950), b) Spring accumulated FFDI values for Australia from 1950 to 2019. Accumulated FFDI for spring 2019 shown in orange. Linear trend line shown in black. Pictures and data were published in the Bureau of Meteorology's special statement [33] under Creative Commons licensing arrangements.

High temperatures, rainfall deficit and prolonged drought resulted in increase in fuel availability and very high fire danger indexes [36,37]. As of 20 March 2020, the fires burnt almost 19 million hectares, destroyed over 3,000 houses, killed 33 people and more than 1 billion animals [38] (Table 2).

Table 2. Fire statistics for 2019/20. These figures are preliminary and may be revised when official statistics are released at the end of the 2019/20 financial year.

State	Burned area, ha	Number of fires	Houses lost	Lives lost
VIC	1,505,004	3,500	396	5
NSW	5,595,739	10,520[1]	2,475	25
QLD	2,500,000	NA	48	0
TAS	36,000	NA	2	0
WA	2,200,000	NA	1	0
SA	286,845[2]	1,324	186	3
NT	6,800,000	NA	5	0
ACT	60,000	NA	0	0
Total	**18,983,588**	**15,344**	**3113**	**33**

NA – data is not available

[1] Number of fires in NSW includes only those attended by the NSW RFS. This does not include all vegetation fires but provides a relative measure of fire activity.

[2] This number is expected to increase significantly when fires in remote arid areas of the state are mapped.

3.2 Number of fires, burned area, life and house loss

3.2.1 New South Wales

Much of central and northern NSW has experienced very much below average rainfall most of 2019, with some areas experiencing driest on record conditions [33]. Long-term rainfall deficiencies, record low for some areas in the north of the state, have severely impacted on water resources and firefighting tactics [39]. At the beginning of August (end of Australian winter) nearly all of NSW was in of the following categories: drought affected (55 %), experiencing drought (23 %), and experiencing intense drought (17 %). The first 'Section 44' emergency declaration of the fire season was made on 10 August 2019, one of the earliest on record [40]. Significant soil moisture deficit and windy conditions resulted in a significant number of bushfires [36].

A total of 5,595,739 hectares were burned, 2475 houses and 25 lives lost in 10,520 bushfires in NSW (Figure 5). Two mega-blazes were recorded in NSW. The Gospers Mountain fire started on 26 October 2019 and burned approximately 512,626 hectares, becoming one of the biggest forest fires in Australian history. By 11 January, three fires on the border of NSW and Victoria, the Dunns Road fire, the East Ournie Creek, and the Riverina's Green Valley merged and created a second mega-fire which burned through 895,744 hectares. Fires in NSW burned more area than any single fire season during the last 20 years (Figure 5a).

