Supplementary information

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Wildfires: Australia needs a national monitoring agency

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Supplementary Materials

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Introduction

Establishing whether the 2019/2020 bushfires are anomalous is no simple task because there is no harmonised national bushfire information system in Australia. Rather, each state and territory has developed their own system to map fires and vegetation types, prohibiting a simple database query about the extent and historical trends of the current Australian bushfire season.

Here we use the European Space Agency's FireCCI51[1] burnt area data from January 2001 to June 2020 for five broad vegetation types across the Australian continent. These data allowed us to statistically determine if the fires of the 2019/20 season are anomalous since 2001. In addition, to put the current fire season into a broader geographical and historical perspective, we jointly analysed the National Indicative Aggregated Fire Extent Dataset (NIAFED)[2] and the written records of all major fires in Australia from at least 1851 compiled by Ellis et al.[3] and Roxburgh et al.[4].

Methods

The geographic analysis was based around five broad Australian vegetation types informed by Murphy et al.'s[5] pyrogeographic description of Australia. These land cover categories were derived from the Global Land Cover Characteristics (GLCC) dataset using the original 1km scale[6]. Some land cover classes were combined into broader groups: *Herbaceous Wetland* was combined with the *Water* class and excluded from the analysis; *Grassland*, *Shrubland*, *Mixed Shrubland/Grassland* and *Barren or Sparsely Vegetated* were combined into a single class to represent *Sparse/Treeless* vegetation; and various cropland, pasture and urban classes were combined into a single *Agriculture/Urban* class. For the Australian context, *Evergreen Broadleaf Forest* class was classified as *Eucalyptus Forest* noting that this would have subsumed small areas of rainforest and other forest types[7]. In addition, the *Savanna* class, which represents woodlands and savannas, was split in two at the Tropic of Capricorn (23.44°S) to create separate *Temperate Woodland* and *Tropical Woodland* classes.

Burnt area (BA) information was obtained from a global BA dataset produced by the FireCCI project. This product is based on changes in MODerate resolution Imaging Spectroradiometer (MODIS) 250m near infrared (NIR) reflectance data guided by MODIS active fires[1]. The FireCCI51 product covering the period of January 2001 to June 2020 was used for this analysis. The algorithm detects BA by anomalous changes in NIR reflectance using monthly composites to mitigate the impacts of clouds, cloud shadows and very oblique observations. The FireCCI51 BA product has been validated using Landsat data, showing similar accuracy to NASA BA products, with higher sensitivity for small patches, but lower temporal reporting accuracy (90% of pixels within 10 days of true burning date)[1]. Both global products tend to underestimate BA, but temporal anomalies are identified consistently. To enable the estimation of the BA anomalies, historical average and standard deviation of BA was computed for 0.25-degree cells from the 2001-2018 fire seasons (July to June) and compared with the current fire season (July 2019 to June 2020). Z-scores for each cell ((value – mean)/standard deviation) were computed to map spatio-temporal anomalies. Additionally, the BA z-scores for each of the five land cover types was calculated, based on the original 1 km resolution of the GLCC product. The five broad cover categories were used to determine area burnt in each year over the length of the FireCCI51 product record.

For the current fire season, the total area burnt across the continent was also obtained from the NIAFED[2] for the period July 2019 to June 2020. It is important to note that the NIAFED data has several caveats, most notably the lack of 'national coherency' reflecting the amalgamation of different data streams from multiple different sources, and that it reports much larger areas burnt than satellite BA products. Using NIAFED data source and the FireCCI51 BA product, the area of fires that intersected the extra-tropical *Eucalyptus Forest* vegetation class was calculated. Written records of all major fires in Australia since at least 1851 compiled by Ellis et al.[3] and Roxburgh et al.[4] were digitalized. Given that these authors only provide a broad description of the location of the areas affected by the fires, the approximate coordinate of the centre of the burnt area was found as the centroid of a polygon delineated by three or more locations mentioned in their report, the middle of the line between two locations or the listed location if only one location was mentioned. The extent of the historical fires that occurred in the *Eucalyptus Forest* domain was compared to the area of the fires that burnt at least to some extent (> 0 ha) extra-tropical *Eucalyptus* Forests in the NIAFED and FireCCI51 data.

