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Islands on fire: Fire and threatened species patterns across Australia's islands

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ABSTRACT

Australia and its islands have a long history of fire, which has shaped their ecosystems and unique species. Fire patterns in Australia have changed since European settlement in 1788 with land use and climate changes. Australia has over 9000 islands, which serve as safe havens for threatened species conservation. Nevertheless, their recent fire histories and characteristics remains understudied. We used remote sensing and long-term governmental datasets to study spatiotemporal variation in fire characteristics across Australia's islands. We examined human activity and lightning patterns as predictors of fire characteristics on islands. We then examined the correspondence between island fire metrics and their threatened species richness. We found that a quarter of all Australian islands with an area over 1 km^2 for which remote sensing fire data was available (n = 167 islands) had at least 10 fire events over the past two decades. This includes large fires that burnt substantial island areas, such as the 2020 wildfires on K'gari (Fraser Island) and the 2019/2020 wildfires on Kangaroo Island. These fires burnt 31 % and 40 % of the islands, respectively. Human population size was an important predictor of fire intensity. Threatened species were associated with islands with higher fire intensities and larger burnt areas. While some Australian island species may benefit from fire, large and intense fires may lead to species declines and jeopardize the role of islands as safe havens and refuges for threatened species. Further knowledge sharing between researchers, practitioners, Indigenous peoples and additional stakeholders can support future management of fire and threatened species on islands.

1. Introduction

Since European settlement, Australia has seen the loss of a wide range of native species across the majority of its diverse bioregions, representing up to a tenth of all global extinctions (Woinarski et al., 2019). Australia holds 50 % of all mammal extinctions globally, for example (Short and Smith, 1994). Across the Australian continent and its multiple islands, 608 animal species and 1447 plant species are listed under the Australian Environment Protection and Biodiversity Conservation (EPBC) Act as threatened, and 103 species are listed as extinct (Commonwealth of Australia 2025). Many of these are also listed on the IUCN red list. Threatening processes, such as invasive predators, land transformation, and climate-related impacts are often pronounced on islands (Commonwealth of Australia 2021; Legge et al., 2023). Of all species identified as at risk of extinction in the next 20 years, five out of 20 mammals, three of 11 reptiles, and most of the 20 bird species occur only on Australia's islands and are not found on the Australian mainland (Commonwealth of Australia 2021).

Islands are important for their high biodiversity and conservation value (Legge et al., 2018; Baxter et al., 2021) and have potential to provide safeguarding of species from threats that are prevalent on mainland Australia, such as invasive predators (Legge et al., 2018). Islands may also serve as refuges where existing threatened species and insurance populations can be kept safer, with biosecurity measures and the eradication of invasive species more feasible in some cases (Doherty et al., 2017; Wise et al., 2019). Studies suggest that island safe havens can be pivotal for some species to avoid extinction (Legge et al., 2018), with predator-free sites showing increases in species populations after invasive species eradication (Commonwealth of Australia. 2021). As of 2018, Australia had 101 safe haven islands (out of 590 islands known to

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be cat and fox-free), holding 30 translocated mammal populations and protecting 109 in situ threatened mammal populations (Legge et al., 2018). Australian islands are a target of multiple conservation projects, including the protection of northern quolls from the spreading threat of cane toads (Rankmore et al., 2008), creation of disease free insurance populations of Tasmanian devils (Wise et al., 2019) and providing habitat for endangered passerine species after extreme range contractions caused by stressors such as land clearance and invasive predators (Webb et al., 2019).

Nevertheless, as many species occurring on islands are endemic, island ecosystems are overwhelmingly vulnerable to extinctions and widespread stressors, such as invasive species and fire events, which may result in islands functioning as ecological traps rather than safe havens (Kirkwood and O'Connor, 2010; Woinarski et al., 2011). Smaller islands may exhibit additional threats due to reduced habitat availability, habitat diversity and generally lower population sizes of various species (Kirkwood and O'Connor, 2010).