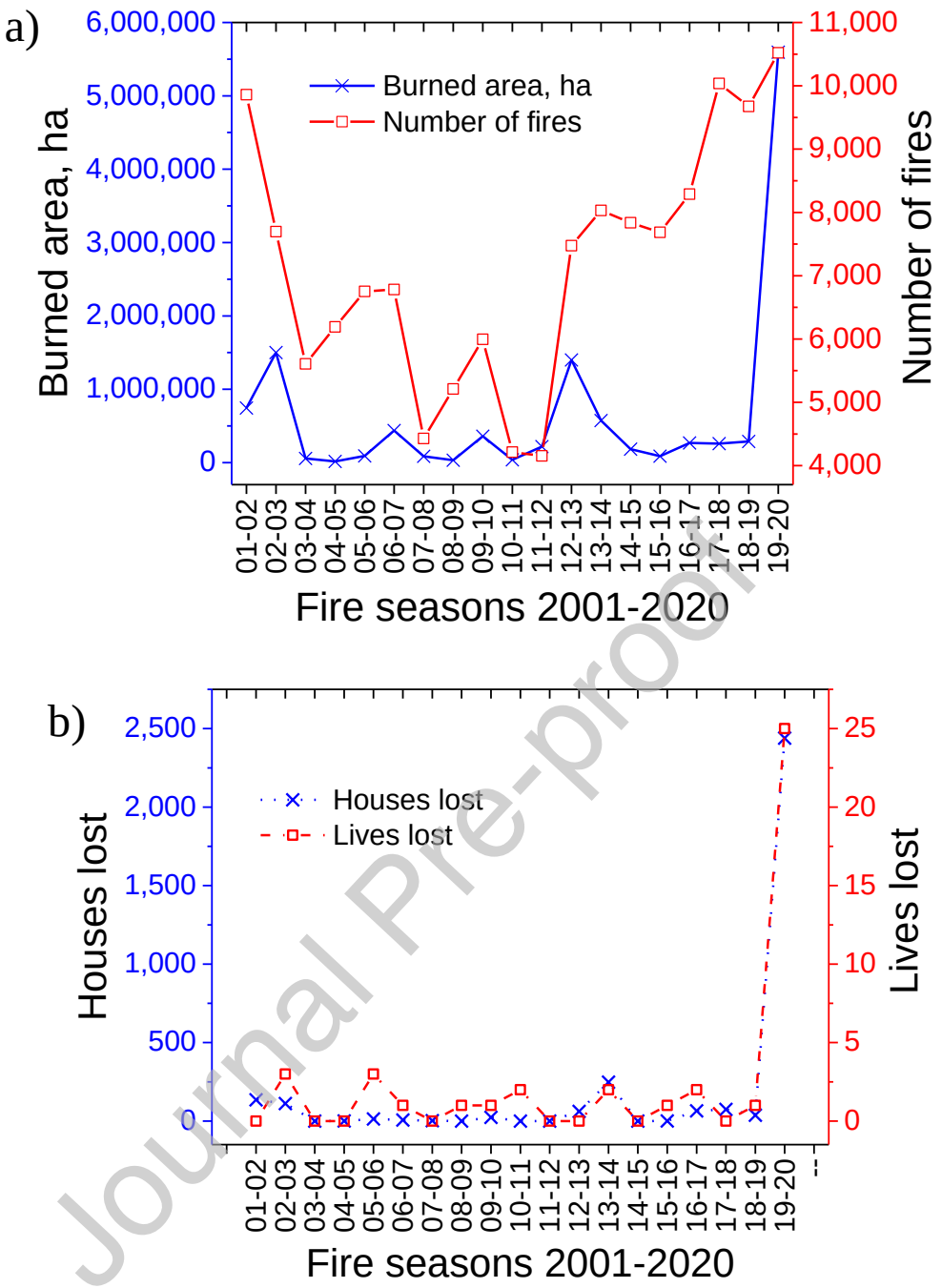


Figure 5. Bushfire aftermath for 2001-2020 fire seasons in NSW: a) Burned areas and number of fires for each season, B) Houses and lives lost for each season. Colour of a plot corresponds to a specific axis.

Last fire season was exceptional with burned area and lives lost more than one order of magnitude higher, and with houses lost almost two orders of magnitude higher compared to the previous average, 370,000 hectares, 1 life and 43 houses respectively (Figure 5). The burned area before 2019 was below half a million hectares and relatively consistent, with two spikes in 2002/2003 and 2012/2013.

Table 3. Regression analysis for 2001-20 fire seasons in NSW.

	2001-2019 dataset					2001-2020 dataset				
Impact category	**m**	**SE**	**p**	**r**	**R^2**	**m**	**SE**	**p**	**r**	**R^2**
Burned area (y) vs Fire season (x)	-14695	446590	0.479	-0.178	0.032	70032	1245657	0.197	0.310	0.096
Number of fires (y) vs Fire season (x)	116	1804	0.177	0.333	0.111	154	1828	0.061	0.438	0.192
Burned area (y) vs Number of fires(x)	85	423491	0.143	0.360	0.129	319	1137799	0.031	0.496	0.246
Houses lost (y) vs Fire season (x)	0.470	68	0.881	0.038	0.001	38	525	0.100	0.389	0.151
Lives lost (y) vs Fire season (x)	-0.013	1.09	0.789	-0.068	0.005	0.368	5.37	0.120	0.369	0.136
Lives lost (y) vs Houses lost (x)	0.005	1.04	0.259	0.281	0.079	0.01	1.08	7.7×10^{-14}	0.982	0.965

where *m* is the slope of the regression line, *SE* is the standard error of the regression, *p* is the significance, *r* is the Pearson's correlation coefficient, R^2 is the coefficient of determination, *x* is the predictor variable, *y* is the response variable.

Before 2019/20 the regression line of the burned area over time had a negative slope converting to a positive with 2019/20 dataset and it was near-borderline significance (p=0.197) (Table 3). The number of fires was decreasing till 2012 and constantly increasing after (Figure 5a). It had a positive slope for both datasets with higher slope for 2001-2020 dataset. Analysis of data showed a notable positive linear relationship between the number of fires and burned area. It was close to the limit of significance (p=0.14) for 2001-2020 dataset and statistically significant (p=0.03) for 2001-2020 dataset.