Results

According to NIAFED from 1 July 2019 to 22 June 2020, Australian bushfires burnt a total area of around 39.8 Mha. The FireCCI51 BA data estimate 30.38 Mha from July 2019 to June 2020 for the whole country, which is below historical average (47 Mha). However, the same dataset shows that the east coast of Australia has clearly been affected by anomalous fires, with some areas burnt more than 15 times the standard deviation above the average BA (Figure 1).

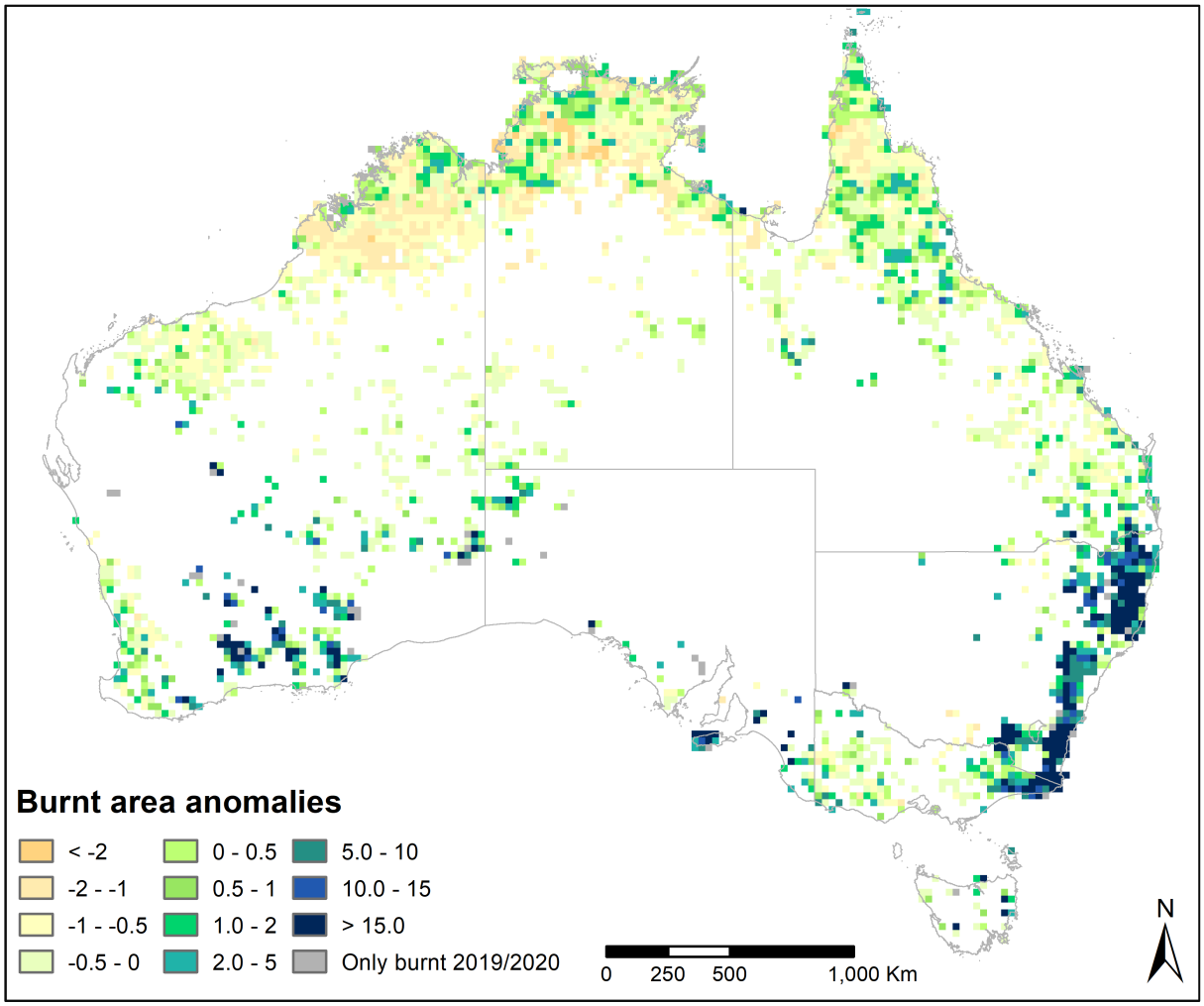

Figure 1. Geographic pattern of burnt area (BA) anomalies for those cells burnt in the 2019/20 fire season, calculated as Z values of temporal BA variation compared to the FireCCI51 time series (2001-2018). Fire season covers from July to June.

The FireCCI51 data also show that 5.67 Mha of *Eucalyptus* Forest has been burnt across the continent in the whole season. This area is 9.17 standard deviations above the mean of the previous 18-year satellite records (Figure in the main text, top panel). By contrast, the same FireCCI51 data for the other four Australian land cover types do not show such a statistically significant historical departure in the area burnt in the 2019/20 fire season. What is more, the *Tropical Woodland* (the most commonly burnt land cover in Australia) burnt in the last fire season 40% less than the average of this land cover.

The historical record demonstrated that fire seasons with > 1 Mha burnt have occurred across Australia since settlement. Of the 18 recorded events 7 have included large areas of *Eucalyptus Forest*, and the remaining 10 have occurred in the remote outback in grassland and savannas environments (Figure in the main text, bottom panel). The precise area of *Eucalyptus Forest* burnt is uncertain in the written historical record. According to the intersection of our estimate of *Eucalyptus Forest* perimeters and the burnt area of the NIAFED

