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DETERMINING THRESHOLD CONDITIONS FOR EXTREME FIRE BEHAVIOUR

Annual project report 2019-2020

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EXECUTIVE SUMMARY

At this phase the project was focused on development of a new method to test flammability of live vegetation in dynamic conditions and understanding influence of climatic changes on the 2019/20 bushfire season in New South Wales (NSW), Victoria, and South Australia (SA).

Understanding live vegetation fuel properties and how they behave when exposed to radiant heat and flame allows us to better predict fire behaviour in forested areas. This study aims to determine a more effective, replicable and accurate method of testing flammability in live vegetation by comparing the impact different radiant heating regimes have on the ignitibility of live vegetation samples. Current methodologies are limited in their ability to provide accurate quantification of flammability due to their reliance on static heat flux exposure, which does not accurately replicate how live plants experience radiative heat flux during a wildfire in their natural environment. Two heating regimes were tested for this study – a static heat flux to reflect current methods and a dynamic (increasing) heat flux to more accurately replicate real conditions of an approaching fire front. Piloted-ignition and unpiloted-ignition were also tested for both of these heating regimes. A Variable Heat Flux (VHFlux) Apparatus was used to study flammability of *Acacia floribunda, Cassinia arcuata*, *Pinus radiata* and bark from *Eucalyptus obliqua*. Time to pyrolysis (production of volatile products), smouldering, flaming ignition, complete consumption and radiant exposure (the radiant energy received by a sample over a time of heating, H_e) were used as ignitability measures. It was observed that time and radiant exposure required to reach flaming ignition (and the other ignitibility metrics) was higher under a dynamic heating regime. It was also observed that the presence of a pilot igniter greatly increased the number of samples that reached flaming ignition, and decreased the time and H_e required to reach flaming ignition (and the other ignitibility metrics). These results suggest clear differences observed between heating regimes for time and H_e required for ignition and other ignitibility measures, which supports the validity of using dynamic heating regimes and the VHFlux apparatus as a standardised method. Adoption of this methodology is recommended to ensure more realistic data on flammability of individual plant species and plant communities, which will ultimately lead to better informed and more accurate wildfire behaviour modelling.

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 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. The total impact of the 2019/20 bushfire season to the economy is estimated to be as much as A$40 billion. Due to the record burned area, at least 1 billion vertebrate animals were lost. It will take many years to restore the economy in impacted areas, and for animal and vegetation biodiversity to recover. Understanding of high-level trends of number of fires, area burned, houses and lives lost for the last two decades in south-eastern Australia will provide useful insights to fire managers for future strategies and policies.

END-USER PROJECT IMPACT STATEMENT

Brad Davis, *NSW Rural Fire Service, NSW*

Understanding and having the ability to predict dynamic fire behaviours in extreme wildfire events is crucial to fire behaviour analysts and fire managers. This project is delivering work on the flammability of live vegetation, which plays an important role in fire behaviour and surface fire transition to crown fires.

There are limitations to current approaches, and in 2019-2020 this project has made important steps towards developing a new standardised methodology for testing flammability of live plant species in dynamic conditions. At maturity, this approach will provide a methodology to determine more realistic data on flammability of individual plant species and plant communities, leading to better informed, more accurate, and dynamic fire behaviour modelling.

This work established a successful proof-of-concept, and hence opens the door to a possible new standard for the future. The next steps for this work may include refinement of the methodology and the expansion of tests to further species. While this work is useful for better understanding the role of live fuel moisture in fire behaviour, it may also be useful for the validation of existing models.

Potentially, the continuation of this work will lead towards fuel-type dependent dynamic flammability metrics as an input into the next generation of fire spread simulation and modelling.

INTRODUCTION

In the last decade, there have been extreme wildfire events around the world resulting in substantial social, economic and environmental impacts. They threaten many lives and cost billions of dollars in damage (Table 1). The majority of the most destructive fires have occurred in south-eastern Australia, California in USA, the Mediterranean region of Europe, south-western Canada, and Siberia and Far East of Russia.

Name	Region	Impact
2018 Camp fire	USA	85 fatalities and nearly 19,000 structures destroyed [1]
2018 Attica fires	Greece	102 fatalities and approximately 3000 houses burned [2]
2017 Thomas fire	USA	1,300 structures lost and 2.2 billion USD in damages [3]
2017 British Columbia fires	Canada	1.2 million hectares burned and 65,000 people evacuated [4, 5]
2017 Wildfires	Portugal	112 human lives lost with 424,000 hectares burned [6]
2016 Fort McMurray wildfire	Canada	2,400 houses lost and 6 billion CND in damages [4, 5]
2016 Wildfires	Portugal	4 people killed and more than 1,000 evacuated [7],
2015 Wildfires	Russia	33 people killed and 1,300 houses burned [8]
2015 South Australia fires	Australia	2 lives lost and 88 houses burned [9]
2013 Red October fire	Australia	224 structures destroyed and 1 person died [10, 11]
2012 Chios fire	Greece	9 villages evacuated and 7,000 hectares burned [12]
2011 Slave Lake fire	Canada	374 properties destroyed and 700 million CND in damages [13]
2011 Bastrop County Complex fire	USA	2 deaths and 1,645 homes lost [14]
2010 Wildfires	Russia	53 fatalities and 2,500 houses lost [15, 16]

TABLE 1. EXAMPLES OF WILDFIRES WITH LARGE SOCIAL, ECONOMIC AND ENVIRONMENTAL IMPACTS FROM 2010 – 2020.

A number of recent wildfires have impacted communities in locations where historically fires are rare or extraordinary events. For example, wildfires occurred in the tropical and temperate rainforests of Chile in 2014 and 2017 with 11 people killed and hundreds of homes destroyed [17, 18]. In Bolivia in 2017 wildfires resulted in 3 deaths, 1,479 people injured, and 3,000 homes lost [19]. There were wildfires close to the Arctic circle in Sweden, Norway, Greenland and Scotland [20-22]. In 2014 wildfires in Sweden killed one person, damaged or destroyed 71 buildings, and over 1000 people were evacuated [23]. In 2019 hundreds of people were forced to evacuate due to an extraordinary high number of extreme wildfires in Norway and Sweden [22].

Understanding and having the ability to predict fire behaviour in wildfire events is essential to ensure the safety of communities living in or near the Wildland-Urban Interface. There are a number of different factors that influence wildfire behaviour. These include weather and climatic influences, as well as the type and arrangement of fuels being impacted [24-26]. Fuel properties can determine if fire transitions into canopies and if firebrand generation occurs, which can increase the fire intensity and rate of spread [27].

Understanding flammability of particular fuel types is crucial to understanding fire behaviour. Historically, flammability has been predicted on the basis of fuel loads and ecological vegetation communities. Determining the flammability of individual plant species, particularly understory species, can provide us with a much better understanding of expected fire behaviour in the broader landscape [27, 28]. This is particularly relevant for species that dominate the understory and canopy in forested ecosystems [29, 30]

Flammability has been studied extensively in the literature. However, there are a number of limitations with previous studies on live plants. These include extrapolation of leaf-scale results to approximate whole-plant flammability, use of uncalibrated and simplistic apparatuses to test larger samples, and the use of static heat flux exposure instead of more realistic dynamic heat flux exposure. To eliminate these limitations, we develop a new method to test flammability of vegetation.

Climate change is already influencing fire seasons around the world [25, 31-33]. 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 [34, 35]. Australia's bushfire season 2019/20 (Black Summer fires 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. To understand the impact of these climatic changes, we conducted a preliminary analysis of the 2019/20 bushfire season and compared it with the fire seasons over the last two decades in the states of New South Wales (NSW), Victoria, and South Australia (SA).

RESEARCH APPROACH AND FINDINGS

IGNITIBILITY OF LIVE PLANTS

This section is based on the research master project prepared and published during this phase of the project: Miller, T. (2019). Role of dynamic and static heat flux on ignitibility of live plants. University of Melbourne, Melbourne, Australia.

The aim of this study was to determine the impact of different heating regimes on flammability of live vegetation and to propose a new method to test it.

Methods

Sample collection

Multiple species were selected to determine whether an influence on flammability was solely due to the difference in heating regime, or if species characteristics (fuel density and arrangement) were also drivers. The study species were selected primarily due to variability in fuel density and arrangement between them as well as their availability and proximity to the experimental location. The plants were located at the University of Melbourne's campus in Creswick, Victoria (Latitude -37.430, Longitude 143.899). Species selected for this study were *Acacia floribunda*, *Cassinia arcuata*, *Pinus radiata* (juvenile) and Bark from *Eucalyptus obliqua* (referred to as Acacia, Cassinia, Pine and Bark henceforth).

Acacia, Cassinia and Pine. Samples were collected immediately before each experiment to ensure the samples would exhibit the flammability characteristics of the live plant as much as possible during the experiment, and to standardise live fuel moistures of the samples. The samples collected were approximately 300mm in length, and were intended to be representative of the standard shape and arrangement of fuel demonstrated by the live plant (Figure 1).

The moisture content of the samples was measured at the beginning and end of each experimental day to demonstrate the variability of the moisture content of the sample species over the course of a day. To do this, an additional sample was collected when collecting both the first and last sample of the day. These samples were weighed, dried in an oven at 100°C for greater than 24 hours, and re-weighed to determine the percentage weight of water in each sample.

Bark. Bark samples were collected from outer layer of trees the day prior to experimentation and cut to size (length 200mm, width 40mm, depth 10mm) and placed in an oven at 30°C overnight to allow for moisture content stabilisation. Fuel moisture content has a significant influence on the flammability of bark, so moisture stabilisation was essential to ensure this was not a confounding factor [36]. Samples were removed from the oven immediately prior to experimentation.

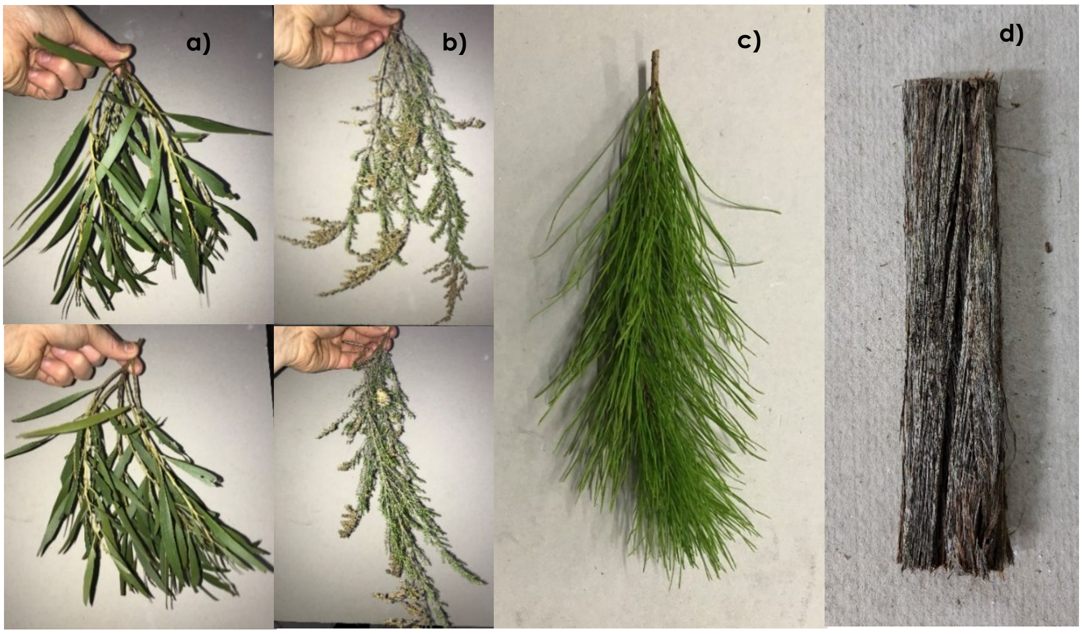


FIG. 1. IMAGES OF REPRESENTATIVE SAMPLES: a) *ACACIA FLORIBUNDA* (FRONT AND SIDE VIEW), b) *CASSINIA ARCUATA* (FRONT AND SIDE VIEW), c) *PINUS RADIATA* (JUVENILE), AND d) BARK FROM *EUCALYPTUS OBLIQUA*.

The Bark samples were measured for moisture content at the beginning and end of each experimental day similar to the above species. However, the samples were collected from the 30°C oven in which they had been placed the day prior, rather than from the live plant. Once collected from the 30°C oven, samples were weighed, dried in an oven at 100°C for greater than 24 hours, and re-weighed to determine the percentage weight of water in each sample.

Species properties measurement

Five additional samples of each species were collected. Dimension measurements (length, width and depth) were collected from each sample, and the mean calculated to determine representative sample dimensions for each species.

Volume of solid fuel in each sample V_{fuel} was measured by submerging each sample in a measuring cylinder filled with water. The difference in water level before and after submersion of the sample provided the volume of the solid fuel in each sample. The mean of the volume measurements was then calculated to determine a representative solid fuel volume for each species.

Bulk volume of each sample V_{bulk} was obtained by calculating a sector of volume of a solid of revolution. A solid of revolution is a solid 3D figure obtained by rotating a plane curve around the axis of revolution. Volume of Bark samples was calculated as the volume of parallelepiped.

Porosity was calculated by using the following formula:

$$\varphi = 1 - \frac{V_{fuel}}{V_{bulk}}, \quad (1)$$

where V_{fuel} is the volume of solid fuel; V_{bulk} is the total or bulk volume of material, including the solid and void components.

Bulk density was also calculated by dividing the dry mass by the bulk volume for each species. Porosity and bulk density were then used to determine the significance they play in influencing flammability in live plants, which is discussed further below.

Projected area was also used as a measure to characterise each of the sample species. This was calculated by scanning three samples of each species and analysing the scanned image in R version 3.6.0 [37] to produce the projected area. Projected area was not calculated for Bark samples because they were considered to be solid samples.

Equipment

The Variable Heat Flux (VHFlux) Apparatus was used for this study (Figure 2). Two heating regimes were tested – a static heat flux to reflect current methods and a dynamic (increasing) heat flux to more accurately replicate real conditions (an approaching fire front). Piloted-ignition and unpiloted-ignition were also tested for both of these heating regimes.

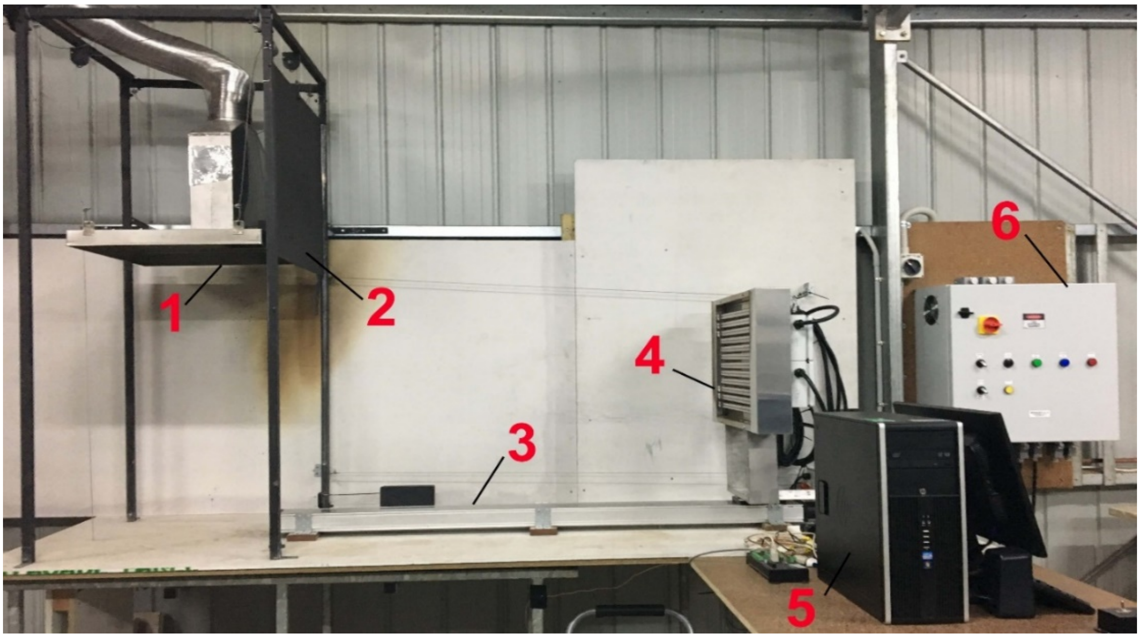


FIG. 2. VARIABLE HEAT FLUX (VHFLUX) APPARATUS 1) AN EXHAUST SYSTEM, 2) A SHUTTER, 3) A LINEAR STAGE, 4) A RADIATIVE PANEL, 5) A PC CONTROL SYSTEM AND 6) A POWER CONTROL BOX.