A regression line of the houses lost over time had a positive slope for both datasets (Figure 5b). However, for 2001-20 dataset, it was almost 2 orders of magnitude higher and statistically significant (p=0.1). Before 2019, the slope for the lives lost was negative and not statistically significant. With additional data from 2019/20, it became positive and marginally significant (p=0.12). A positive linear relationship between the houses and lives lost existed for the 2001-2019 dataset and it was not statistically significant (p=0.26). However, with additional data from 2019/20 it became 2 times higher and it was statistically significant (p=7.7×10^{-14}). Lives lost were approximately 1% of houses lost. An absolute error was 0.85 lives for 2001-2020.

3.2.3 Victoria

In 2019/2020, Victoria was experiencing its third consecutive year of significant rainfall deficit, especially across the coastal and foothill forests of Gippsland [39]. These areas had severe moisture deficit soils. Combined with above average temperatures, it resulted in an increase in surface fine fuel loads and higher flammability in live vegetation [36]. During spring in 2019, cold fronts generated rainfall in southern Victoria leading to normal fire conditions [33].

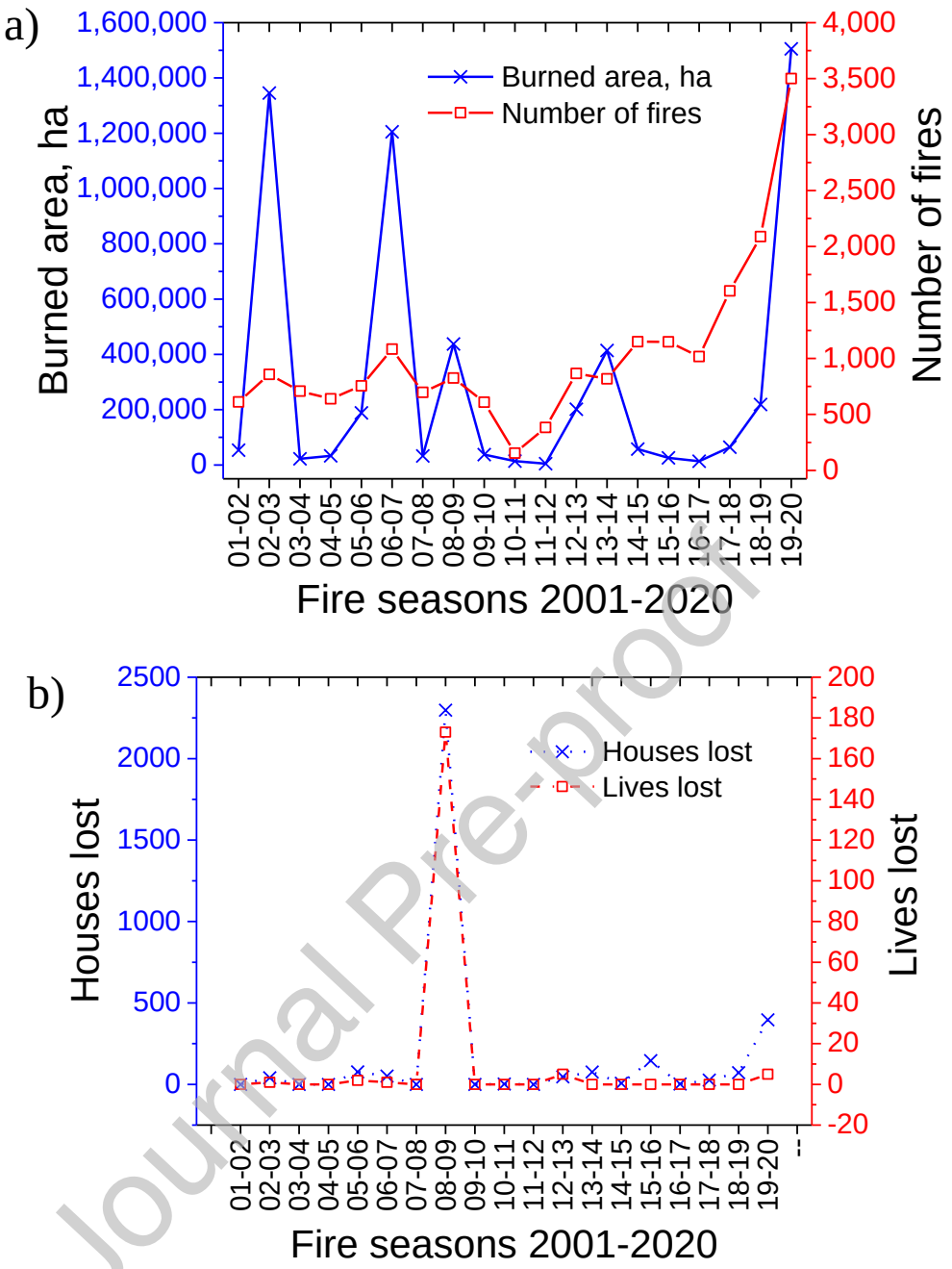


Figure 6. Bushfire aftermath for 2001-2020 fire seasons in Victoria: a) Burned areas and number of fires for each season; b) Houses and lives lost for each season. Colour of a plot corresponds to a specific axis.