and FireCCI51 records that at least partially overlapped those areas, the current bushfires exceeded this historical estimate having burnt between 7.5 Mha (FireCCI51) and 8.1 Mha (NIAFED) in the *Eucalyptus Forest* biome (including 1.8 Mha and 1 Mha of non-*Eucalyptus* Forests using FireCCI51 and NIAFED, respectively). The previously largest recorded fire in the *Eucalyptus Forest* biome, the 1851 event, has been estimated to have burnt 5 Mha across central Victoria (Figure in the main text, bottom panel).

Discussion

We show that the 2019/20 bushfire season burnt 30.38 Mha across the whole of Australian mainland and Tasmania according to FireCCI51 data (Table 1). The most striking impacts were found in the *Eucalyptus Forest*, where 5.67 Mha were burnt. This huge area is anomalous, being 7.59 times bigger than the average burnt area in *Eucalyptus Forest* for the previous 18 years.

There are records of large *Eucalyptus* Forest fires since at least 1851**,** but all are smaller than the 2019/20 event. An important caveat is that unlike the more accurate FireCCI51 and NIAFED, fire perimeter records in the historical data are of poor accuracy for both area burnt and geolocation, being little more than guesstimates. This frustrates a formal statistical analysis of area burnt before 2001.

Our findings harmonise with Boer et al.[8], who intersected the NASA BA Product, acquired between November 2000 and June 2019, with a Global Biome Classification[9] to globally contextualise the NSW and Victoria government burnt area polygons for the period between 1 September 2019 and 13 January 2020 (Table 1). They found that the proportion (>21%) of Australian 'temperate broadleaf and mixed' forest biome burnt in the 2019/20 fire was starkly different from the annual median proportion of all other continental forest biomes elsewhere in the world (c. 5%), including frequently burnt Asian and African Tropical and Subtropical Dry Broadleaf forests (8–9%).