The VHFlux apparatus is a radiative panel containing 12 infrared short-wave lamps producing radiative heat flux. The panel is mounted on a 1.5m linear stage that allows it to move forward and backwards, creating a variable heat flux. The apparatus is connected to a PC control system which controls the conditions of the experiment, as well as collect relevant data. A programmable step motor controller PCL601USB (Anaheim Automation, Inc.) is used to change movement speed within the range of 0.001-0.3 m/s. A remotely operated shutter is positioned between the panel and the sample to protect the sample from heat radiation prior to the experiment. The power control box controls the radiant heat flux produced by the lamps.

The apparatus was configured as per Figure 3 below. Samples were positioned 51mm from the radiative heat panel at its forward-most position, and 30mm above the pilot igniter. The pilot igniter was located below the fuel to simulate ignition from flame and transition of surface fire to elevated fuels. The pilot igniter was secured 102mm from the radiative heat panel at its forward-most position (Figure 3a), and 170mm above the base of the sample stage (Figure 3b).

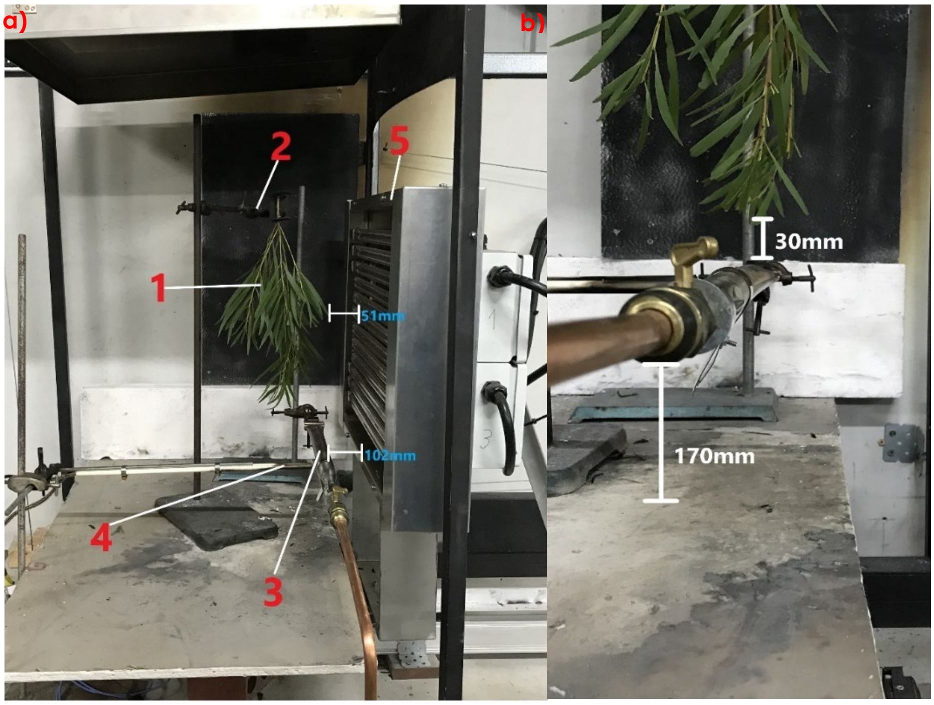


FIG. 3. EXPERIMENTAL DESIGN: a) HORIZONTAL ARRANGEMENT: 1) SAMPLE, 2) CLAMP, 3) PILOT IGNITER, 4) SPARK IGNITER, 5) RADIATIVE PANEL; b) VERTICAL ARRANGEMENT.

Samples were held in place by a single clamp secured around the branch (Figure 3a), except for Bark samples which required a clamp at each end of the sample. Insulation was used for the Bark samples to ensure the conductive heat from the clamps did not influence ignitability.

The pilot igniter consisted of a modified barbeque gas burner connected to a gas bottle via a series of copper pipes. A flow regulator was installed onto the gas bottle to regulate the flame height of the igniter. The regulator was set to 25kPa producing a flame height of 20 ± 5mm. A spark igniter was used to ignite the pilot igniter, which was remotely controlled via a switch at the PC control system desk.

We recorded each experiment with a DSLR camera (Canon EOS 600D). This camera was placed on a tripod and was situated approximately 2m perpendicular to the sample stage. It was remotely operated from the computer desk using a data cable connection to the PC control system and the Canon Capture software.

Heating regimes

To determine the radiative heat flux exposure to samples during the experiments, a water-cooled heat flux sensor SBG01-100 (Hukseflux Thermal Sensors B.V.) was used. The heat flux meter was placed 51mm from the radiative heat panel and radiative heat flux measurements (kW/ m^2) were recorded for a ten-minute period. The mean of these measurements was calculated at 63kW/ m^2, which was henceforth assumed to be the radiative heat flux exposed for static experiments.

The radiative heat panel was programmed to travel 500mm over a ten-minute (600s) period for the dynamic increasing heat flux regime. The machine ran from 551 to 51mm from the sample to simulate a fire front moving towards the sample. The heat flux meter was placed at the same position as for calibration of static experiments to determine the sample's exposure to radiative heat flux over this period. A dynamic heat flux curve was created from these measurements to determine the radiant exposure – the radiant energy received by a sample over a time of heating (Figure 4):

$$H_e = \int_{t1}^{t2} q_r(t)\, dt, \qquad (2)$$

where H_e is the radiant exposure of a surface ("e" for "energetic"), J/m²; *t* is time, sec; q_r is radiative heat flux, J/s·m² (W/m²).

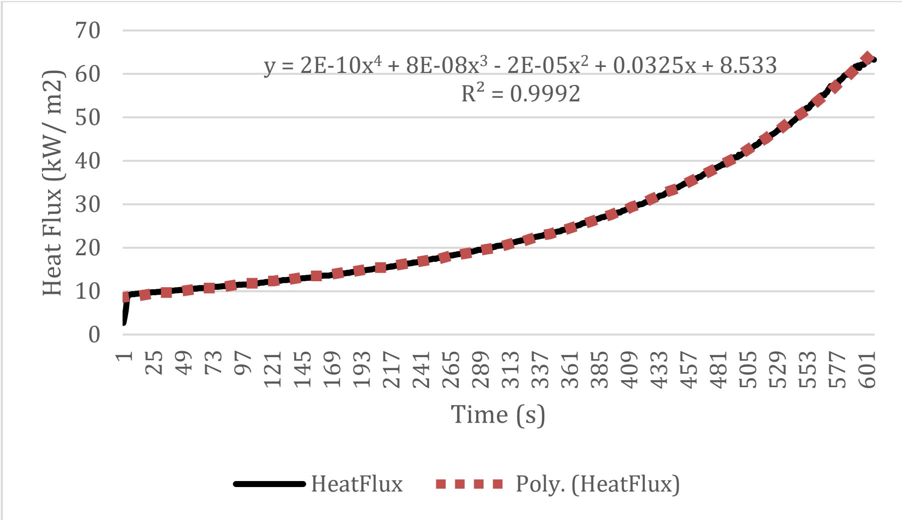


FIG. 4. DYNAMIC HEAT FLUX CURVE PRODUCED FROM CALIBRATION EXPERIMENTS AND FITTED WITH POLYNOMIAL FUNCTION.

The radiant exposure H_e over the ten-minute (600s) period for the dynamic experiments was ~15700 J/m². The experimental time for the static heat flux was calculated to ensure that samples were exposed to the same total H_e as for the dynamic regime. The experimental time for the static experiments was determined to be 250s.

Experimental procedure

Experiments were conducted over the course of eight experimental days, 7th – 10th May and 27th – 30th May 2019. On each day, 10 static and 10 dynamic tests for one species were completed using either piloted or unpiloted ignition. Static and dynamic tests were alternated throughout each experimental day to ensure any changes in sample moisture content over the course of the day did not present bias between heat flux regimes. Unpiloted and piloted experiments were not alternated as the extra time required to adjust the apparatus between experiments would result in significantly longer experimental period.

Samples were collected from the live plant immediately prior to the experiment or in the case of Bark retrieved from the 30°C oven. Samples were then placed in the apparatus as demonstrated above, ensuring the sample was 51mm from the radiative heat panel and 30mm above the pilot igniter (Figure 3). Once the sample was secure in the apparatus, the shutter was closed and the radiative heat panel was moved backwards 1000mm, switched on, and allowed to heat for five minutes to ensure maximum energy output from the panel. The panel was kept at a distance of 1000mm from the shutter whilst heating to limit any damage that may be caused due to extended exposure of radiant heat.

Recording began in the static experiments when the panel was moved to the pre-experimental position. The shutter was then raised, and the panel moved to 51 mm from the sample in 1 second hereafter the static experimental position. Preliminary tests showed that this 1 second of movement did not influence preheating and ignition of samples. The start time of the experiment was when the panel reached the experimental position. The experiment was considered concluded when either the sample had been completely consumed or the experimental time (t=600s) had finished.

The dynamic experiments required a different process. Once pre-heating was complete, the shutter was raised and the pre-programmed dynamic movement cycle for the panel was initiated using the PC control system. The pre-programmed dynamic movement cycle consisted of the panel quickly moving forward 500mm in approximately one second (consistent with the static experiment), followed by slow movement of the panel another 500mm towards the sample over a ten-minute period. The start time of the experiment was when the panel had completed its first 500mm movement. Once the panel reached the forward-most position at 51mm from the sample, it quickly moved backwards 1000mm and the experiment was considered complete.

The piloted experiments were conducted using the same process as above, however an additional step to ignite the pilot igniter was added after recording started and before opening the shutter. To ignite the pilot igniter the gas bottle was opened fully and the spark igniter was switched on. The spark igniter was stopped immediately after the pilot ignitor was lit. The experiment would then continue as above for both static and dynamic regimes.

Data analysis

Video footage collected during the experiments was viewed in VLC media player to determine the time (s) to pyrolysis (production of volatile products), smouldering, leaf/foliage drop, flaming ignition, and complete consumption for each experiment. The start time of an experiment was considered to be the time at which the radiative heat panel arrived at its starting position. An explanation of how each ignitibility measure was defined is in Table 2 below.

Ignitibility Measure	Definition
Pyrolysis	First visible smoke is emanating from sample
Smouldering	Heavy smoke emanating from sample as a result of flameless thermal degradation– defined as point when smoke is thick enough to show as different colour in video playback
Foliage Drop	First leaf/needle falls from sample
Flaming Ignition	Flames produced from sample
Complete Consumption	All leaves/needles consumed from sample
Flaming Ignition to Complete Consumption	Interval between first flame produced and consumption of all leaves/needles from sample
False Ignition	Ignition of sample due to influence of the pilot light rather than from the influence of the radiative heat panel

TABLE 2. EXPLANATION OF EACH IGNITIBILITY MEASURE

These results were then used to calculate the total radiant exposure (kJ/m^2) of the sample at each of the above measures. For static experiments, this was calculated using the function f(t)=63t, where t is equal to time in seconds. For dynamic experiments, it was calculated using the equation in Figure 4 for the function $f(t) = 2E\text{-}10t^4 + 8E\text{-}08t^3 - 2E\text{-}05t^2 + 0.0325t + 8.533$, where t is equal to time in seconds. The definite integral for this function can be seen in the equation (3) below.

$$\int_{x_1}^{x_2} y(t) = \left(\frac{2E-10t^5}{5} + \frac{8E-8t^4}{4} - \frac{2E-5t^3}{3} + \frac{0.325t^2}{2} + 8.533t\right)\Big|_{t_1}^{t_2} \quad (3)$$

The time between first flaming ignition and complete consumption was also calculated as an additional measure for discussion. The results of this calculation were also converted into radiant exposure using the process outlined above.

Data were analysed in R version 3.6.0 [37]. The ggplot2 package [38] in R was used to plot results as boxplots and jitter plots.

Median were chosen as the measure of comparison for the results due to the non-normal distribution of results and small sample sizes. Small sample sizes were experienced due to not all samples reaching flaming ignition. Measures of statistical significance of differences were not calculated also due to the non-normal distribution and small sample sizes. However, any differences observed in the results were still notable in the context of this study, and will be discussed in detail below.

Results

Using the calculations and methods outlined above, Table 3 was produced to show the mean moisture content, porosity, bulk density and projected area measures for each species used for this study.

Table 3 shows that mean moisture content for Acacia, Cassinia and Pine were similar, but Bark had a moisture content less than half of the other species, which is due to the pre-experimental drying period. The variability in mean moisture content for Bark was also much higher than in the other species. Porosity was also similar in Acacia, Cassinia and Pine samples, but Bark had a porosity 6 times less than the other species. Bulk density was similar for Acacia, Cassinia and Pine, but Bark had a bulk density almost 100 times greater than the other species. Projected area for Pine was observed to be 1.4 and 1.5 times lower than Acacia and Cassinia respectively.

Species	Mean Moisture Content (%)	Porosity (φ)	Bulk Density (kg/m³)	Projected Area (cm²)
Acacia	52.03 ± 2.77	0.997	1.54	1027 ± 10
Cassinia	53.98 ± 1.62	0.996	1.30	1066 ± 34
Pine	65.51 ± 2.54	0.996	1.76	715 ± 177
Bark	23.07 ± 16.94	0.167	166	N/A

TABLE 3. SUMMARY OF MEASURES USED TO CHARACTERISE A REPRESENTATIVE SAMPLE FOR EACH SPECIES.

Table 4 shows the number of samples that reached flaming ignition under each test condition for each species. For Acacia, Cassinia and Pine 1-4 (of 10) samples reached flaming ignition in unpiloted experiments. In piloted experiments 7-10 samples reached flaming ignition, which suggests that the presence of the pilot ignitor greatly increased the likelihood of a sample reaching flaming ignition in these species. However, all Bark samples reached flaming ignition under all test conditions. There was no notable difference for any species in the number of samples that reached flaming ignition when comparing static and dynamic heating regimes. Lower sample sizes were used for Bark samples in piloted experiments due to false ignition causing destruction of samples.

Species	Samples Reaching Flaming Ignition			
	Unpiloted		Piloted	
	Static	Dynamic	Static	Dynamic
Acacia	1	1	8	9
Cassinia	4	3	10*	10*
Pine	4	2	10*	7
Bark	10*	10*	8*	5*

TABLE 4. NUMBER OF SAMPLES FOR EACH EXPERIMENT TYPE THAT REACHED FLAMING IGNITION. SAMPLES MARKED WITH * INDICATE THAT ALL SAMPLES REACHED FLAMING IGNITION. IN MOST SPECIES MAXIMUM SAMPLE SIZE WAS 10, BUT FOR BARK THE MAXIMUM SAMPLE SIZES WERE LOWER DUE TO THE INFLUENCE OF THE PILOT IGNITOR.