A total of 3500 fires were recorded during the 2019/2020 fire season in Victoria. These fires resulted in 1,505,004 hectares burned, 396 houses and 5 lives lost (as of 20 March 2020) (Figure 6). The number of fires and the burned area were one of the biggest in Victorian history. One of the most destructive was the Mallacoota fire in the far east of the state. A small fire started on 29 December 2019, 30 kilometres west of Mallacoota [41]. Mallacoota is a small town and iconic tourist destination in the East Gippsland region of Victoria with a population of approximately 1,000 people, increasing by about 8,000 at Christmas [42]. By 5 pm on 30 December, the Emergency Management Victoria issued a warning that it was too late to evacuate, and people should take shelter immediately [41]. On 31 December,

approximately 4,000 people, including 3,000 tourists remained in Mallacoota. By 11 am, fire began to burn the outskirts of Mallacoota. People gathered at the boat ramp on the coastline, with Country Fire Authority members working to protect them. By 1.30 pm, the fire had reached the water's edge. Roads to Mallacoota were blocked for 37 days due to bushfires and fallen trees. On January 2, for the first time in Victoria's history, a state of disaster was declared. On January 3, approximately 1,160 people from Mallacoota were evacuated on two naval vessels. The last group of people was evacuated on January 8. At least 300 homes were lost.

The number of fires in Victoria has been increasing in the last 20 years with a gap in 2010/11 and 2011/12 fire seasons (Figure 6a), irrespectively to dataset (Table 4). Relationships were relatively strong (r>0.59) and statistically significant (p<0.01). Burned area in Victoria was variable over the last 20 years with considerable spikes in 2002/03, 2006/07, 2008/09, 2013/14 and 2019/20. However, the regression line of the burned area had a negative trend for all datasets, with 25 times higher slope for 2001-2019 dataset (r=-0.33, p=0.18). A positive linear relationship between the number of fires and burned area was observed. The slope became 3 times higher with 2019/20 fire season data. Relationship was moderate (r=0.55) and was essentially significant (p=0.015).

Table 4. Regression analysis for 2001-20 fire seasons in Victoria.

	2001-2019 dataset					**2001-2020 dataset**				
Impact category	**m**	**SE**	**p**	**r**	**R^2**	**m**	**SE**	**p**	**r**	**R^2**
Burned area (y) vs Fire season (x)	-24568	388326	0.183	-0.329	0.108	-952	497886	0.964	-0.011	0.0001
Number of fires (y) vs Fire season (x)	48	365	0.01	0.588	0.346	82	587	0.004	0.630	0.396
Burned area (y) vs Number of fires(x)	116	407865	0.616	0.127	0.016	360	416873	0.015	0.547	0.299
Houses lost (y) vs Fire season (x)	2.7	40.7	0.2	0.327	0.107	8.7	85.4	0.04	0.487	0.237
Lives lost (y) vs Fire season (x)	-0.02	1.32	0.77	0.077	0.006	0.06	1.64	0.42	0.203	0.041
Lives lost (y) vs Houses lost (x)	0.007	1.29	0.399	0.219	0.048	0.011	1.27	0.003	0.656	0.431

The 2008/09 fire season was extraordinary in terms of the houses and lives lost (Figure 6b). A series of bushfires, sadly remembered as the Black Saturday bushfires, mostly contributed to this [43]. A total of 173 people died in these fires, and 2 029 houses were lost. As a result, both the houses and lives lost values in the 2008/09 fire season were higher than 3 standard deviations for all data (2001-2020). In order, to understand trends during last 20 years we excluded the 2008/09 fire season from the houses and lives lost analysis. The number of houses and lives lost in the 2019/20 fire season were well above average, 32 and 0.5 respectively (excluding 2008/09). The houses lost data had positive trend for both datasets (r>0.32). For 2001-20 dataset, the slope was 3 times higher and relationship was significant (p=0.04). With 2019/20 data, the lives lost trend changed from negative to positive. However, both of them had a weak correlation and significance. A linear relationship between the number of houses and lives lost was positive for both datasets and significant for 2001-20 dataset (p=0.003).