Fire has been an important process on many parts of Earth since terrestrial plants appeared, contributing to shaping the composition, traits and types of many ecosystems that exist today (Bowman et al., 2009). Different biomes across the globe are made up of differing vegetation types, climates and weather, which create a mosaic of fire patterns with differing intensities, spatial scales and frequency (Murphy et al., 2013). The variations in fire patterns across landscapes are commonly referred to as 'fire regimes'; i.e. when, where and which fires take place, depending on climate, vegetation properties, human land use and other factors (Gill and Allan, 2008; Krebs et al., 2010). These regimes can be characterised by fire intensity (fire radiative power), fire severity (the damage caused to vegetation, fauna or to human communities), fire type (e.g., crown vs. understory, wildfire vs. prescribed fire), temporal and spatial scale, as well as seasonality (Pausas and Keeley, 2009).

Australian ecosystems are some of Earth's most fire-prone regions (Russell-Smith et al., 2007), including some ecosystems and species that have been long adapted to fire, hosting fauna and flora that can thrive under natural fire regimes (Scott, 2000). Multiple species in Australia have evolved and are adapted to these fire-prone environments, while others in less fire prone regions are more adapted to unburnt or rarely burnt ecosystems (Russell-Smith and Bowman, 1992; Pastro et al., 2011). Across Australia, many invertebrates, amphibians, reptiles and birds are often resilient to the short term effects of fire, though some mammals and other species are less resilient to these effects (Bradstock, 2008; Chia et al., 2015).

While many species have adapted to such natural fire regimes, more recently, Santos et al. (2022) have suggested that 'inappropriate fire regimes' are a major threatening process for 88 % of Australia's terrestrial mammalian taxa. Some regions of Australia are now showing high intensity fires with larger geographic extents or longer fire intervals than recorded previously, including in areas where there were in the past early season, regular, cool burns (Santos et al., 2022).

Indigenous aboriginal people and Torres Strait Islanders have managed vast areas of the Australian continent and some of its islands for over 65,000 years, influencing local habitats, ecosystems and biodiversity (Bliege Bird et al., 2008; Clarkson et al., 2017; Norman et al., 2022). Cultural burning, or low-intensity patch burning, is regaining broad recognition and appreciation for its role in reducing fuel, mitigating wildfires, and supporting biodiversity (Cook et al., 2012; Bardsley et al., 2019). European settlement in 1788 resulted in the suppression of this long-lasting practice, contributing to substantial changed fire dynamics and the increased severity of bushfires since the 18th century, impacting native biodiversity and human communities (Fletcher et al., 2021; Laming et al., 2022). Suppression of natural and cultural fire regimes can directly lead to increases in the occurrence of high-intensity fire events with large geographical extents, through increases in fuel loads (Turner et al., 2003) and is known to have negative effects on biodiversity (Levin et al., 2012), burning vegetation and food sources and leaving certain species more susceptible to predation (Pastro et al., 2011). Highly intense large-scale fires can spread across the landscape quickly, leaving fewer unburnt patches and fewer refuges for animals, and vastly restricting recolonization (Bowman and Murphy, 2010; Lindenmayer et al., 2013; Chia et al., 2015).

Fire regimes, the impacts of fire on focal threatened species, and other impacting factors related to fire, such as land tenure, have been relatively well studied for the Australian continent (Olson et al., 2001; Bardsley et al., 2019; Kelly et al., 2020; Santos et al., 2022). However, unlike mainland Australia, fire regime and the relationship between threatened species and fire on Australian islands is far less known and needs to be more thoroughly investigated if we aim to efficiently undertake informed conservation actions on islands. The 2019–2020 bushfire season in Australia has shed light on the ecological devastation that wildfire can cause to both protected and human modified areas and the vast impacts of some wildfires on native biodiversity on islands. In a recent large fire in 2019–2020 on Kangaroo Island (Indigenous name Karta Pintingga) in South Australia, 40 % of all the island's landscape burnt, including most of its protected areas, resulting in at least 23 animal species and 31 plant species requiring urgent management (Bonney et al., 2020; Commonwealth of Australia 2021). Some island vegetation communities are not fire tolerant, with fire events having the potential to remove all vegetation cover in one fire event, leading to local extinction for species and populations who are unable to find refuge (Moro et al., 2018). On the other end of the spectrum, some islands, such as Melville Island (Yermalner) off northern Australia, consist of vegetation communities that require fire management and have persisted in the presence of a long history of cultural fire regimes for many thousands of years (Robinson et al., 2021).