Heating regime

Static vs dynamic heating regime – Unpiloted experiments. Time required for flaming ignition was greater than 5 times higher under a dynamic heating regime for all species (Figure 5). Differences in Bark samples were much greater, with time required approximately 40 times higher under a dynamic regime. H_e required for flaming ignition was greater than 2 times higher under a dynamic heating regime for all species (Figure 6). Differences in Bark samples were much greater, with H_e required almost 10 times higher under a dynamic heating regime.

Time between flaming ignition and complete consumption (consumption time hereafter) was approximately 1.3 times higher under a static heating regime for all species (Figure 7). H_e between flaming ignition and complete consumption (consumption H_e hereafter) was greater than 1.6 times higher under a dynamic heating regime for all species (Figure 8).

Static vs dynamic heating regime – Piloted experiments. Time required for flaming ignition was greater than 5.8 times higher under a dynamic heating regime for all species (Figure 5). Differences in Bark samples were much greater, with time required more than 60 times higher under a dynamic regime. It was also observed that there is much higher variability in time to flaming ignition under a dynamic heating regime for all species, especially in piloted experiments. H_e required for flaming ignition was greater than 1.3 times higher under a dynamic heating regime for all species (Figure 6). Differences in Bark samples were much greater, with H_e required over 12 times higher under a dynamic heating regime.

Consumption time was greater than 1.5 times higher under a dynamic heating regime for Cassinia and Bark samples, 1.2 times higher under a static heating regime for Acacia samples, and approximately equal for both heating regimes for Pine samples (Figure 7). Consumption H_e was greater than 2 times higher under a dynamic heating regime for all species except Cassinia, where consumption H_e was 1.8 times higher under a static heating regime (Figure 8).

Unpiloted vs piloted experiments – Static heating regime. Time and H_e required for flaming ignition were greater than 1.4 times higher in unpiloted experiments for all species (Figure 5 and 6).

Consumption time and H_e were greater than 1.8 times higher in piloted experiments in all species except Bark, where they were approximately 1.8 times higher in unpiloted experiments (Figure 7 and 8).

Unpiloted vs piloted experiments – Dynamic heating regime. Time and H_e required for flaming ignition were greater than 1.3 and 1.5 times higher in unpiloted experiments respectively for all species (Figure 5 and 6).

Consumption time was more than 1.1 times higher in piloted experiments for all species. Differences in Cassinia samples were much greater, with consumption time 16.5 times higher in piloted experiments (Figure 7). Consumption H_e was greater than 1.6 times higher in piloted experiments for Acacia and Cassinia samples, more than 1.1 times higher in unpiloted experiments for Bark samples, and approximately equal for both experiment types for Pine samples (Figure 8).

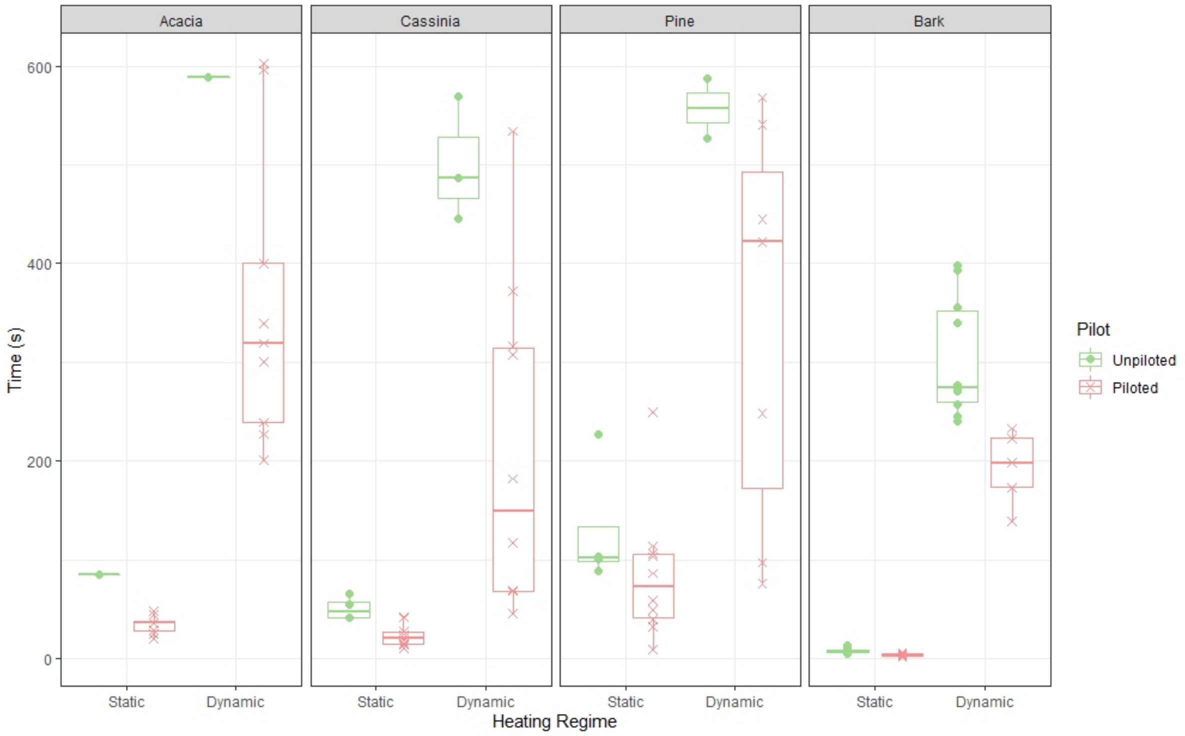


FIG. 5. TIME (S) TO FLAMING IGNITION COMPARING STATIC AND DYNAMIC HEATING REGIMES (X-AXIS) IN BOTH UNPILOTED (GREEN) AND PILOTED (RED) EXPERIMENTS.

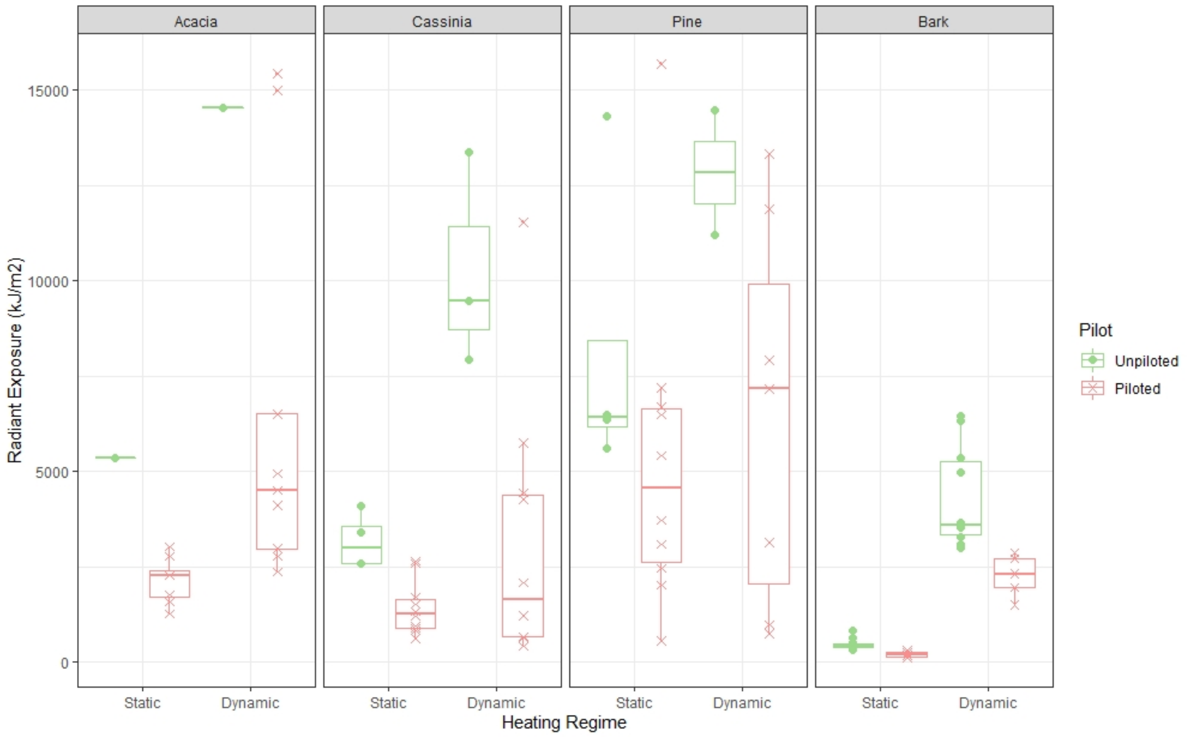


FIG. 6. RADIANT EXPOSURE/H_E (KJ/M²) AT FLAMING IGNITION COMPARING STATIC AND DYNAMIC HEATING REGIMES (X-AXIS) IN BOTH UNPILOTED (GREEN) AND PILOTED (RED) EXPERIMENTS.

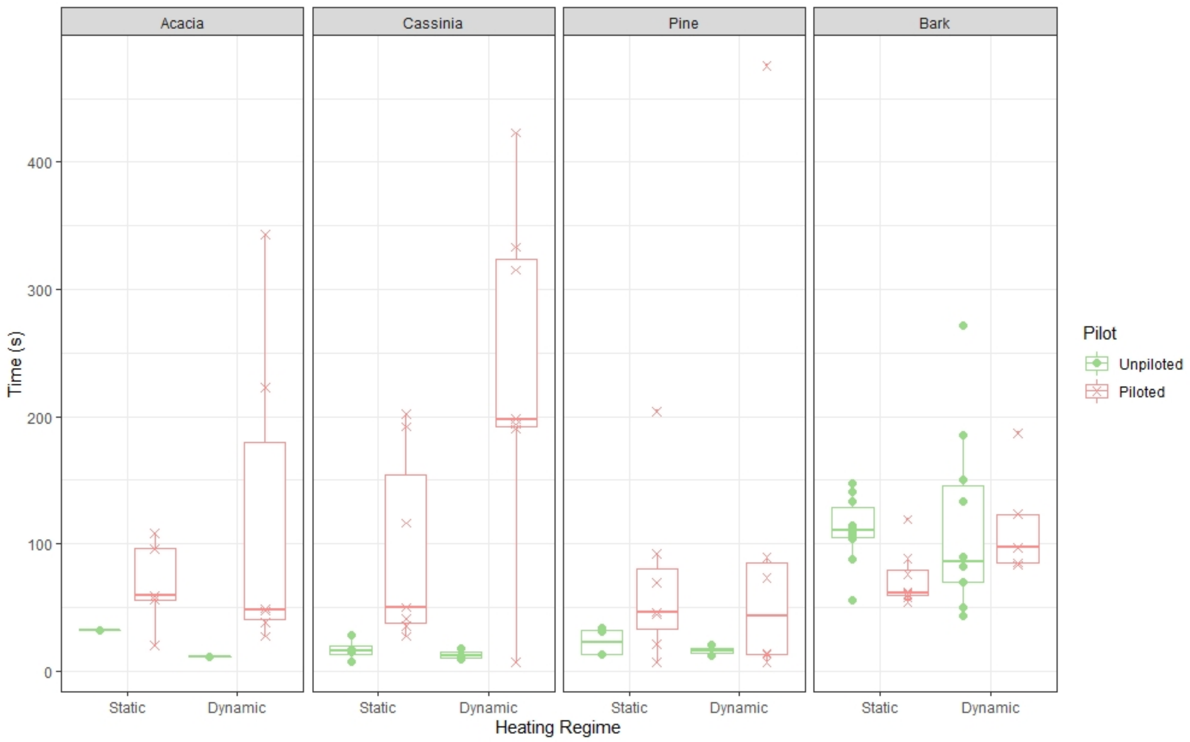


FIG. 7. TIME (S) BETWEEN FLAMING IGNITION AND COMPLETE CONSUMPTION (CONSUMPTION TIME) COMPARING STATIC AND DYNAMIC HEATING REGIMES (X-AXIS) IN BOTH UNPILOTED (GREEN) AND PILOTED (RED) EXPERIMENTS.

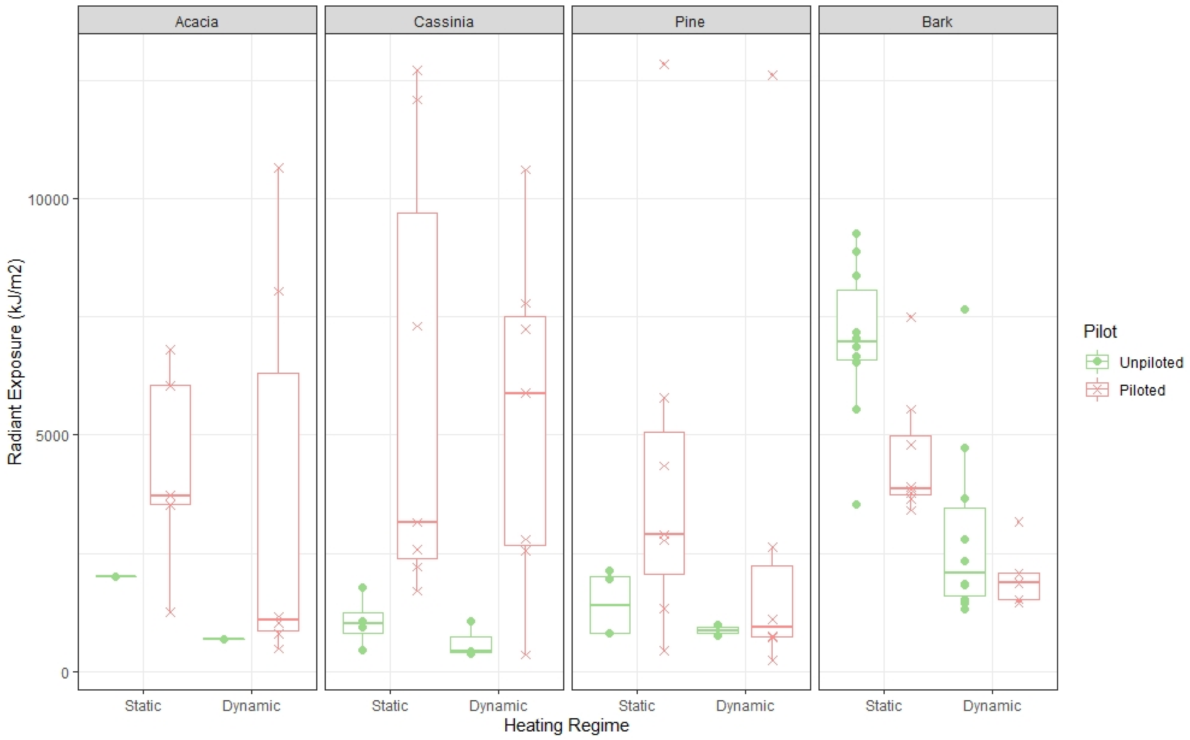


FIG. 8. RADIANT EXPOSURE/H_E (KJ/M²) BETWEEN FLAMING IGNITION AND COMPLETE CONSUMPTION (CONSUMPTION TIME) COMPARING STATIC AND DYNAMIC HEATING REGIMES (X-AXIS) IN BOTH UNPILOTED (GREEN) AND PILOTED (RED) EXPERIMENTS.

Ignitibility measures by species

The use of a pilot ignitor was observed to have an impact on the ability to confidently identify when flaming ignition occurred in some samples. A number of other ignitibility measures (Table 2) were identified and measured as surrogates for flaming ignition so that the influence of difference heating regimes on flaming ignition could still be determined despite the impact of the pilot ignitor.