3.2.4 South Australia

Average to below average rainfall has occurred across South Australia, with some areas experiencing persistent dry conditions since the start of 2018 [32]. Annual rainfall totals were in the lowest 10% of historical observations for most of South Australia. Maximum temperatures for the year were also well above average and the highest on record for most of South Australia. December brought an exceptionally warm end to the year, with the month the warmest December on record. South Australia was second-highest with an area-averaged accumulated FFDI value for spring. In the Agricultural districts of South Australia the highest peak area-averaged FFDI value for the season on 20 November was over 100, which was easily the highest on record for the region as a whole in spring and the highest for any day of the year for at least 50 years [33].

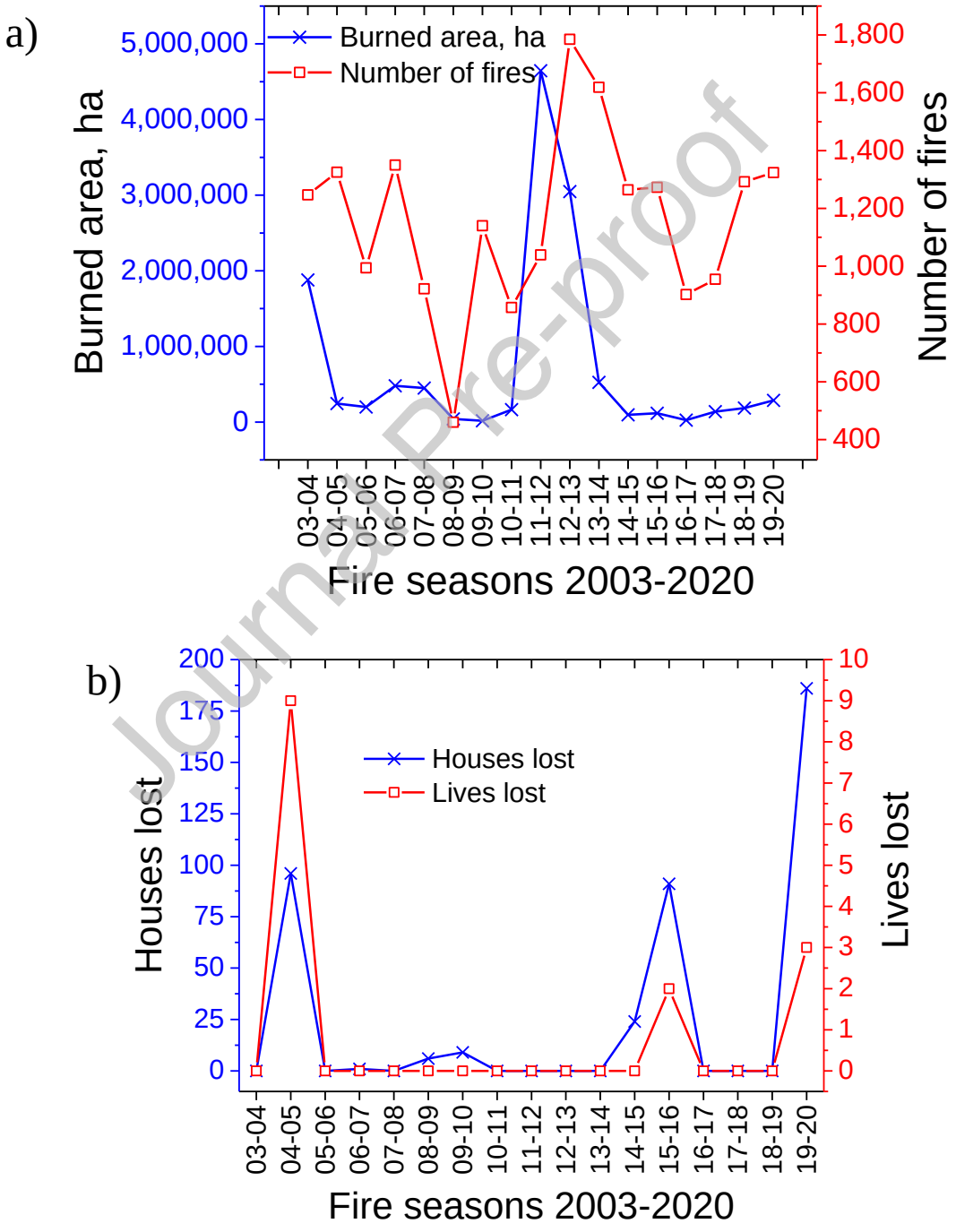


Figure 7. Bushfire aftermath for 2003-2020 fire seasons in South Australia: a) Burned areas and number of fires for each season; b) Houses and lives lost for each season. Colour of a plot corresponds to a specific axis.