It is therefore timely to study, quantify and better understand how fire characteristics vary across multiple islands to enhance our ability to prioritize conservation and management decisions on Australia's islands. We aim to fill major gaps in our understanding of the spatial and recent temporal patterns of fire across Australia's islands over the past two decades (2000−2022) and to examine the correspondence between fire characteristics and threatened species on Australia's islands. We hypothesized that:

1. Fire characteristics can be explained by a combination of environmental, climatic and human related factors, including fire regimes, lightning patterns and human activity.
2. Threatened species richness across Australian islands will be positively correlated with island size and fire characteristics.

2. Methods

2.1. Study area

We used the database recently created by our research group named Island Occurrences of Threatened Australian Species (IOTAS), which includes all Australian islands under State, Federal and Commonwealth jurisdictions, ranging from tropical to subantarctic (n = 9285; Fig. 1) (Baxter et al., 2021). This database provides the spatial layer of the Australian islands we used, basic taxonomic and distributional information for Australia's 2428 species and subspecies listed as threatened under the IUCN Red List or the EPBC Act and specific information for threatened species on islands.

2.2. Datasets used

We included three fire datasets, including two datasets derived from remote sensing: the MCD64A1 and MODIS Active Fires Collection 6.1 dataset (Table S1), and another governmental dataset available from Geoscience Australia (GA), known as the 'Historical Bushfire Boundaries' (Ryu et al., 2023) (Fig. 1). The MCD64A1 dataset consists of a monthly, global gridded 500 m product that contains burned area, date