Acacia. Time required to reach all of the ignitibility measures in both unpiloted and piloted experiments was more than 4.5 times higher under a dynamic heating regime (Table 5). Much larger differences were observed in the pyrolysis measures, where time required was 22 and 103 times higher in unpiloted and piloted experiments respectively. Time required to reach all of the ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments (Table 5).

H_e required to reach all of the ignitibility measures in both unpiloted and piloted experiments was more than 1.2 times higher under a dynamic heating regime, with the highest observed difference in pyrolysis in the piloted experiments where H_e required was 22 times higher (Table 6). H_e required to reach all of the ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments (Table 6).

Flammability measure	Acacia				Cassinia				Pine				Bark			
	Unpiloted		*Piloted*		*Unpiloted*		*Piloted*		*Unpiloted*		*Piloted*		*Unpiloted*		*Piloted*	
	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic
Pyrolysis	16	346.5	3	308	6	271	1	1	48	462	1	1	1	128	1	130
Smouldering	24.5	480	21.5	319	12.5	443	11	149.5	56.5	515	47.5	377.5	3.5	183.5	1.5	171
Foliage Drop	39.5	500	26.5	210	33	465	2.5	37	83.5	529	54.5	14	N/A	N/A	N/A	N/A
Ignition	85	589	36	319	47.5	487	20	149.5	102	557.5	72.5	422	6.5	274.5	3	198
Consumption	117	600	87	392.5	82	562	65	497	137	573.5	141	555	117.5	432.5	65.5	306

TABLE 5. SUMMARY OF RESULTS MEDIAN SHOWING TIME (S) REQUIRED FOR EACH SPECIES TO REACH PYROLYSIS, SMOULDERING, FOLIAGE DROP, IGNITION AND CONSUMPTION. FOLIAGE DROP FOR BARK IS NOT SHOWN DUE TO IT NOT BEING MEASURABLE FOR THESE SAMPLES.

Flammability measure	Acacia				Cassinia				Pine				Bark			
	Unpiloted		*Piloted*		*Unpiloted*		*Piloted*		*Unpiloted*		*Piloted*		*Unpiloted*		*Piloted*	
	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic
Pyrolysis	1008	5119	189	4184	378	3540	63	8.5	3024	8517	63	8.5	63	1351	63	1376
Smouldering	1544	9187	1355	4498	788	7843	693	1648	3560	10650	2993	5935	220	2103	94.5	1924
Foliage Drop	2489	9996	1670	2502	2079	8619	158	339	5261	11359	3434	123	N/A	N/A	N/A	N/A
Ignition	5355	14544	2268	4498	2993	9460	1260	1648	6426	12843	4568	7163	410	3605	189	2318
Consumption	7371	15232	5481	6403	5166	12982	4095	9870	8631	13710	8883	12605	7403	7498	4127	4224

TABLE 6. SUMMARY OF RESULTS SHOWING MEDIAN RADIANT EXPOSURE/H_E (KJ/M^2) REQUIRED FOR EACH SPECIES TO REACH PYROLYSIS, SMOULDERING, FOLIAGE DROP, IGNITION AND CONSUMPTION. FOLIAGE DROP FOR BARK IS NOT SHOWN DUE TO IT NOT BEING MEASURABLE FOR THESE SAMPLES.

Cassinia. Time required to reach all of the ignitibility measures in both unpiloted and piloted experiments was more than 7 times higher under a dynamic heating regime, except pyrolysis in the piloted experiments which was approximately equal (Table 5). Much larger differences were observed in pyrolysis in the unpiloted experiments, where time was 45 times higher. Time required to reach all of the ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments (Table 5). Much larger differences were observed in the pyrolysis under a dynamic heating regime, where time required was 271 times higher in unpiloted experiments.

H_e required to reach all of the ignitibility measures in both unpiloted and piloted experiments was more than 1.3 times higher under a dynamic heating regime, except for pyrolysis in piloted experiments where H_e was approximately 7 times higher under a static heating regime (Table 6). Much larger differences were observed in pyrolysis and smouldering in unpiloted experiments where H_e was more than 9 times higher. H_e required to reach all of the ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments (Table 6). Much larger differences were observed for pyrolysis under a dynamic heating regime, where H_e was more than 400 times higher in unpiloted experiments.

Pine. Time required to reach all ignitibility measures in both unpiloted and piloted experiments was more than 4 times higher under a dynamic heating regime, except for foliage drop in piloted experiments where time was approximately 4 times higher under a static heating regime, and pyrolysis in piloted experiments where time was approximately equal under both heating regimes (Table 5). Time required to reach all ignitibility measures for both static and dynamic heating regimes was more than 1.2 times higher in unpiloted experiments, except for consumption under a static heating regime where time was 1.3 times higher in piloted experiments (Table 5). Much larger differences were observed in pyrolysis under static and dynamic heating regimes where time required was 50 and 450 times higher respectively. H_e required to reach all ignitibility measures in both piloted and unpiloted experiments was more than 1.4 times higher under a dynamic heating regime, except for pyrolysis and foliage drop in piloted experiments where H_e was 7 and 28 times higher under a static heating regime respectively (Table 6). H_e required to reach all ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments, except for consumption under a static heating regime where H_e was approximately equal for both experiment types (Table 6). Much larger differences were observed in pyrolysis under static and dynamic heating regimes where time required was 48 and 996 times higher respectively.

Bark. Time required to reach all ignitibility measures in both unpiloted and piloted experiments was more than 3.7 times higher under a dynamic heating regime (Table 5). Much larger differences observed in pyrolysis, smouldering and ignition measures where time was more than 50 times higher under a dynamic heating regime. Time required to reach all ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments, except for pyrolysis where time was approximately equal under both experiment types (Table 5).

H_e required to reach all ignitibility measures in both unpiloted and piloted experiments was more than 8.8 times higher under a dynamic heating regime, except for consumption where H_e was approximately equal for both heating regimes (Table 6). H_e required to reach all ignitibility measures for both static and dynamic heating regimes was more than 1.1 times higher in unpiloted experiments, except for pyrolysis where H_e was approximately equal for both experiment types (Table 6).

False ignitions. Mean time to false ignition was more than 4 times higher under both heating regimes for Acacia samples when compared to the other species (Table 7). The number of samples impacted by false ignition was much lower for Bark samples when compared to the other species (Table 7). Bark samples were also destroyed when impacted by false ignition, which did not occur in the other species.

Species	Mean Time to False Ignition (sec)	
	Static	Dynamic
Acacia	12.4 ± 9.7 (n=10)	111 ± 103 (n=9)
Cassinia	2.8 ± 3.8 (n=10)	5.9 ± 13.9 (n=9)
Pine	1.9 ± 2.9 (n=10)	3.4 ± 5.2 (n=10)
Bark	1 (n=2)	9.6 ± 8.7 (n=5)

TABLE 7. MEAN TIME TO FALSE IGNITION IN PILOTED EXPERIMENTS. SAMPLE SIZE (N) IS ALSO SHOWN.

Discussion

Building on past studies conducted on flammability of building materials [39-45], we tested the influence of different heating regimes on the ignitibility of live vegetation. Large differences were observed in the results based on both heating regime and ignition type, the implications of which will be discussed further below.

Key findings and consistencies with previous studies

There have been no previous studies that investigate the influence of different heating regimes on flammability of live vegetation. However, consistencies were found between this study and previous studies on the flammability of building materials using dynamic heating regimes [39-45]. Samples under a dynamic heating regime required more time and radiant exposure to reach ignition (and other ignitibility measures). This difference is due to the period of low heat flux exposure at the beginning of the dynamic heating regime, which allows time for convective cooling of the samples to occur. These results were also observed in studies on flammability of wooden building materials using increasing dynamic heat flux [39, 40, 42, 45, 46].

Samples under a static heating regime required more time and radiant exposure between ignition and complete consumption in unpiloted experiments. It was observed that during static heating regime experiments ignition would occur in multiple stages, which would reduce the density and continuity of fuels resulting in more time and H_e required to reach complete consumption [26, 47]. However, this pattern was not observed in piloted experiments, which is likely due to the influence of false ignitions on the results. This will be discussed in further detail below.

We also observed that time and radiant exposure required to reach ignition and other ignitibility measures was generally higher in unpiloted experiments. This is consistent with a study by Bilbao, Mastral [44] into degradation and ignition of wood under constant and variable heat flux. They found that the presence of a pilot igniter can ignite the pyrolysis gases before the critical temperature for unpiloted ignition is reached, which lowers the time to ignition [44, 48]. Bilbao, Mastral [44] also demonstrated that the number of samples with ignition success is higher for the same heating conditions when a pilot igniter is present, which is consistent with the results observed in this study.

Inconsistencies in the characteristics of the fuel types resulted in exceptions to the patterns above. From the four species, there were two distinct fuel types used in this study. Live fuels (Acacia, Cassinia and Pine) all demonstrated high porosity and low bulk density, whereas Bark had much lower porosity and high bulk density (Table 3). It was also evident that the live samples were often much less consistent in size, shape and fuel arrangement than Bark samples due to the natural variability of fuel arrangement in live plants. Variability in results was much higher in live samples due to the variations in density and continuity of fuels, which plays a significant role in the ignitibility of live plants [47, 49].

Differences were also observed in the results between live plant species. In particular, Acacia samples were found to have much lower likelihood of flaming ignition in unpiloted experiments than Cassinia and Pine samples (Table 4). It was also observed that Acacia samples were less susceptible to false ignitions than Cassinia and Pine samples, evident by the much higher time to false ignition in Acacia samples (Table 7). Given the similar porosity, bulk density and moisture content for Acacia, Pine and Cassinia samples (Table 3), other chemical or physical species traits were likely influencing this result.

Projected area was expected to have influence on time to flaming ignition. However, the differences in this measure between the species (Table 3) were not consistent with the differences observed in the results for the heating regimes (Figure 5). The results were consistent only for the static regime where increase in the projected area resulted in lower igniton time irrespective to piloted or unpiloted ignition. These results make sence, as bigger projected area exposed to radiative heat flux in a short period of time produces more pyrolysis products and has lower ignition time respectively. One possible explanation of variability for dynamic regime is influence of convection, which could modify heat and mass transfer of the sample by cooling it down. In static regime convective heat losses are much lower than exposed radiative heat flux and they can be neglected. It is likely that other physical and chemical characteristics of species such as leaf surface area to volume ratio, leaf thickness, and presence or absence of volatile chemicals also contributed to difference in results. However, due to the limited information in the literature about some of the sample species this data was not available to provide a comparison.

Addressing limitations of previous studies

The methodology used in this study was designed to overcome the limitations of methods used in previous studies. Laboratory experiments testing flammability of individual plant elements have been limited in their ability to extrapolate results to infer whole-plant or fuel-bed flammability [50]. The VHFlux apparatus overcomes this limitation, as it has the ability to test whole-plant or shoot-level samples. This ensures that physical structure and arrangement of samples is considered, providing a more realistic representation of flammability of the species in its natural environment [50, 51].

Our study has also addressed the limitations of boundary condition of previous studies [28, 52, 53]. This has been achieved by measuring and calibrating the radiative heat flux output from the VHFlux apparatus, as well as conducting experiments in a controlled environment free from any confounding effects on the sample. This ensured that consistent and replicable experiments were conducted throughout the study.

Introducing the use of dynamic heat flux to test ignitibility of live plants has allowed our study to overcome another significant limitation of previous studies. Our results have shown that type of heating regime has an influence on the ignitibility of live plants. This suggests that it is important to test flammability of live plants under a dynamic heating regime that most accurately replicates that of an approaching fire front. Using a dynamic heat flux in place of the previously used static heat flux will increase the accuracy of flammability data for live plant species.

Limitations of this study

The most significant limitation to this study was the influence of false ignitions. The pilot igniter had a large impact on some of the piloted experiment results. The presence of the pilot flame under the sample often resulted in false ignitions (see Table 2 for definition), which altered the fuel properties of the sample before flaming ignition occurred. This most noticeably impacted on measurements of consumption time and H_e, which were lower under a dynamic heating regime in unpiloted experiments but higher under dynamic heating regime for piloted experiments. Under the dynamic heating regime, samples were exposed to a low radiant heat flux for an extended period at the start of the heating cycle. This period of low radiant exposure allowed time for false ignitions to start and fully extinguish, which significantly altered the fuel arrangement and continuity of samples before flaming ignition could occur. As such, when flaming ignition did occur full consumption of the sample would take much longer, if it occurred at all [47, 49]. This also resulted in much more variability in the results under a dynamic heating regime, which has implications on using results for modelling.

These false ignitions also impacted the results for other ignitibility measures in piloted experiments. Pyrolysis was often difficult to identify when false ignitions occurred, as the smoke produced after the false ignition masked any evidence of pyrolysis gases. As a result, in some cases time to pyrolysis was likely recorded to be much lower than what is truly representative of the samples. The same occurred for foliage drop measurements due to the false ignitions causing foliage to fall before it would occur as a result of radiant heat exposure. This was particularly evident in Pine samples, as their needles were observed to be more sensitive to foliage drop than other species. Alterations to the type and positioning of the pilot igniter in the apparatus will need to occur to ensure that impacts of false ignitions on results are mitigated.

Not all samples reached ignition during the experiments, which meant that lower sample sizes were used and the data was not normally distributed. Testing on large plant samples increases inconsistency of results and reduces flaming ignition success, due to plant heterogeneity and non-uniformity. To avoid both of these limitations, a larger number of repetitions is required to increase the successful ignitions to a minimum of 10. However, the limited timeframe available to conduct this study did not allow for further tests to be conducted to increase the sample size.

Overcoming these limitations will be important in ensuring the success of this methodology for future research.

Future implications

This study has proposed an improved methodology for testing flammability in live plants. With this improvement comes the ability to provide data that can expand current wildfire behaviour models to include species-specific (physical and chemical) traits rather than relying solely on surface fuel loads. This was shown in a study by Zylstra, Bradstock [54], which demonstrated that accuracy of wildfire behaviour models could be significantly improved by incorporating the effects of vegetation structure and species-specific traits as inputs. The validity of this approach is supported by our study, with the effect of some species-specific traits on ignitibility evident in the results (as discussed earlier). The presence of these influences on ignitibility, coupled with the outcomes of Zylstra, Bradstock [54] study, suggests that having an extensive dataset on flammability of individual species has the potential to greatly improve wildfire behaviour models. Testing different ranges of densities, porosities, moisture contents and chemical compositions of species (wax, oils, resins, etc.) could also provide valuable knowledge to further inform fire behaviour models.

We chose one type of dynamic heating regime to test in our study. However, the rate of spread of a wildfire is highly variable and dependent on weather conditions, which exposes live plants to a variety of different heating regimes. Studies on flammability of building materials have explored the effect of different types of dynamic heating regimes, and have demonstrated that different heating rates result in differences in flammability results [39-45]. Our methodology could be extended to include exposure of samples to a variety of dynamic heating regimes based on typical rates of spread. This, in combination with the above inclusions, could lead to dynamic wildfire behaviour models that have the ability to adjust flammability inputs based on weather conditions and fuel properties to produce more accurate outputs of intensity and rate of spread.

Conclusion

Our study has proposed a new standardised methodology for testing ignitibility of live plant species, with potential for extending further to flammability metrics. The validity of using dynamic heating regimes as a standardised method has been demonstrated, with clear differences observed between heating regimes for time and H_e required for ignition and other ignitibility measures. The influences observed on ignitibility due to the pilot ignitor and species characteristics were heavily outweighed by the influence of the heating regime.

The VHFlux apparatus allows for flammability testing of live plant samples using dynamic heating regimes where parameters can be controlled to create repeatable and accurate testing in a controlled environment. This far exceeds the suitability of current methodologies and apparatuses [26, 52, 53, 55, 56].