In South Australia, 286,845 hectares burned, 186 houses and 3 lives lost in 1,324 bushfires in the 2019/20 fire season (Figure 7). On 20 December 2019, some of the worst bushfires in South Australia started from a series of lightning strikes. These fires were declared contained one week later, however three days after that, on 30 Decemeber 2019, another band of lightning started more fires in the remote Ravine de Casoars Wilderness Area. These fire combined with the existing fires and became known as The Kangaroo Island Fire [44]. The fires were officially contained on 21 January 2020 after burning for more than three weeks and blackening more than 210,000 hectares [45]. It burned most of the Ravine de Casoars Wilderness Area, Flinders Chase National Park, Cape Bouguer Wilderness Area, Cape Torrens Wilders Area, Western River Wilderness Area, and Kelly Hill Caves Conservation Park. The fire caused significant stock losses for local farmers [45] and burnt between $100 million and $900 million of plantation timber [46].The island blaze destroyed 89 homes and hundreds of other buildings along with high visitation tourism assets including Flinders Chase Visitor Centre, Kelly Hill Cave Visitor Centre and world-renown Southern Ocean Lodge. The fire also claimed two lives.

Another destructive fire began in the rural residential Adelaide Hills on 20 December 2019, known as the Cuddlee Creek fire [47]. This fire burned 23,295 hectares, destroy 84 homes and hundreds of other buildings and thousands of stock. This fire also burnt through world famous viticulture and winery areas, large parts of the water catchment for Adelaide, the state's capital city, and killed one person.

The total burned area and number of fires in 2019/20 were not abnormal for South Australia. The burned area and number of fires were below or close to average values, 765,719 hectares and 1,152 respectively. Number of fires and area burnt are usually dominate by remote fire in arid parts of South Australia which have minimal impact on human lives and are not normally actively suppressed by fire agencies. However due to the proximity to higher density population and associated economically valuable land uses, houses and lives lost were above average for SA - more than 10 times higher for the houses lost and 4 times higher for the lives lost.

Table 5. Regression analysis for 2001-20 fire seasons in SA.

	2001-2019 dataset					**2001-2020 dataset**				
Impact category	**m**	**SE**	**p**	**r**	**R^2**	**m**	**SE**	**p**	**r**	**R^2**
Burned area (y) vs Fire season (x)	-27142	1309693	0.717	-0.098	0.010	-32008	1354388	0.629	-0.126	0.016
Number of fires (y) vs Fire season (x)	6.6	326	0.716	0.099	0.010	8.9	316	0.580	0.145	0.021
Burned area (y) vs Number of fires(x)	1183	1304682	0.285	0.285	0.081	1110	1271787	0.297	0.269	0.072
Houses lost (y) vs Fire season (x)	-0.481	32.6	0.790	0.072	0.005	3	51.1	0.259	0.290	0.084
Lives lost (y) vs Fire season (x)	-0.146	2.24	0.251	-0.305	0.093	-0.076	2.31	0.517	-0.169	0.029
Lives lost (y) vs Houses lost (x)	0.059	1.32	7.9×10^{-5}	0.827	0.683	0.03	1.73	0.003	0.673	0.453

Data showed that there was no notable difference between 2003-2019 and 2003-2020 datasets for the burned area and the number of fires (Figure 7a). In both cases, the burned area had a negative trend and the number of fires had a positive trend. For all datasets, the Pearson's correlation coefficient was between 0.016 and 0.099 and relationships were not statistically significant, above p=0.58. A weak positive linear relationship between the number of fires and burned area was found for both datasets. For 2003-2020 dataset, the Pearson's correlation coefficient was r=0.27 (R^2=0.07) and it was approaching to significance level (p=0.3). For 2003-2019 dataset coefficients were similar (r=0.29, R^2 =0.08, p=0.29).

Slightly different patterns were observed for the houses and lives lost depending on the dataset (Figure 7b). Before 2019/2020, the regression line of the houses lost had a negative slope (m=-0.5) converting to a pronounced positive with 2019/20 data (m=3). The lives lost data had a negative trend for both datasets. However, for 2003-2020 dataset, the slope decreased (m=-0.076) compared to 2003-2019 dataset (m=-0.146). A very strong positive linear relationship between the houses and lives lost was for 2003-2019 dataset (r=0.83, R^2=0.68) and it was statistically significant (p=7.9x10^{-5}). With additional data from 2020, it became less pronounced but still considerable (r=0.67, R^2=0.45) and statistically significant (p=0.003).