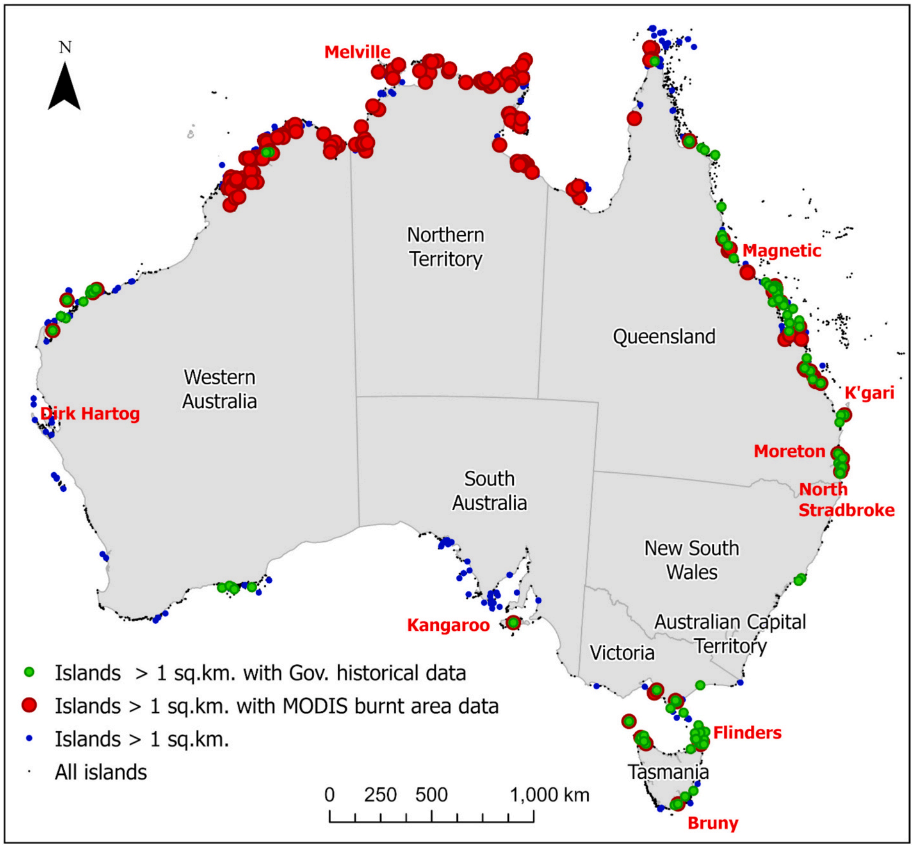

Fig. 1. Overview of the study area, highlighting the Australian islands with fire data based on the MODIS burnt areas (shown in red; $n = 167$ islands) and islands with governmental historical data (shown in green; $n = 121$). Statistics for the nine islands whose names are shown in red are provided in Table 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of burn and data quality information (Giglio et al., 2015). The MODIS Active Fires Collection 6.1 dataset consists of a global point dataset, including the location, date, and time of detection of active fires, and fire radiative power (NASA FIRMS 2022). Monthly fire data was obtained for Australia (including Australian islands) between November 2000 to February 2022. The Geoscience Australia dataset of bushfire boundaries includes both bushfires (the local term in Australia for wildfires) and prescribed fires, and is a vector dataset of burnt area polygons covering the whole of Australia and its islands, except the Northern Territory, with some fires dating back to the early 1900s. Data for Australian fire regimes were available from the spatial database 'Major Fire Regime Niches of Australia' (Murphy et al., 2013); these fire regimes have been defined through literature review and expert elicitation, combining vegetation, fuel and fire types, and climate regions (Table S1; Murphy et al., 2013).

We included data for land tenure, human presence, ecoregion and lightning strikes from the Collaborative Australian Protected Areas Database (CAPAD), Australian population grid 2021, Conservation Management Zones of Australia and the World-Wide Lightning Location Network, respectively (Table S1). The CAPAD 2020 provides both spatial and textual information about government, Indigenous, and privately protected areas for Australia (Commonwealth of Australia 2021). The Australian population grid 2021 gives an Australia-wide human population per 1 km pixel grid (Australian Bureau of Statistics 2021). The Conservation Management Zones of Australia dataset contains 23 geographic areas/ecoregions, classified according to their ecological and threat characteristics (Commonwealth of Australia 2021). The World Wide Lightning Location Network provided global monthly lightning strike count data (Jacobson et al., 2006).

2.3. Explanatory and response variables included in the study

Due to the coarse spatial resolution of remotely sensed derived fire products, we excluded islands below 1 km^2 and those that did not align with any burned area pixels (MCD64A1), thus resulting in a dataset that included 704 islands. Due to discrepancies between MCD64A1 and MODIS active point fire detections (hereafter referred to as 'active points') for islands smaller than 10 km^2 (Fig. S1; Table 1), we excluded islands below 10 km^2 from some analysis. We also excluded from the analysis Australia's remote oceanic islands (Norfolk, Lord Howe, Christmas, Heard and Macquarie Islands), whose biogeography is very different. Our dataset for the full analysis included a total of 167 islands (Table 1).

Fire patterns are described and quantified in the scientific literature using different metrics, including fire intensity, severity, fire type, frequency, fire size, percent island area burnt, and seasonality (Pausas and Keeley, 2009). The datasets enabled us to calculate the following metrics: fire intensity, percent island area burnt, fire size (km^2) and fire frequency. We measured fire intensity using NASA's MODIS active fire product as Fire Radiative Power in Megawatts (MW). We calculated the monthly burnt area, and the monthly percent of pixels burnt on each island. Two separate measures of frequency (active and proportional) were calculated at the island level. Active point frequency was determined using MODIS Hotspot per Active Fire Detection and describes the number of active points per island. Proportional frequency was determined using MCD64A1 Burned Area and describes the months burnt divided by the total number of months over the study period (Table S1). We calculated the average size of wildfires and prescribed fires for 121 islands larger than 1 km^2, from the Geoscience Australia dataset of the historical boundaries of wildfires, to examine temporal changes and to

Table 1
Islands included in the fires on islands study analysis (see also map in Fig. 1).

Islands included	Sample size	Analysis
Islands above 1 km^2 in area which matched the MODIS satellite product of burned areas (MCD64A1)	704	Fire metric calculation Maps
Islands above 1 km^2 in which fires were identified using remote sensing datasets (excluding oceanic islands)	167	Statistical analysis of the variables explaining fire metrics
Islands above 1 km^2 in which fires were identified using the remote sensing datasets and for which a fire regime class was assigned	105	Differences in fire metrics between fire regimes
Islands above 10 km^2 and with at least 10 fire events based on the remote sensing datasets over the study period (between Nov 2000 - Feb 2022)	48	Seasonal analysis
Islands above 1 km^2 in which there were fires in the governmental dataset of 'Historical Bushfire Boundaries' (this dataset did not include fires in the Northern Territory of Australia)	121	Comparison with the remote sensing fire datasets, separation between bushfires and prescribed fires

compare with the fire datasets derived from remote sensing.