Adoption of this methodology is recommended to ensure more realistic data on flammability of individual plant species and plant communities. This will ultimately lead to better informed, more accurate, and dynamic wildfire behaviour modelling.

NUMBERS BEHIND AUSTRALIA'S CATASTROPHIC 2019/20 BUSHFIRE SEASON

This section is based on the invited paper prepared and published under the CC BY-NC-ND 4.0 license during this phase of the project: Filkov, A., Ngo, T., Matthews, S., Telfer, S., & Penman, T. (2020). Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience*, 1, 44-56. doi:https://doi.org/10.1016/j.jnlssr.2020.06.009.

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?

Methods

We collected all available information about weather and bushfires impact to understand the novelty of the Black Summer fires 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 9). 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 [57, 58]; data about impact of bushfires were obtained from the annual reports of the fire service agencies responsible for firefighting in the state.

FIG. 9. 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 level *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.

Bushfire season

Preconditions

The Bureau of Meteorology has determined 2019 was Australia's warmest year on record (Figure 10) [57]. It broke records of area-averaged mean temperature (+1.33 °C) and mean maximum temperatures (+1.59 °C, Figure 10b). 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.

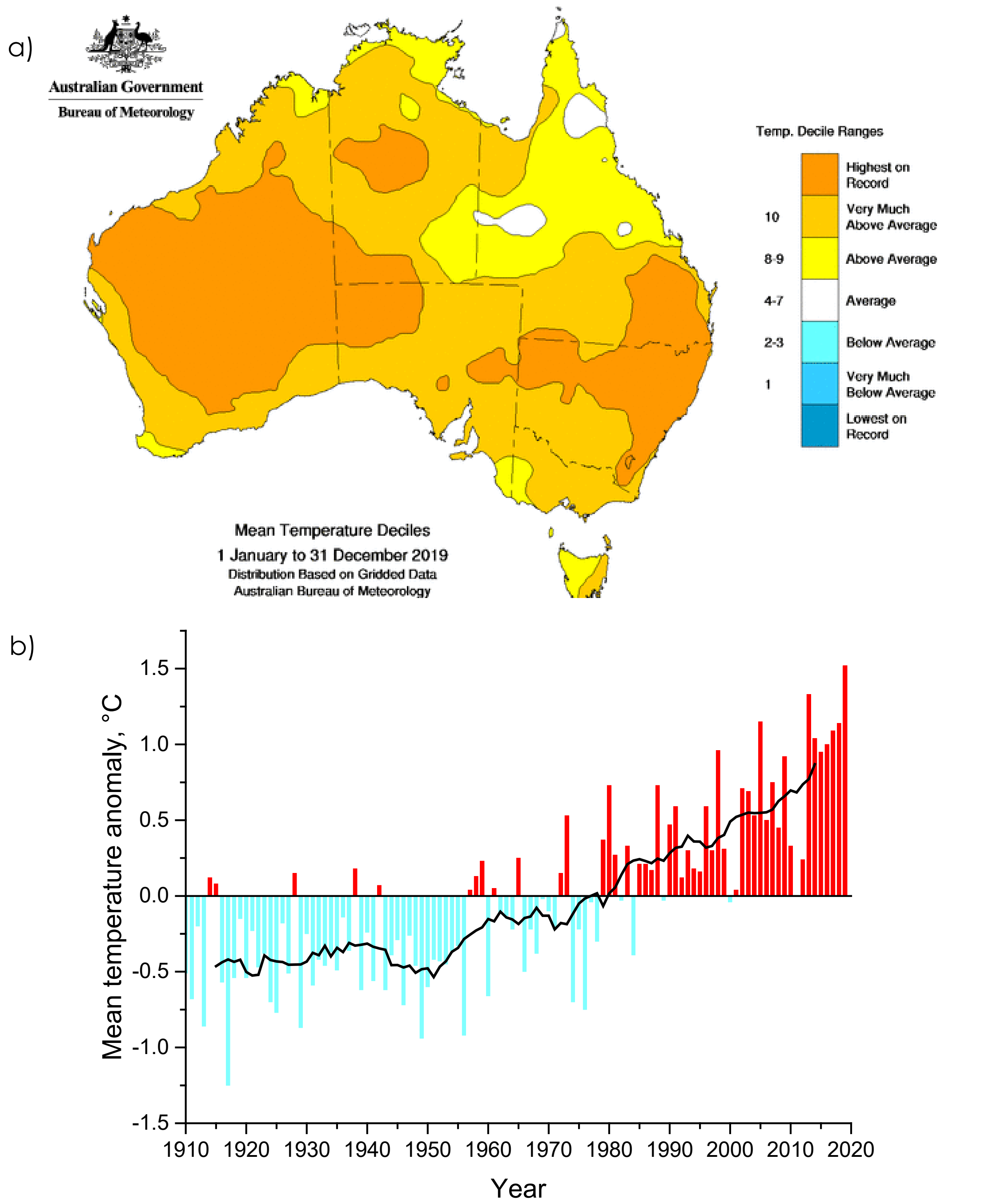


FIG. 10. AIR TEMPERATURE [57]: a) ANNUAL MEAN TEMPERATURES COMPARED TO HISTORICAL TEMPERATURE OBSERVATIONS, b) MEAN TEMPERATURE ANOMALIES AVERAGED OVER AUSTRALIA. DECILES SHOW WHETHER TEMPERATURE IS ABOVE AVERAGE, AVERAGE OR BELOW AVERAGE FOR THE TIME PERIOD AND AREA CHOSEN. THE BLACK LINE SHOWS THE 11-YEAR MOVING AVERAGE. PICTURES AND DATA WERE PUBLISHED IN THE BUREAU OF METEOROLOGY'S ANNUAL STATEMENT [57] UNDER CREATIVE COMMONS LICENSING ARRANGEMENTS.

2019 was also the driest year on record for Australia at 277.6 mm (annual mean) [57], although parts of Queensland's northwest and northern tropics were wetter than average (Figure 11a). Rainfall was 40 % below the 1961–1990 average (Figure 11b). 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 [59]) was one of the main influences on Australia's climate during 2019, and contributed to very low rainfall and low humidity across Australia.

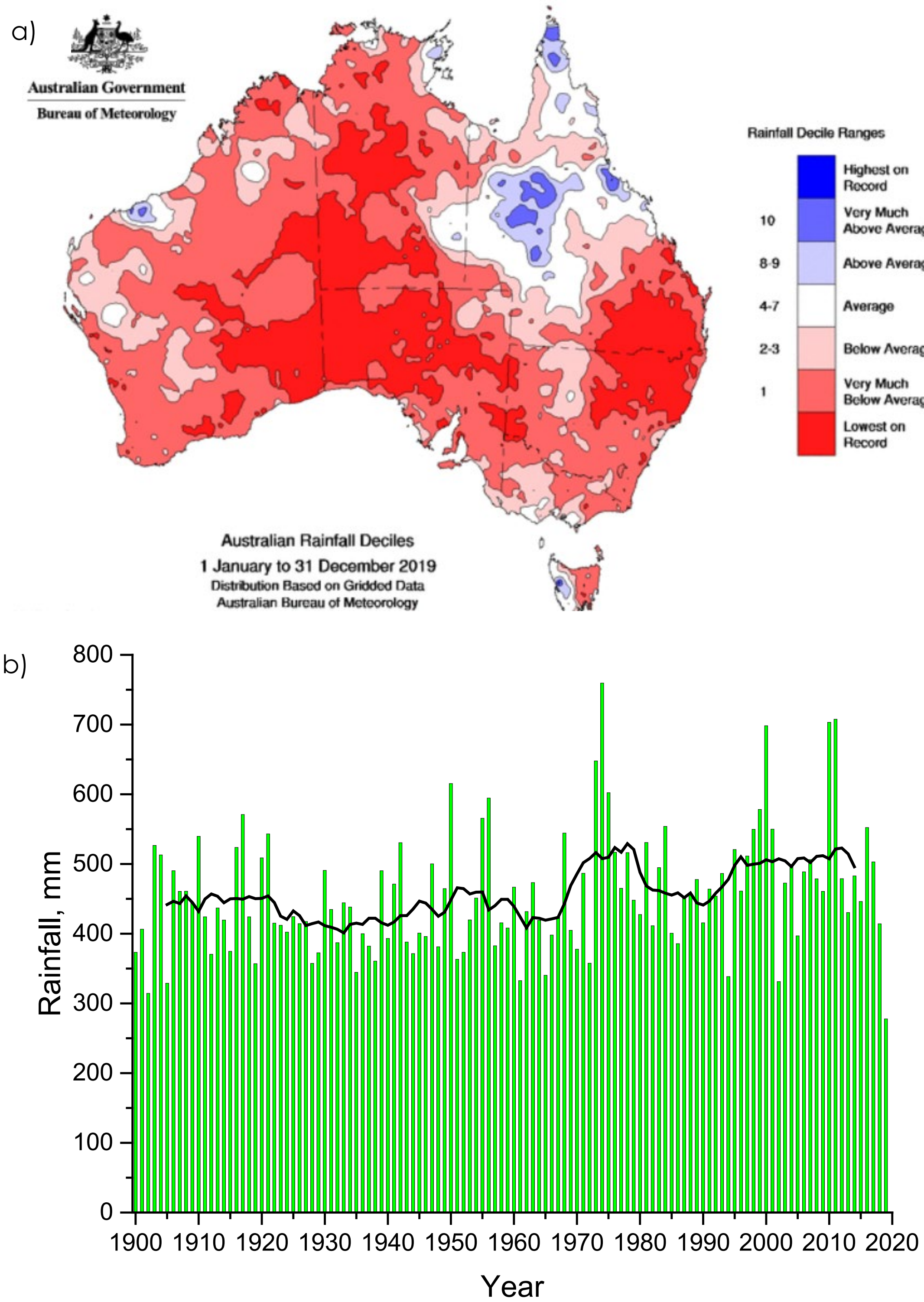


FIG. 11. RAINFALL [57]: a) RAINFALL DECILES FOR JANUARY TO DECEMBER 2019, b) ANNUAL MEAN RAIN. THE BLACK LINE SHOWS THE 11-YEAR MOVING AVERAGE. PICTURES ARE TAKEN FROM THE BUREAU OF METEOROLOGY'S ANNUAL STATEMENT [57]. DECILES SHOW WHETHER RAINFALL IS ABOVE AVERAGE, AVERAGE OR BELOW AVERAGE FOR THE TIME PERIOD AND AREA CHOSEN. PICTURES AND DATA WERE PUBLISHED IN THE BUREAU OF METEOROLOGY'S ANNUAL STATEMENT [57] UNDER CREATIVE COMMONS LICENSING ARRANGEMENTS.

Forest Fire Danger Index (FFDI) is used in Australia to measure the degree of fire danger in Australian forests [60]. 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 12a) [58]. 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 12a). 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 12b).

a)

b)

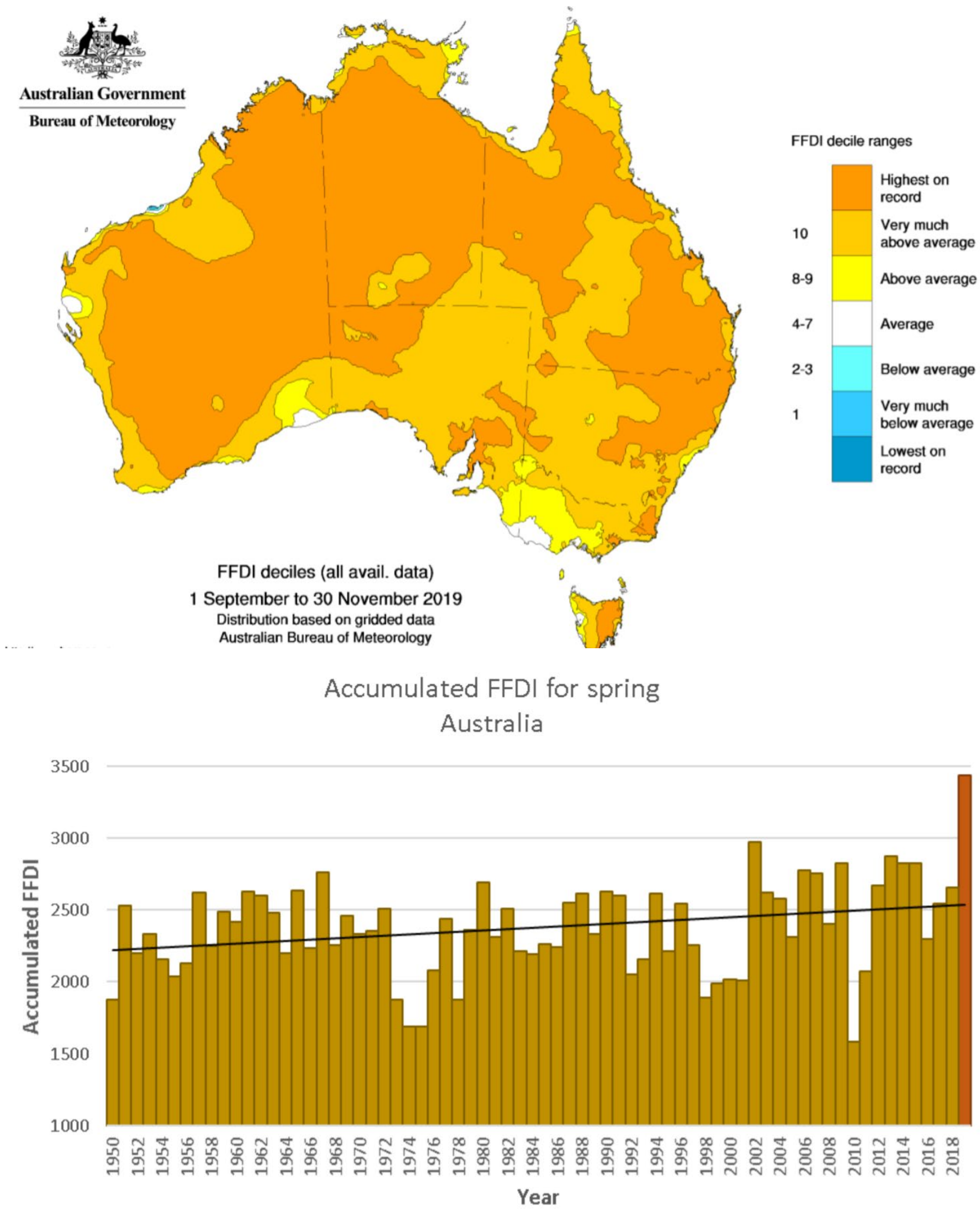


FIG. 12. FOREST FIRE DANGER INDEX [58]: a) ACCUMULATED-FFDI DECILES FOR SPRING 2019 (BASED ON ALL YEARS SINCE 1950), b) SPRING ACCUMULATED FFDI VALUES FOR AUSTRALIA FROM 1950 TO 2019. ACCUMULATED FFDI FOR SPRING 2019 SHOWN IN ORANGE. LINEAR TREND LINE SHOWN IN BLACK. PICTURES AND DATA WERE PUBLISHED IN THE BUREAU OF METEOROLOGY'S SPECIAL STATEMENT [58] UNDER CREATIVE COMMONS LICENSING ARRANGEMENTS.

High temperatures, rainfall deficit and prolonged drought resulted in increase in fuel availability and very high fire danger indexes [61, 62]. 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 [63] (Table 8).

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]	2,439	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**	**3077**	**33**

TABLE 8. 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. 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.

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 [58]. Long-term rainfall deficiencies, record low for some areas in the north of the state, have severely impacted on water resources and firefighting tactics [64]. 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 [65]. Significant soil moisture deficit and windy conditions resulted in a significant number of bushfires [61].