We acknowledge that our analysis of the area burnt is simplistic in that it is based on a broad global vegetation classification and relies exclusively on satellite data. Our historical analysis is also a first approximation; finer scale determination requires the application of historical reconstruction techniques, such as historical records and palaeoecological markers like charcoal in sediments, to map the extent of past fires amongst different vegetation types[10]. It is important to note that these efforts are inherently constrained by the sparse occurrence of high-resolution natural archives, such as lake deposits, and the unsuitability of the great majority of Australian trees for fire history reconstruction using dendrochronological analyses[11].

A more substantial criticism is that we have only considered area burnt rather than the extent and spatial patterns of fire severity. Fire severity is a measure of the combustion of vegetation and associated damage and death of plants, examples being the difference between complete canopy defoliation or tree death of forests compared to a surface fire that causes negligible damage to trees and shrubs. Even though several methods to derive burn severity estimations from satellite data have been developed in the last years (either using post-fire reflectance models[12] or fire radiative power[13]), they are mostly regionally oriented and need to be

adapted to different biomes[14]. Improved burn severity mapping is essential to understand the ecological and biodiversity effects and environmental impacts of fire, particularly carbon emissions and soil erosion. Our analysis is also constrained by an absence of nationally consistent fine scale vegetation maps that discriminate local-scale habitat diversity such as rainforest patches in tracts of *Eucalyptus Forests*.

In sum, the combined FireCCI51 burnt area analysis, joint interrogation of the NIAFED and written historical records of bushfires demonstrated that the 2019/20 bushfires burnt a historically anomalous area since at least 1851**,** particularly by burning such a large area of *Eucalyptus Forests* across such a extensive geographical range.

Data availability statement

The Australian government fire boundaries can be obtained from the National Indicative Aggregated Fire Extent Database (http://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B9ACDCB09-0364-4FE8-9459-2A56C792C743%7D),
The FireCCI51 dataset is available from the European Space Agency Climate Change Initiative (https://www.esa-fire-cci.org/)
The vegetation mapping is derived from the United States Geological Survey Global Land Cover Characterization (https://www.usgs.gov/centers/eros/science/usgs-eros-archive-land-cover-products-global-land-cover-characterization-glcc?qt-science_center_objects=0#qt-science_center_objects).

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Table 1 Contrasting estimates of area burnt for the 2019/20 Australian Bushfires for three different geographic domains: continent (plus Tasmania); eastern Australia; and three different classifications of *Eucalyptus* Forests and Woodlands.

Bushfire Domain	**Method**	**Area (Mha)**	**Source**
Australian Continent 2019/20 Fire Season	Compilation of official fire records from all State and Territory Governments between 1 July 2019 to 22 June 2020	39.8	[2]
	European Space Agency (ESA) satellite-derived Burnt Area Product between July 2019 and June 2020	30.38	This study
2019/20 Summer fire (all land covers)	Unknown	18	[15]
	Unknown	12.6	[16]
	Unknown	10	[17]
	43 temperate, Mediterranean and subtropical bioregions defined in the Australian Interim Biogeographic Regionalization for Australia dataset and the Compilation of official fire records from all State and Territory Governments between 1 July 2019 and 13 February 2020	9.7	[18]
	Government compilation and satellite-derived land cover dataset between July 2019 and 22 June 2020	8.1	[2]
	ESA satellite-derived Burnt Area Product at least partially intersecting forest land cover between July 2019 and June 2020	7.5	This study

Bushfire Domain	Method	Area (Mha)	Source
Australian Temperate Forests	Government compilation intersected with an Australian bioregional classification between September 2019 and January 2020	7	[2]
Temperate Broadleaf Forest	Burnt Polygons provided by the Victorian and NSW Government between September 2019 and 13 January 2020	5.8	[8]
Eucalyptus *Forests*	ESA satellite-derived Burnt Area Product intersected with satellite-derived land cover dataset between July 2019 and June 2020	5.67	This study