The unit of analysis for our study was the islands themselves, therefore each island was assigned a monthly value for each fire variable. To determine a set of fire variable metrics for the analysis, we calculated the mean, maximum and standard deviation for fire intensity, percent island area burnt and fire size ($n = 704$). Additionally, we calculated four different measurements for fire frequency using the active and proportional fire frequency measures (n = 704). These frequencies included the number of active points for each island above 1 km^2, the proportion of months in which there was any fire on a given island, the proportion of months in which >0.64 % of an island burnt (25th percentile for percent island area burnt) and proportion of fires that burnt >0.50 km^2 of the area of an island (25th percentile for fire size).

To select fire metrics in our analysis, the mean, maximum and standard deviation for each fire metric (fire intensity, percent island area burnt and fire size) and all these frequency metrics were run through a correlation matrix (Spearman). The analyses showed that mean fire intensity had the lowest correlation with the other fire variables, whereas higher correlations were found between fire size and fire frequency (Table S2). The four fire metrics (response variables) we chose to include in our analysis were fire radiative power (MW), percent island area burnt, fire size (km^2) and fire frequency (months/year; Table S3).

We used Principal Component Analysis to select the set of explanatory variables using the Factor Analysis of Mixed Data method which accounts for both continuous and categorical data. Given that the variables of Climate zone, Ecoregion and Fire regime were highly correlated (Fig. S2), we chose to use Fire regime out of the three, as it combines both vegetation type and climate classifications. Over 90 % of fire events in Australia are caused by humans, either (1) as a management tool of prescribed fires to reduce the risk of large fires and to reduce the risk to communities living near wildfire prone areas (5.4 % of all fires), (2) non-deliberate fires started by campers and hikers, industrial activities, other accidents (35.2 %), or (3) deliberate fires, incendiary (13.3 %) or suspicious (36.2 %) (Bryant, 2008). Therefore, our analysis included the following five explanatory variables: percent area under Indigenous tenure, percent area under protected area tenure, population size, percent area of the island which is populated (% residential), fire regime and lightning strike count (Table S4).

2.4. Data analysis

In order to visualize the fire regime variability in more detail, we present the temporal variability of fire metrics for nine of Australia's largest islands over the study period, representing different climate zones. Given that the governmental dataset of the historical extent of fire boundaries did not include the Northern Territory, our multivariate analysis was only conducted based on the fire properties derived from remote sensing sources.

To investigate variation in fire patterns across Australian islands in their fire regime, we assigned each island a fire vegetation niche based on the database developed by Murphy et al. (2013). We excluded from the Major Fire Regime Niches of Australia database the regimes for "unclassified" due to lack of data and tropical/subtropical pasture and temperate pasture/cropland as these were not natural ecosystems. Because the spatial data of Murphy et al. (2013) did not cover all islands, we assigned some of the islands manually to their respective fire regime, determined by their closest and ecologically appropriate neighboring fire regime. We ran an ANOVA and Tukey HSD (Honestly Significant Difference) test to determine how fire patterns varied spatially between different fire regimes across different Australian islands.

For the fire seasonality analysis, we only included islands above 10 km^2 and with over ten fire events over the study period ($n = 48$), so that we could confidently assign them to a fire season, based on the time when fires predominantly occurred. We determined fire seasons as the season with the highest proportion of fires over the study period. We defined the following four seasons: December–February summer season, March–May autumn season, June–August winter season and September–November Spring season.

To examine how selected explanatory variables (Table S4) explained fire patterns (fire intensity, percent island area burnt, fire size and frequency) across Australian islands, we analysed each fire metric using generalized linear models (ANCOVA, as applied in XLStat). We log transformed all fire response variables as their values ranged over several orders of magnitude.