A total of 5,595,739 hectares were burned, 2439 houses and 25 lives lost in 10,520 bushfires in NSW (Figure 13). 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 13a).

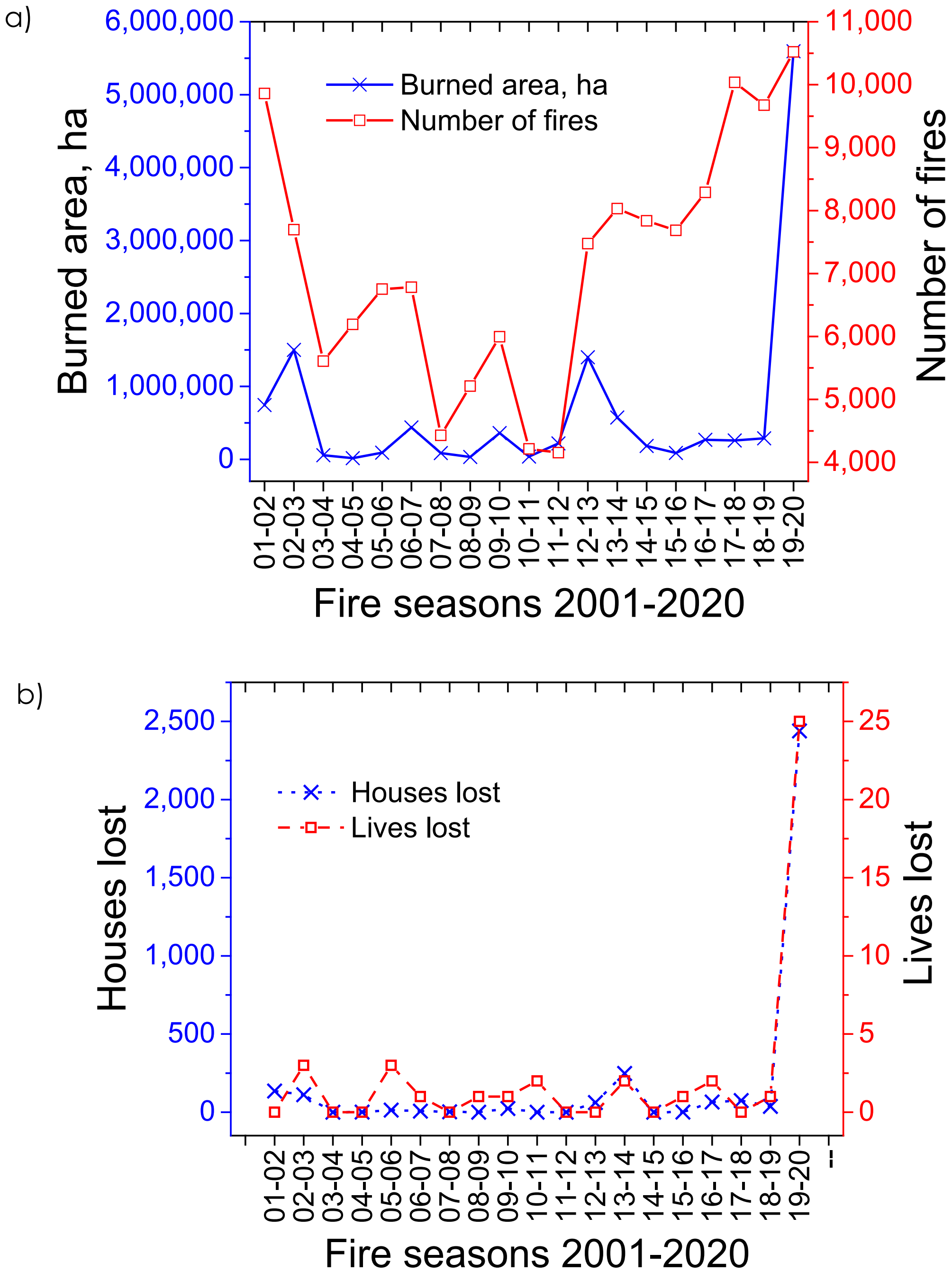


FIG. 13. BUSHFIRE AFTERMATH FOR 2001-2020 FIRE SEASONS IN NSW: a) BURNED AREAS AND NUMBER OF FIRES FOR EACH SEASON, b) HOUSES AND LIVES LOST FOR EACH SEASON. COLOUR OF A PLOT CORRESPONDS TO A SPECIFIC AXIS.

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 13). The burned area before 2019 was below half a million hectares and relatively consistent, with two spikes in 2002/2003 and 2012/2013.

	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

TABLE 9. REGRESSION ANALYSIS FOR 2001-20 FIRE SEASONS IN NSW.

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 9). The number of fires was decreasing till 2012 and constantly increasing after (Figure 13a). 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 13b). 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 ($p=7.7 \times 10^{-14}$). Lives lost were approximately 1% of houses lost. An absolute error was 0.85 lives for 2001-2020.

Victoria

In 2019/2020, Victoria was experiencing its third consecutive year of significant rainfall deficit, especially across the coastal and foothill forests of Gippsland [64]. 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 [61]. During spring in 2019, cold fronts generated rainfall in southern Victoria leading to normal fire conditions [58].

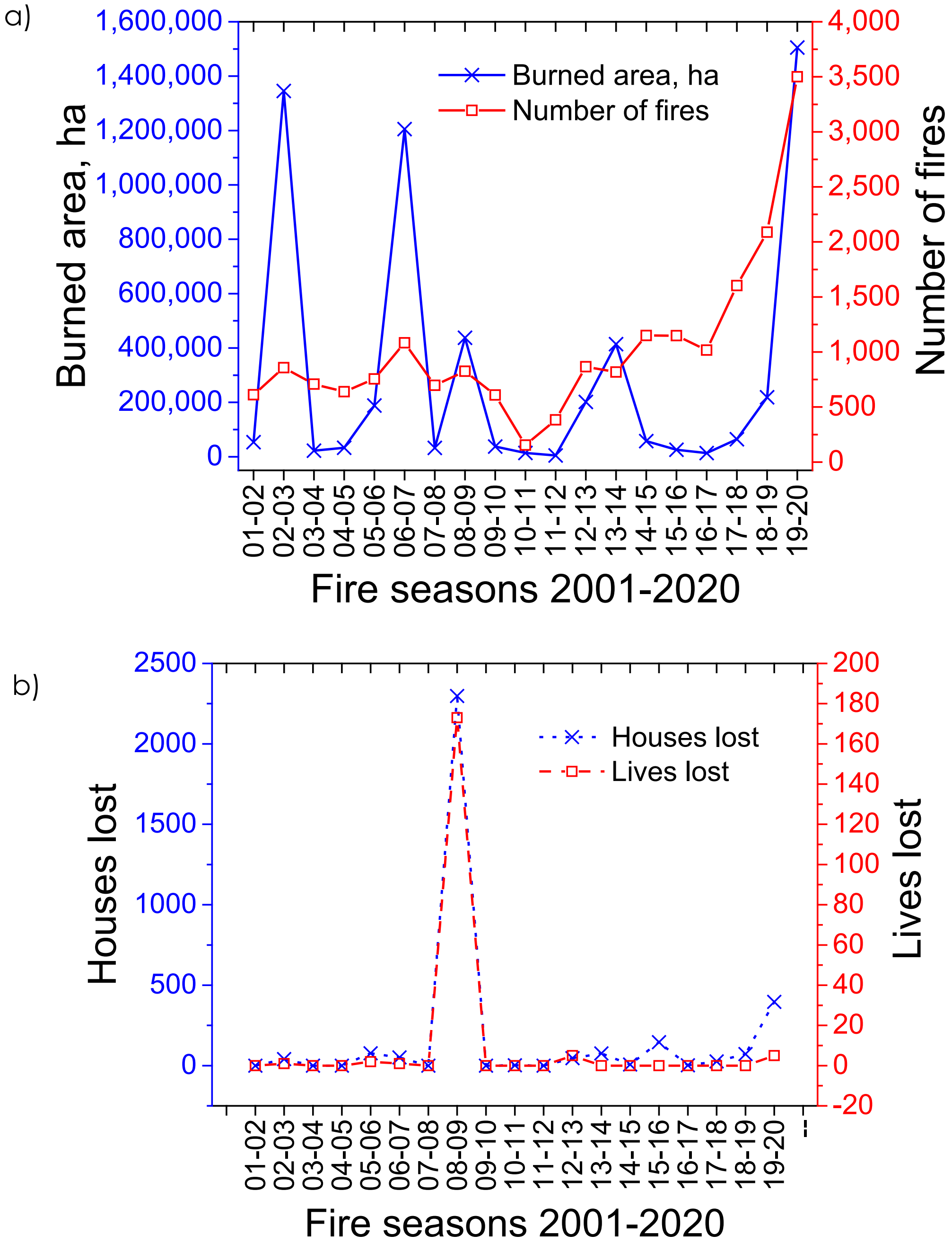


FIG. 14. BUSHFIRE AFTERMATH FOR 2001-2020 FIRE SEASONS IN VICTORIA: a) BURNED AREAS AND NUMBER OF FIRES FOR EACH SEASON; b) HOUSES AND LIVES LOST FOR EACH SEASON. COLOUR OF A PLOT CORRESPONDS TO A SPECIFIC AXIS.

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 14). 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 [66]. 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 [67]. 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 [66]. 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 14a), irrespectively to dataset (Table 10). 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).

	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

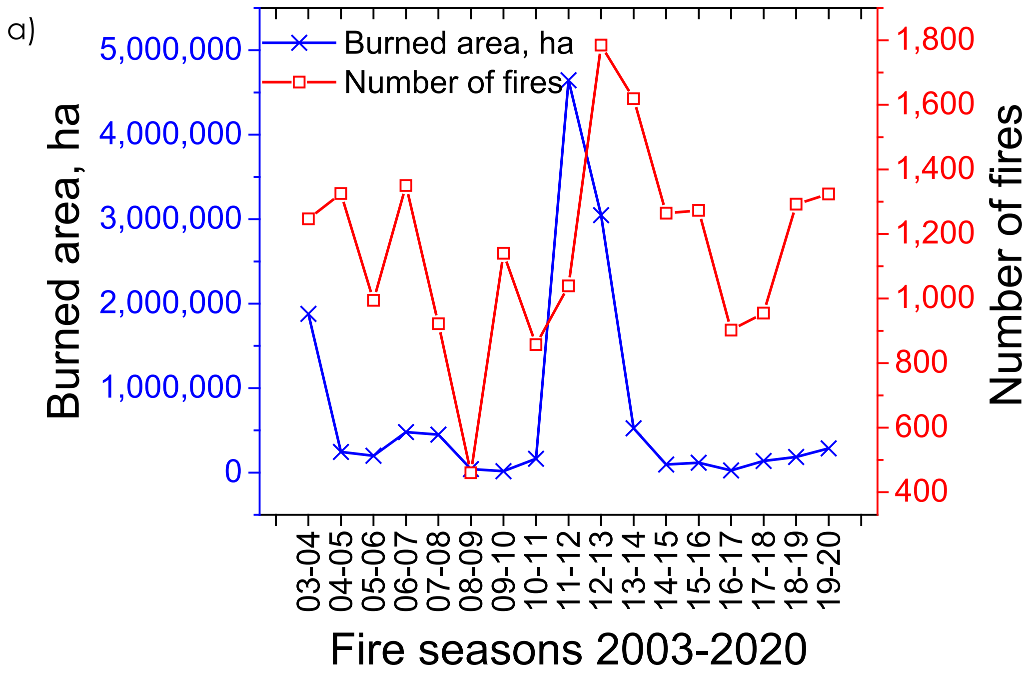
TABLE 10. REGRESSION ANALYSIS FOR 2001-20 FIRE SEASONS IN VICTORIA.

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.

The 2008/09 fire season was extraordinary in terms of the houses and lives lost (Figure 14b). A series of bushfires, sadly remembered as the Black Saturday bushfires, mostly contributed to this [68]. 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).

South Australia

Average to below average rainfall has occurred across South Australia, with some areas experiencing persistent dry conditions since the start of 2018 [57]. 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 [58].



b)

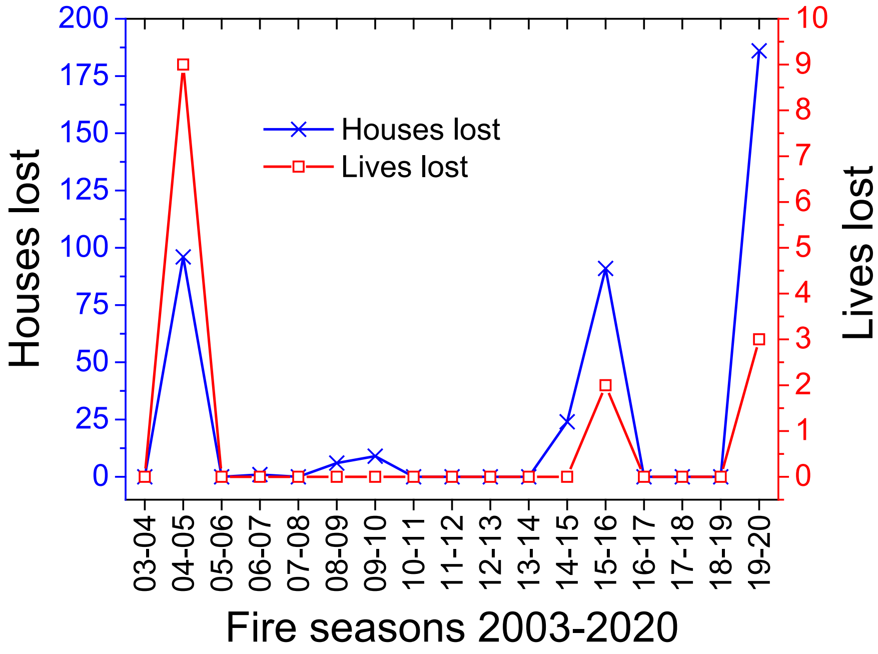


FIG. 15. BUSHFIRE AFTERMATH FOR 2003-2020 FIRE SEASONS IN SOUTH AUSTRALIA: a) BURNED AREAS AND NUMBER OF FIRES FOR EACH SEASON; b) HOUSES AND LIVES LOST FOR EACH SEASON. COLOUR OF A PLOT CORRESPONDS TO A SPECIFIC AXIS.

In South Australia, 286,845 hectares burned, 186 houses and 3 lives lost in 1,324 bushfires in the 2019/20 fire season (Figure 15). 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 fires combined with the existing fires and became known as The Kangaroo Island Fire [69]. The fires were officially contained on 21 January 2020 after burning for more than three weeks and blackening more than 210,000 hectares [70]. 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 [70] and burnt between $100 million and $900 million of plantation timber [71].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 [72]. 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.

	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

TABLE 11. REGRESSION ANALYSIS FOR 2001-20 FIRE SEASONS IN SA.

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.

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 15a). 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 15b). 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 ($p=7.9\times10^{-5}$). 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).

Impact

Smoke

Smoke from the bushfires has shrouded much of Australia's south-eastern coast (Figure 16). According to early estimates from the Global Fire Emissions Database, the bushfires likely contributed 900 million metric tons of carbon emissions [63, 73]. Borchers Arriagada, Palmer [74] 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, Chen [75] 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.