3.3 Environmental impact

3.3.1 Smoke

Smoke from the bushfires has shrouded much of Australia's south-eastern coast (Figure 8). According to early estimates from the Global Fire Emissions Database, the bushfires likely contributed 900 million metric tons of carbon emissions [48]. Borchers Arriagada, *et al.* [49] estimated population exposure to particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) for the regions of NSW, Queensland, the ACT and Victoria between 1 October 2019 and 10 February 2020 and found that $PM_{2.5}$ concentrations exceeding the 95th percentile of historical daily mean values were recorded by at least one monitoring station in the study area on 125 of 133 days. Based on their estimation, bushfire smoke was responsible for 417 excess deaths, 1124 hospitalisations for cardiovascular problems and 2027 for respiratory problems, and 1305 presentations to emergency departments with asthma. Liu, *et al.* [50] estimated that such an increase in daily $PM_{2.5}$ concentration to induce an increase of at least 5.6% in daily all-cause mortality, 4.5% in cardiovascular mortality, and 6.1% in respiratory mortality.

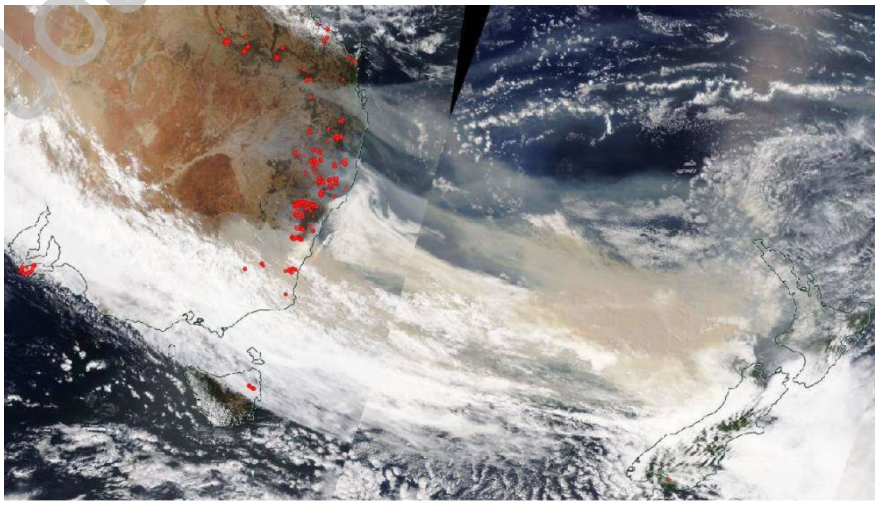


Figure 8. Smoke from bushfires. This image was taken by NASA's Aqua satellite using the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument on 05 January 2020 [51].

Thick smoke covered populated areas of coastal New South Wales, including Sydney, particularly from November through to January. Westerly winds continued to blow smoke from fires burning further inland towards the coast, resulting in poor air quality in the Sydney Basin and many other areas along the New South Wales coast. Sydney experienced 81 days of poor or hazardous air quality in 2019, more than the last 10 years combined. The national capital, Canberra, at one point during the fires, had the world's worst air quality. According to Yu, *et al.* [52], in most areas of Sydney, 24-h average of particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) concentrations in December 2019 exceeded 100 µg/m³ (5 time lower before bushfires), which is four-times higher than the World Health Organisation guideline value of 25 µg/m³ (Figure 9).

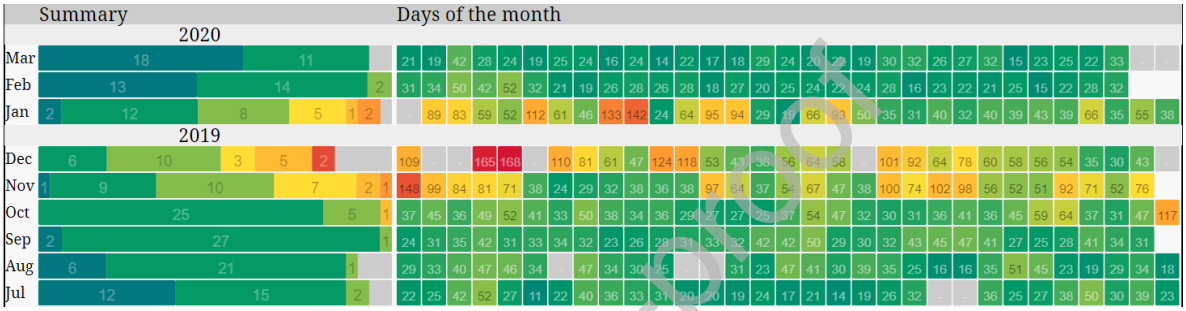


Figure 9. Daily Air Quality Index (AQI) based on concentration of PM2.5 at Randwick Sydney East station [53]. AQI is calculated as the 24 hours average of hourly readings. Air pollution level: 0-50 is Good, 51-100 – Moderate, 101-150 - Unhealthy for Sensitive Groups, 151-200 – Unhealthy. Colours represent sublevels of AQI: light green ~ 0-25, medium green ~ 25-50, dark green ~ 50-75, yellow ~ 75-100, orange ~ 100-125, dark orange ~ 125-150, red ~ 150-175.

A blanket of smoke from the Australian fires covered the whole South Island of New Zealand on 1 January 2020 [54] (Figure 8). People as far south as Dunedin reported smelling smoke in the air. The smoke moved over the North Island the following day and affected glaciers in the country, giving a brown tint to the snow. By 7 January 2020, the smoke was carried approximately 11,000 kilometers across the South Pacific Ocean to Chile, Argentina, Brazil, and Uruguay [55].

3.3.2 Wildlife

Over 1 billion animals were estimated to have been killed in the fires, according to ecologist Chris Dickman of the University of Sydney [38]. The estimate was based on a 2007 World Wide Fund for Nature (WWF) report on impacts of land clearing on Australian wildlife in New South Wales. Dickman's calculation had been based on highly conservative estimates and the actual mortality would therefore be higher. The figure provided by Dickman included mammals (excluding bats), birds, and reptiles; and did not include frogs, insects, or other invertebrates. These values were estimates and did not account for variation in fire intensity within fires.

Ecologists feared some endangered species were driven to extinction by the fires [56]. Animals that survived a bushfire could still find suitable habitats in the immediate vicinity, which was not the case when an entire distribution is decimated in an intense event. Besides immediate mortality from the fires, there were on-going mortalities after the fires from

starvation, lack of shelter, and attacks from predators such as foxes and feral cats that are attracted to fire-affected areas to hunt. According to the Department of Agriculture, Water and the Environment [57], 471 plants, 191 invertebrates and 76 terrestrial vertebrates may be at increased risk of extinction due to the wildfires and require urgent assessment.

On Kangaroo Island a third of the island was burnt. Large parts of the island are designated as protected areas and provide habitat for a large number of animals. NASA estimated that half of the Kangaroo Island's 50,000 koalas may have been killed [44]. A quarter of the beehives of the Ligurian honeybees that inhabited the Island were believed to have been destroyed. Experts have expressed concerns over the survival of several endangered species on the island including the Kangaroo Island dunnart (*Sminthopsis aitkeni*) - a mouse-like marsupial - and the Glossy Black-Cockatoo (*Calyptorhynchus lathami*) [58]. Also, tens of thousands of farm animals, mainly sheep, were killed in the fire on the island [46].

3.3.3 Financial

Damage from the bushfires is estimated to have had a $20 billion impact to the economy, greatly exceeding the record A$4.4 billion set by 2009's Black Saturday fires [59,60]. According to AM Best credit rating agency, bushfires resulted in A$1.7 billion in insurance losses and they are expected to rise [61]. Consulting firm SGS Economics estimated that smoke produced by bushfires caused between A$12 million and A$50 million worth of daily disruption of Sydney [62]. All of the above is likely to make a record impact to Australian economy.

4. Summary

There is no doubt that the fire season of 2019/20 was extraordinary. A total of 18,983,588 hectares were burned, 3113 houses and 33 lives lost in 15,344 bushfires in Black Summer fires. NSW had the highest number of fires, area burned, houses and lives lost for the last 20 years. Two mega-blazes occurred in NSW and burned more than in any fire season during the last 20 years. Victoria had the highest number of fires, area burned, and houses lost (except for the Black Saturday fires). SA had the highest number of houses lost in the last 20 years. Relationships between the burned area and number of fires, the houses and lives lost had positive trend for all states irrespective of the dataset. A negative relationship between the houses and lives lost for SA was the only exception. Multiple studies [26,63-66] show that fire weather will become more severe in many regions around the world. Based on this and observed positive trends for all categories for NSW and Victoria, it is likely that the values will continue to increase in these states in the future. SA before 2019/20 was in a relatively good position showing negative trends for almost all categories. However, the 2019/20 fire season changed that for the worse. The magnitude of effect from increased fire weather may depend on how these conditions alter vegetation across Australia, however the indications shown in this analysis are concerning for fire managers.

Smoke from bushfires significantly impacted on people with cardiovascular and respiratory problems and increased mortality. It also had indirect impact on the economy by disrupting communities [62]. The total impact of the 2019/20 bushfire season to the economy is estimated to be as much as A$40 billion [60]. Due to the record burned area, at least 1 billion vertebrate animals were lost [38]. It will take many years to restore the economy in impacted areas, and for animal and vegetation biodiversity to recover.

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