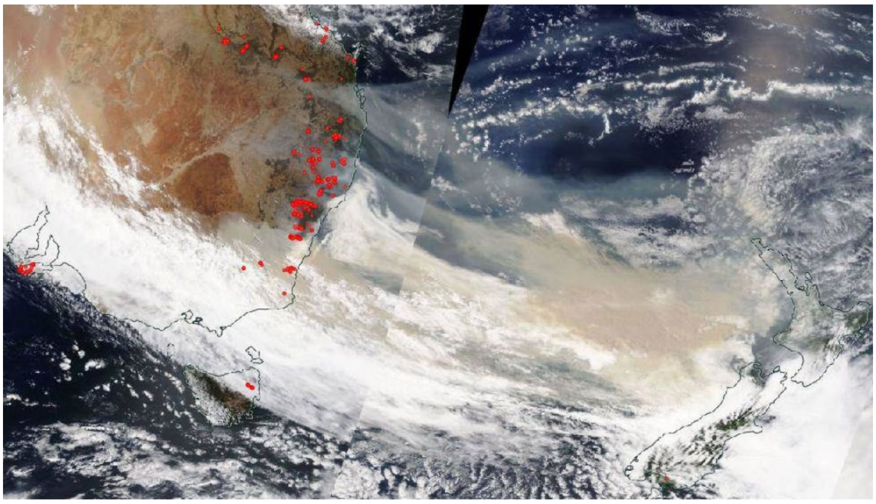


FIG. 16. SMOKE FROM BUSHFIRES. THIS IMAGE WAS TAKEN BY NASA'S AQUA SATELLITE USING THE MODIS (MODERATE RESOLUTION IMAGING SPECTRORADIOMETER) INSTRUMENT ON 05 JANUARY 2020 [76].

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, Xu [77], 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 17).

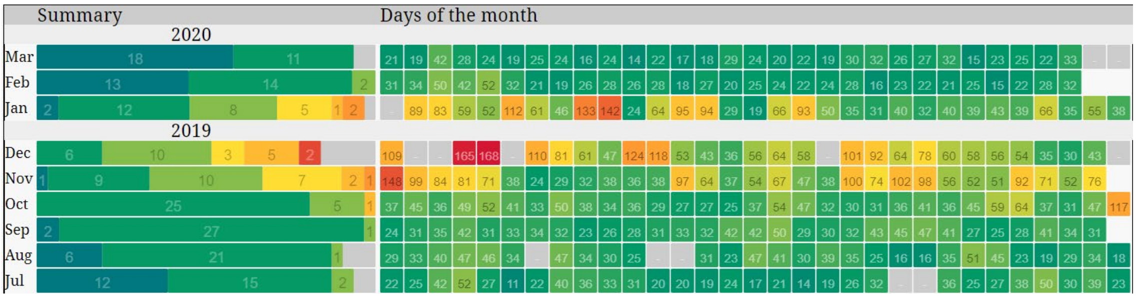


FIG. 17. DAILY AIR QUALITY INDEX (AQI) BASED ON CONCENTRATION OF PM2.5 AT RANDWICK SYDNEY EAST STATION [78]. AQI IS CALCULATED AS THE 24 HOURS AVERAGE OF HOURLY READINGS. AIR POLLUTION LEVEL: 0-50 IS GOOD, 51-100 – MODERATE, 101-150 - UNHEALTHY FOR SENSITIVE GROUPS, 151-200 – UNHEALTHY. COLOURS REPRESENT 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 [79] (Figure 16). 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 [80].

Wildlife

Over 1 billion animals were estimated to have been killed in the fires, according to ecologist Chris Dickman of the University of Sydney [63]. 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 [81]. 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 [82], 272 plant, 16 mammal, 14 frog, nine bird, seven reptile, four insect, four fish and one spider species are threatened. Among them Critically Endangered (31 species), Endangered (110 species) and Vulnerable (186 species).

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 [69]. 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*) [83]. Also, tens of thousands of farm animals, mainly sheep, were killed in the fire on the island [71].

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 [84, 85]. According to AM Best credit rating agency, bushfires resulted in A$1.7 billion in insurance losses and they are expected to rise [86]. 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 [87]. All of the above is likely to make a record impact to Australian economy.

Conclusion

Australia's warmest and driest year on record was 2019 [57]. It had the highest mean temperature, mean maximum temperatures, January temperature, 40 % below the 1961–1990 average total rainfall, and the lowest 10% of historical observations of annual rainfall on record. Additionally, eight previous years are in the ten warmest years on record for Australia and each month from July through December was amongst the ten driest months on record. A positive Indian Ocean Dipole lead to low rainfall across Australia. A long-term rainfall deficiency combined with the very high temperatures resulted in extremely dangerous fire weather across much of eastern and southern Australia. More than 95% of Australia by area had spring accumulated FFDI values that were very much above average, including almost 60% of the country that was the highest on record.

There is no doubt that the fire season of 2019/20 was extraordinary. 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.

Similar patterns were observed for NSW and Victoria. Before the 2019/20 fire season, the burned area and the number of lives lost were decreasing, while the number of fires and houses lost were increasing. After inclusion of the 2019/20 fire season, the number of lives lost and burned area changed trend to increasing and the slope of other categories increased. The burned area in Victoria was the only exception. It did not change trend, but the slope decreased. In SA all categories had a negative trend before 2019/20, except for the number of fires. After 2019/20, only the number of houses lost changed trend to positive. For the rest, the slope increased, except for the lives lost. 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. It should be noted that the analysis is limited by 20 years dataset.

Multiple studies [31, 88-91] 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. We can see changes in the slopes and trends for the worse (Table 11). 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 may be a significant problem in the future. It impacts on people with cardiovascular and respiratory problems and increases mortality. It also has indirect impact on the economy. For instance, smoke produced by bushfires in December 2019 and January 2020 caused up to A$50 million worth of daily disruption of Sydney [87].

Due to the record burned area, an enormous number of animals was killed. According to some estimations [63], at least 1 billion animals were lost. It is believed that 49 animal species, 47 plants and one spider had at least 80% of their habitat area affected by bushfires and are at the Endangered or Critically Endangered level now [92].

The total impact of the 2019/20 bushfire season to the economy is estimated to be as much as A$40 billion according to Wilkie [85]. It will take many years to restore the economy and infrastructure in impacted areas, and for animal and vegetation biodiversity to recover.

KEY MILESTONES

3.1.1: Determination of the ignition time of various natural fuels under variable heat flux
3.1.2: International Conference (Presentation & Publication)
3.1.3: Quarterly Report
3.2.1: Research note (describing progress in investigation)
3.2.2: Quarterly Report
3.3.1: Paper submitted for approval
3.3.2: Quarterly Report
3.4.1: Influence of extreme fire behaviours on fire propagation summary report
3.4.2: Poster for BNHCRC Conference
3.4.3: Quarterly Report, Annual Report, Self Assessment Matrix

UTILISATION AND IMPACT

SUMMARY

This project proposed a new method to test flammability of live vegetation in dynamic conditions and produced educational material on different aspects of dynamic fire behaviours.

NEW METHOD TO TEST FLAMMABILITY OF VEGETATION

Output Description

A new standardised methodology for testing flammability of live plant species in dynamic conditions was proposed. The validity of using dynamic heating regimes as a standardised method has been demonstrated, with clear differences observed between heating regimes. The VHFlux apparatus allows for flammability testing of live plant samples using dynamic heating regimes where parameters can be controlled to create repeatable and accurate testing in a controlled environment.

Extent of Use

- National and international level. There is a high demand in such method around the world.

Utilisation Potential

- Adoption of this methodology is recommended to ensure more realistic data on flammability of individual plant species and plant communities.

Utilisation Impact

- This will ultimately lead to better informed, more accurate, and dynamic wildfire behaviour modelling.

Utilisation and Impact Evidence

- A few organisations and individuals have shown great interest in using the Variable Heat Flux Apparatus as a new method to test flammability of vegetation. Charles Darwin University has requested to test flammability of invasive species and tests will commence in July 2020. A project "Up in flames: measuring how plants burn" led by Dr Jane Cawson from the University of Melbourne has already been utilising this method.

PRIORITISATION OF EXTREME FIRE BEHAVIOURS

Output Description

A series of curated documents (a "FirePedia") on different aspects of fire behaviour was produced in cooperation with BNHCRC. This document provides the reader with an introduction to dynamic fire behaviours that may be observed during bushfires and which may result in significant dangers to people, communities, infrastructure and the environment.

Extent of Use

- National and international level.

Utilisation Potential

- Developed documents will provide useful insights into extreme fires and dynamic fire behaviours and can be used to inform practitioners such as fire behaviour analysts of fire phenomena they should be on the lookout for. After reading the documents, the reader should be able to describe a number of dynamic fire behaviours, understand in general terms why dynamic fire behaviours pose a potentially severe danger to fire-fighters, community, infrastructure and the environment, and understand situations in which dynamic fire behaviours may lead to elevated fire danger.

Utilisation Impact

- Improved understanding of extreme fires and dynamic fire behaviours – the conditions in which they are likely to occur, the impact on the predictability of fire propagation and intensity, strategies for fire suppression, and the subsequent impact on community and firefighter safety.

Utilisation and Impact Evidence

- Cooperation with BNHCRC to develop a "FirePedia".

NEXT STEPS

The last phase of the project will be devoted to publishing of the results and producing of recommendations for future simulators development and improvement.

PUBLICATIONS LIST

PEER-REVIEWED JOURNAL ARTICLES

1. Filkov, A.I.; Duff, T.J.; Penman, T.D. (2020) Frequency of Dynamic Fire Behaviours in Australian Forest Environments // *Fire*, 2020, *3*, 1, pp. 1-17. https://doi.org/10.3390/fire3010001
2. Jane G. Cawson, Victoria Hemming, Andrew Ackland, Wendy Anderson, David Bowman, Ross Bradstock, Tegan Brown, Jamie Burton, Geoffrey J. Cary, Thomas J. Duff, Alexander Filkov, James M. Furlaud, Tim Gazzard, Musa Kilinc, Petter Nyman, Ross Peacock, Mike Ryan, Jason Sharples, Gary Sheridan, Kevin Tolhurst, Tim Wells, Phil Zylstra, Trent D. Penman (2020) Exploring the key drivers of flammability in wet eucalypt forests using expert elicitation // Landscape Ecology, Accepted. Exploring the key drivers of forest flammability in wet eucalypt forests using expert-derived conceptual models. Landscape Ecol. https://doi.org/10.1007/s10980-020-01055-z
3. Filkov, A., Ngo, T., Matthews, S., Telfer, S., & Penman, T. (2020). Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience*, 1, 44-56. doi:https://doi.org/10.1016/j.jnlssr.2020.06.009.
4. Filkov, A.I.; Cirulis, B.; Penman, T.D. (2020) Quantifying merging fire behaviour phenomena using Unmanned Aerial Vehicle technology // International Journal of *Wildland Fire*, Submitted.
5. Cawson, J.; Tumino, B.; Penman, T.; Filkov A. (2020) Mastication for wildfire prevention in shrub-encroached Eucalyptus woodlands – effects on surface fire behaviour // *Forest Ecology and Management*, Submitted.

CONFERENCE PAPERS

1 Filkov A, Cirulis B, Penman T (2019) Quantifying dynamic fire behaviour phenomena using Unmanned Aerial Vehicle technology // In: *23rd International Congress on Modelling and Simulation*, December 2019, Canberra, Pp. 740-746. https://mssanz.org.au/modsim2019/H7/filkov.pdf

2 Nguyen KTQ; Filkov A; Mendis P; Estacio A; Zhang K and Penman T. (2019) Vertical heat transfer of aluminium composite claddings [online]. In: *ICCM22 2019*. Melbourne, VIC: Engineers Australia: Pp. 3204-3210. Availability: https://search.informit.com.au/documentSummary;dn=908381686159433;res=IELENG

3 S Prohanov, D Kasymov, O Zakharov, M Agafontsev, V Perminov, P Martynov, V Reyno, A Filkov (2019) Improvement of Firebrand Tracking and Detection Software // In: *AP Ershov Informatics Conference*, Novosibirsk, Russia, Pp. 290-303.

OTHER

1 Filkov A.I., Cawson J., Swan H.M., Penman D.T. (2020) Wildland fires // Environmental Impact of Fire Handbook. Book chapter. Elsevier. 65 p. In Press.

2 Miller, T. (2019). Role of dynamic and static heat flux on ignitibility of live plants (Short Research Project). University of Melbourne, Melbourne, Australia.

TEAM MEMBERS

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END-USERS

End-user organisation	End-user representative	Extent of engagement
RFS, NSW	Simon Heemstra (lead end-user)	Annual reports, discussion of new projects
	Stuart Matthews (lead end-user)	Collaboration on a paper, data provider, quarterly and annual reports
	Brad Davies	Quarterly reports
CFA, VIC	Tim Well	Merging fires workshop
	Musa Kilinc	Flammability projects, merging fires workshop
DELWP, VIC	Evan Lewis	Data provider
	Andrew Ackland	Merging fires workshop
	Elizabeth Ashman	Merging fires workshop
	Glenn Rudolph	Prescribed burn experiments
	Timothy Miller	Flammability experiments
ACT Parks, ACT	Adam Leavesey	Data provider
DEWNR, SA	Mike Wouters	FirePedia
	Simeon Telfer	Collaboration on a paper, data provider

REFERENCES

1. Brown, T., et al., *The Extreme 2018 Northern California Fire Season*. Bulletin of the American Meteorological Society, 2020. **101**(1): p. S1-S4.
2. Lagouvardos, K., et al., *Meteorological Conditions Conducive to the Rapid Spread of the Deadly Wildfire in Eastern Attica, Greece*. Bulletin of the American Meteorological Society, 2019. **100**(11): p. 2137-2145.
3. Addison, P. and T. Oommen, *Post-fire debris flow modeling analyses: case study of the post-Thomas Fire event in California*. Natural Hazards, 2020. **100**(1): p. 329-343.
4. Government of British Columbia. *Wildfire Causes - Province of British Columbia*. 2020 20 March 2020]; Available from: https://www2.gov.bc.ca/gov/content/governments/organizational-structure/ministries-organizations.
5. Mamuji, A.A. and J.L. Rozdilsky, *Wildfire as an increasingly common natural disaster facing Canada: understanding the 2016 Fort McMurray wildfire*. Natural Hazards, 2019. **98**(1): p. 163-180.
6. Turco, M., et al., *Climate drivers of the 2017 devastating fires in Portugal.* Scientific Reports, 2019. **9**(1).
7. Teodoro, A.C. and A. Amaral, *Evaluation of forest fires in Portugal Mainland during 2016 summer considering different satellite datasets*, in *Proceedings of SPIE - The International Society for Optical Engineering*. 2017.
8. Liesowska, A. *Fire rages on as death toll from two blazes reaches 33*. The Siberian Times 2015 20 March 2020]; Available from: http://siberiantimes.com/ecology/casestudy/news/n0187-fire-rages-on-as-death-toll-from-two-blazes-reaches-33/.
9. Prelgauskas, E., *Helping fire-impacted families in rebuilding: Toward enhanced community resilience outcomes.* Australian Journal of Emergency Management, 2016. **31**(4): p. 56-61.
10. Wilkinson, C., C. Eriksen, and T. Penman, *Into the firing line: civilian ingress during the 2013 "Red October" bushfires, Australia.* Natural Hazards, 2016. **80**(1): p. 521-538.
11. *October 2013: A tribute*, in *Bush Fire Bulletin*. 2014, NSW Rural Fire Service. p. 1-84.
12. BBC News. *Wildfire sweeps across Greek island of Chios*. 2012 20 March 2020]; Available from: https://www.bbc.com/news/world-europe-19323968.
13. Myhre, D., et al., *Precepting at the time of a natural disaster.* Clinical Teacher, 2017. **14**(2): p. 104-107.
14. Kirsch, K.R., et al., *Longitudinal community assessment for public health emergency response to wildfire, Bastrop County, Texas.* Health Security, 2016. **14**(2): p. 93-104.
15. Konovalov, I.B., et al., *Atmospheric impacts of the 2010 Russian wildfires: integrating modelling and measurements of an extreme air pollution episode in the Moscow region.* Atmos. Chem. Phys., 2011. **11**(19): p. 10031-10056.
16. Gilbert, N., *Russia counts environmental cost of wildfires.* Nature, 2010.
17. BBC News. *Chile fire in Valparaiso kills 12 and forces thousands to evacuate*. 2014 20 March 2020]; Available from: https://www.bbc.com/news/world-latin-america-27007884.
18. Al Jazeera News. *Chile: Deadly wildfires displace thousands.* 2017 [cited 2020 20 March 2020]; Available from: https://www.aljazeera.com/news/2017/01/chile-raging-wildfires-displace-thousands-170127144245967.html.
19. Vargas-Cuentas, N.I. and A. Roman-Gonzalez. *Analysis of the environmental impact of the Sama forest fire in Tarija Bolivia*. in *Proceedings of the International Astronautical Congress, IAC 2018, Code 147415*. 2018. Bremen; Germany.
20. Kahn, B. *Wildfire Burns across (Formerly) Icy Greenland*. 2017 [cited 2020 20 March]; Available from: https://www.scientificamerican.com/article/wildfire-burns-across-formerly-icy-greenland/.
21. Freedman, A. *Greenland wildfire part of unusual spike in Arctic blazes this summer*. The Washington Post 2019 20 March 2020]; Available from: https://www.washingtonpost.com/weather/2019/07/18/greenland-wildfire-part-unusual-spike-arctic-blazes-this-summer/.
22. CTIF. *Scotland, Norway and Sweden already severely effected by forest fires due to the dry weather in the north*. 2019 11 June 2020]; Available from: https://www.ctif.org/news/scotland-norway-and-sweden-already-severely-effected-forest-fires-due-dry-weather-north.
23. Johansson, J. and R. Lidskog, *Constructing and justifying risk and accountability after extreme events: public administration and stakeholders' responses to a wildfire disaster.* Journal of Environmental Policy & Planning, 2020. **22**(3): p. 353-365.
24. Schwilk, D.W.J.N.P., *Dimensions of plant flammability.* 2015. **206**(2): p. 486-488.
25. Bradstock, R.A., *A biogeographic model of fire regimes in Australia: Current and future implications.* Global Ecology and Biogeography, 2010. **19**: p. 145-158.
26. Grootemaat, S., et al., *Scaling up flammability from individual leaves to fuel beds.* Oikos, 2017. **126**: p. 1428-1438.
27. Gill, A.M. and P.J.A.f. Zylstra, *Flammability of Australian forests.* 2005. **68**(2): p. 87-93.
28. Dent, J., et al., *Flame Temperatures Saturate with Increasing Dead Material in Ulex europaeus, but Flame Duration, Fuel Consumption and Overall Flammability Continue to Increase.* Fire, 2019. **2**(1).
29. Rejmánek, M., *What makes a species invasive.* Plant invasions: general aspects and special problems, 1995: p. 3-13.
30. Holtkamp, R.H., *Cassinia spp.–cassinia.* Biological control of weeds in Australia. CSIRO Publishing, Collingwood, 2012: p. 146-149.
31. Halofsky, J.E., D.L. Peterson, and B.J. Harvey, *Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA.* Fire Ecology, 2020. **16**(1).
32. Vilà-Vilardell, L., et al., *Climate change effects on wildfire hazards in the wildland-urban-interface – Blue pine forests of Bhutan.* Forest Ecology and Management, 2020. **461**: p. 117927.
33. Parente, J., et al., *Heat waves in Portugal: Current regime, changes in future climate and impacts on extreme wildfires.* Science of the Total Environment, 2018. **631-632**: p. 534-549.

34. Di Virgilio, G., et al., *Climate Change Increases the Potential for Extreme Wildfires.* Geophysical Research Letters, 2019. **46**(14): p. 8517-8526.
35. Matthews, S., et al., *Climate change, fuel and fire behaviour in a eucalypt forest.* Global Change Biology, 2012. **18**(10): p. 3212-3223.
36. Penman, T.E., et al., *Messmate stringybark: bark ignitability and burning sustainability in relation to fragment dimensions, hazard score and time since fire.* International Journal of Wildland Fire, 2017. **26**(10): p. 866-876.
37. R Core Team, *R: A language and environment for statistical computing. R Foundation for Statistical Computing*. 2019: Vienna, Austria.
38. Wickham, H., *ggplot2: Elegant Graphics for Data Analysis*. 2016, Springer-Verlag: New York.
39. DiDomizio, M.J., P. Mulherin, and E.J. Weckman, *Ignition of wood under time-varying radiant exposures.* Fire Safety Journal, 2016.
40. Ji, J., et al., *An Integral Model for Wood Auto-ignition under Variable Heat Flux.* Journal of Fire Sciences, 2016. **24**(5): p. 413-425.
41. Vermesi, I., et al., *Pyrolysis and spontaneous ignition of wood under transient irradiation: Experiments and a-priori predictions.* Fire Safety Journal, 2017. **91**: p. 218-225.
42. Zhai, C., et al., *Pyrolysis and spontaneous ignition of wood under time-dependent heat flux.* Journal of Analytical and Applied Pyrolysis, 2017. **125**: p. 100-108.
43. Kuznetsov, V.T., et al., *Ignition of wood subjected to the decreasing radiant energy flux.* IOP Conference Series: Materials Science and Engineering, 2015. **81**.
44. Bilbao, R., et al., *A model for the prediction of the thermal degradation and ignition of wood under constant and variable heat flux.* Journal of Analytical and Applied Pyrolysis, 2002. **62**: p. 63-82.
45. Reszka, P., et al., *A methodology for the estimation of ignition delay times in forest fire modelling.* Combustion and Flame, 2012. **159**(12): p. 3652-3657.
46. Lizhong, Y., et al., *The influence of different external heating ways on pyrolysis and spontaneous ignition of some woods.* Journal of Analytical and Applied Pyrolysis, 2007. **78**(1): p. 40-45.
47. Caccamo, G., et al., *Monitoring live fuel moisture content of heathland, shrubland and sclerophyll forest in south-eastern Australia using MODIS data.* International Journal of Wildland Fire, 2012. **21**: p. 257-269.
48. Mindykowski, P., et al., *Piloted ignition of wildland fuels.* Fire Safety Journal, 2011. **46**(1-2): p. 34-40.
49. Grootemaat, S., et al., *Burn or rot: leaf traits explain why flammability and decomposability are decoupled across species.* Functional Ecology, 2015. **29**(11): p. 1486-1497.
50. Fernandes, P.M. and M.G.J.N.P. Cruz, *Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions.* 2012. **194**(3): p. 606-609.
51. Pausas, J.G., J.E. Keeley, and D.W. Schwilk, *Flammability as an ecological and evolutionary driver.* Journal of Ecology, 2017. **105**(2): p. 289-297.
52. Jaureguiberry, P., G. Bertone, and S. DÍAz, *Device for the standard measurement of shoot flammability in the field.* Austral Ecology, 2011. **36**(7): p. 821-829.
53. Wyse, S.V., G.L.W. Perry, and T.J. Curran, *Shoot-Level Flammability of Species Mixtures is Driven by the Most Flammable Species: Implications for Vegetation-Fire Feedbacks Favouring Invasive Species.* Ecosystems, 2017. **21**(5): p. 886-900.
54. Zylstra, P., et al., *Biophysical mechanistic modelling quantifies the effects of plant traits on fire severity: species, not surface fuel loads, determine flame dimensions in eucalypt forests.* PLoS One, 2016. **11**(8): p. e0160715.
55. Dahanayake, K.C. and C.L. Chow, *Moisture content, ignitability, and fire risk of vegetation in vertical greenery systems.* Fire Ecology, 2018. **14**(1): p. 125.
56. Babrauskas, V., *Ignition of Wood: A Review of the State of the Art.* Journal of Fire Protection Engineering, 2002. **12**(3): p. 163-189.
57. Bureau of Meteorology. *Annual climate statement 2019*. 2020 20 March 2020]; Available from: http://www.bom.gov.au/climate/current/annual/aus/#tabs=Overview.
58. Bureau of Meteorology, *Special Climate Statement 72—dangerous bushfire weather in spring 2019*. 2019. p. 1-28.
59. Bureau of Meteorology. *Indian Ocean influences on Australian climate*. [cited 2020 20 March 2020]; Available from: http://www.bom.gov.au/climate/iod/.
60. Dowdy, A.J., *Australian fire weather as represented by the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index / Andrew J. Dowdy ... [et al.]*. CAWCR technical report ; no. 10., ed. A.J. Dowdy, et al. 2009, Melbourne: Centre for Australian Weather and Climate Research.
61. Nolan, R.H., et al., *Causes and consequences of eastern Australia's 2019–20 season of mega-fires.* Global Change Biology, 2020. **26**(3): p. 1039-1041.
62. Boer, M.M., V. Resco de Dios, and R.A. Bradstock, *Unprecedented burn area of Australian mega forest fires.* Nature Climate Change, 2020. **10**(3): p. 171-172.
63. Dickman, C. and T. McDonald, *Some personal reflections on the present and future of Australia's fauna in an increasingly fire-prone continent.* Ecological Management & Restoration, 2020. **n/a**(n/a).
64. BNHCRC *Australian Seasonal Bushfire Outlook: August 2019*. HAZARD NOTES, 2019. 1-4.
65. *Rural Fires Act 1997*. 1997 20 March 2020]; Available from: http://www8.austlii.edu.au/cgi-bin/viewdoc/au/legis/nsw/consol_act/rfa1997138/s44.html.
66. McGuire, A. and C. Butt. *Cut off: How the crisis at Mallacoota unfolded*. The Age 2020 20 March 2020]; Available from: https://www.theage.com.au/national/victoria/cut-off-how-the-crisis-at-mallacoota-unfolded-20200117-p53sdn.html.
67. Cunningham, M. *'This one sounds like a monster': Mallacoota on edge as fire closes in*. The Age 2019 20 March 2020]; Available from: https://www.theage.com.au/national/victoria/this-one-sounds-like-a-monster-mallacoota-on-edge-as-fire-closes-in-20191230-p53nlg.html.

68. Morgan, G. and M. Leonard, *Black Saturday: Australia's deadliest bushfire*. Unasylva, 2015. **66**(243-244): p. 32-39.
69. Lynn, J. *Kangaroo Island Shows Burn Scars On One Third of the Land Mass*. 2020 20 March 2020]; Available from: https://www.nasa.gov/feature/goddard/2020/kangaroo-island-shows-burn-scars-on-one-third-of-the-land-mass.
70. Australian Associated Press. *Kangaroo Island fire officially contained*. 2020 20 March 2020]; Available from: https://www.portlincolntimes.com.au/story/6590965/kangaroo-island-fire-officially-contained/.
71. Adams, P. *Bushfires devastate Kangaroo Island farmers and timber industry amid heavy losses*. 2020 20 March 2020]; Available from: https://www.abc.net.au/news/2020-02-02/kangaroo-island-sheep-stock-timber-destroyed-in-bushfires/11917220.
72. 9NEWS. *Adelaide Hills fire continues amid heatwave warnings*. 2019 20 March 2020]; Available from: https://www.9news.com.au/national/adelaide-hills-fire-downgraded-several-blazes-continue-to-burn/041d9ceb-f724-4753-9739-02347b9d1a23.
73. Rathi, A. and L.M. Lombrana. *Australia's Fires Likely Emitted as Much Carbon as All Planes*. Bloomberg Green 2020 20 March 2020]; Available from: https://www.bloomberg.com/news/articles/2020-01-21/australia-wildfires-cause-greenhouse-gas-emissions-to-double.
74. Borchers Arriagada, N., et al., *Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia*. Medical Journal of Australia, 2020.
75. Liu, C., et al., *Ambient Particulate Air Pollution and Daily Mortality in 652 Cities.* New England Journal of Medicine, 2019. **381**(8): p. 705-715.
76. Jenner, L. *Rains Bring Very Temporary Relief to Australia's Fires*. 2020 20 March 2020]; Available from: https://www.nasa.gov/image-feature/goddard/2020/rains-bring-very-temporary-relief-to-australias-fires.
77. Yu, P., et al., *Bushfires in Australia: a serious health emergency under climate change*. The Lancet Planetary Health, 2020. **4**(1): p. e7-e8.
78. *The World Air Quality Index project*. Air quality historical data 2020 20 March 2020]; Available from: https://aqicn.org/city/australia.
79. MacManus, J. *Blood red sun greets NZ on New Years Day as Australian bushfire smoke stains skies*. Stuff 2020 [cited 2020 20 March 2020]; Available from: https://www.stuff.co.nz/national/118546900/blood-red-sun-greets-nz-on-new-years-day-as-australian-bushfire-smoke-stains-skies.
80. McCullough, E. *Smoke from fires in Australia reaches Brazil*. The Brussels Times 2020 20 March 2020]; Available from: https://www.brusselstimes.com/all-news/business/103241/belgiums-hospitality-sector-projected-to-lose-1-7-billion-euros/.
81. Southwell, D., *Design considerations for post natural disaster (fire) on-ground assessment of status of species, ecological communities, habitats and threats (Preliminary Draft)*. 2020. p. 119.
82. DAWE. *Wildlife and threatened species bushfire recovery research and resources*. 2020 20 March 2020]; Available from: https://www.environment.gov.au/biodiversity/bushfire-recovery/research-and-resources.
83. Natural Resources. *New Wildlife and Habitat Bushfire Recovery Program 2019-20 to 2020-21*. 2019 20 March 2020]; Available from: https://www.naturalresources.sa.gov.au/kangarooisland/land-and-water/fire-management/New_Wildlife_and_Habitat_Bushfire_Recovery_Program_2019-20_to_2020-21.
84. Butler, B. *Economic impact of Australia's bushfires set to exceed $4.4bn cost of Black Saturday*. The Gardian 2020 20 March 2020]; Available from: https://www.theguardian.com/australia-news/2020/jan/08/economic-impact-of-australias-bushfires-set-to-exceed-44bn-cost-of-black-saturday.
85. Wilkie, K. *Devastating bushfire season will cost Australian the economy $20BILLION, experts warn*. Daily Mail Australia 2020 20 March 2020]; Available from: https://www.dailymail.co.uk/news/article-7863335/Devastating-bushfire-season-cost-Australian-economy-20BILLION-experts-warn.html.
86. Martin, M. *AM Best: Insurers can contend with mounting bushfire losses*. Insurance Business Australia 2020 20 March 2020]; Available from: https://www.insurancebusinessmag.com/au/news/breaking-news/am-best-insurers-can-contend-with-mounting-bushfire-losses-211540.aspx.
87. McDonald, T. *Australia fires: The huge economic cost of Australia's bushfires*. BBC News 2019 20 March 2020]; Available from: https://www.bbc.com/news/business-50862349.
88. Bowman, D.M.J.S., et al., *The human dimension of fire regimes on Earth.* Journal of biogeography, 2011. **38**(12): p. 2223-2236.
89. Harris, S. and C. Lucas, *Understanding the variability of Australian fire weather between 1973 and 2017.* PLOS ONE, 2019. **14**(9): p. e0222328.
90. Keeley, J. and A. Syphard, *Climate Change and Future Fire Regimes: Examples from California.* Geosciences, 2016. **6**: p. 37.
91. Nitschke, C. and J. Innes, *Interactions between fire, climate change and forest biodiversity.* CAB Reviews Perspectives in Agriculture Veterinary Science Nutrition and Natural Resources, 2006. **1**.
92. Morton, A. *More than 100 threatened species hit hard by Australian bushfires, pushing many towards extinction*. The Guardian 2020 20 March 2020]; Available from: https://www.theguardian.com/environment/2020/jan/20/more-than-100-threatened-species-australian-bushfires-towards-extinction.