2.5. Examining the correspondence between threatened species and fire

We calculated the total number of threatened species, number of species per taxa (fishes, frogs, invertebrates, land birds, mammals, plants, reptiles, and seabirds) and the number of species per threat classification (data deficient, least concern, near threatened, vulnerable, endangered, critically endangered, extinct, extinct in the wild, and no classification) for each island, using the IOTAS database. We calculated a correlation matrix including the numbers of threatened species present and fire metrics (fire intensity, percent island area burnt, fire size and fire frequency) determining the correspondence between variables across the islands. Island area and species richness are often expected to be highly correlated on a log-log scale (Preston, 1962; Connor and McCoy, 1979; Lomolino and Weiser, 2001). We therefore ran a stepwise regression model where the response variable was the log of the number of threatened species on an island, and the explanatory variables were the log of island area and our four fire metrics.

We used ArcGIS Pro 2.9 (ESRI 2011) to extract data from spatial datasets (S1) and QGIS 3.22.6 (QGIS Development Team 2021) to produce all maps. We undertook all data processing in Excel, XLStat and RStudio 4.2.1 (R Core Team, 2022) for our data analysis (inc. packages: *corrplot, ggplot2, ggpubr, FactorMineR, factoextra, betareg, DHARMa, glmmTMB, mgcv*).

3. Results

3.1. Temporal and spatial patterns

Fire patterns varied across islands in the number of fires detected, the fire intensity and the size of fires. Overall, the mean fire intensity across all Australian islands included in this study was 37.4 MW (median of 26.9 MW), the mean monthly percent island area burnt over the study period was 0.36 % (median of 0.17 %) for months with fires (including months without fires, mean monthly percent island area burnt was 0.08 %), the mean monthly burnt area size was 1.75 km^2 (median of 0.02 km^2) and the fire frequency was 0.051 (1.08 months with fires/year) (median of 0.24 months with fires/year) (Fig. 2). We present the temporal trends of three fire metrics for five of Australia's largest islands from different climate zones to demonstrate the datasets that we analyzed (Fig. 3, Table 2).

Islands along northern Australia and Southeast Queensland had higher fire frequency and larger area burned, with Melville Island (Yermalner) showing the largest fire size (Fig. 4c). Subtropical islands, such as K'gari (Fraser Island) and North Stradbroke Island (Minjerribah), saw large burned areas with moderate intensity (Fig. 4b & 4d). Temperate southern islands, like Flinders and Kangaroo Island, had high fire intensities (Fig. 4a). Some arid western islands, like Dirk Hartog Island (Wirruwana), had no fires in the past two decades.

For Australia's larger islands presented as a case study here (Table 2), arid Dirk Hartog Island had no fires detected over the 20 year period. The island area burnt in the other large focal islands was higher and reached 40 % of the island area for the large fires on North Stradbroke Island (Queensland) and Kangaroo Island (South Australia) (Table 2). The maximum monthly percent island area burnt was weakly correlated with fire frequency (r_s = 0.4) and with fire intensity (r_s = 0.33) (Table S2).

3.2. Comparing fire properties using remote sensing and governmental dataset

Of the 3778 fires recorded and included on islands in the governmental dataset between the years 2000 and 2022, over 70 % (2694) were prescribed fires. For 370 (10 %) of these fires, it was not determined in the GA dataset whether a fire was a wildfire or a prescribed fire. Of the remaining 714 wildfires, 112 (16 % of 714) were undeliberately caused, and 35 (5 % of 714) were caused intentionally (incendiaries). Fires below 1 ha in size were rarely documented in this dataset, and only for fire sizes above 10 ha, we were able to find the expected decrease in fire frequency with increasing fire size (Fig. S3; Guk et al., 2023).

In many islands, the area size of prescribed fires was smaller than that of wildfires, sometimes by an order of magnitude (Table 2, Fig. 5). Prescribed fires were often strategically planned to protect local assets, such as the townships, tourist resorts and the east-west Middle Road on Moreton Island (Fig. 5). However, in some islands, such as Magnetic Island in Queensland, the size of prescribed fires was larger than the size of wildfires (Table 2).

In the governmental dataset, the number of islands that had fires increased over time, with most fires recorded since the early 1980s – this probably reflects the completeness of the governmental dataset more than it reflects actual temporal changes in wildfires but may also reflect the increased use of prescribed fires as a management tool (Fig. S4a). In the MODIS data, no temporal pattern in wildfires was noticed between 2001 and 2021 (Fig. S4a). As for the average burnt area of wildfires on islands, significant fluctuations were noted until the year 2000 in the governmental dataset, probably related to the small number of islands covered by this dataset in the years prior to 2000, following which

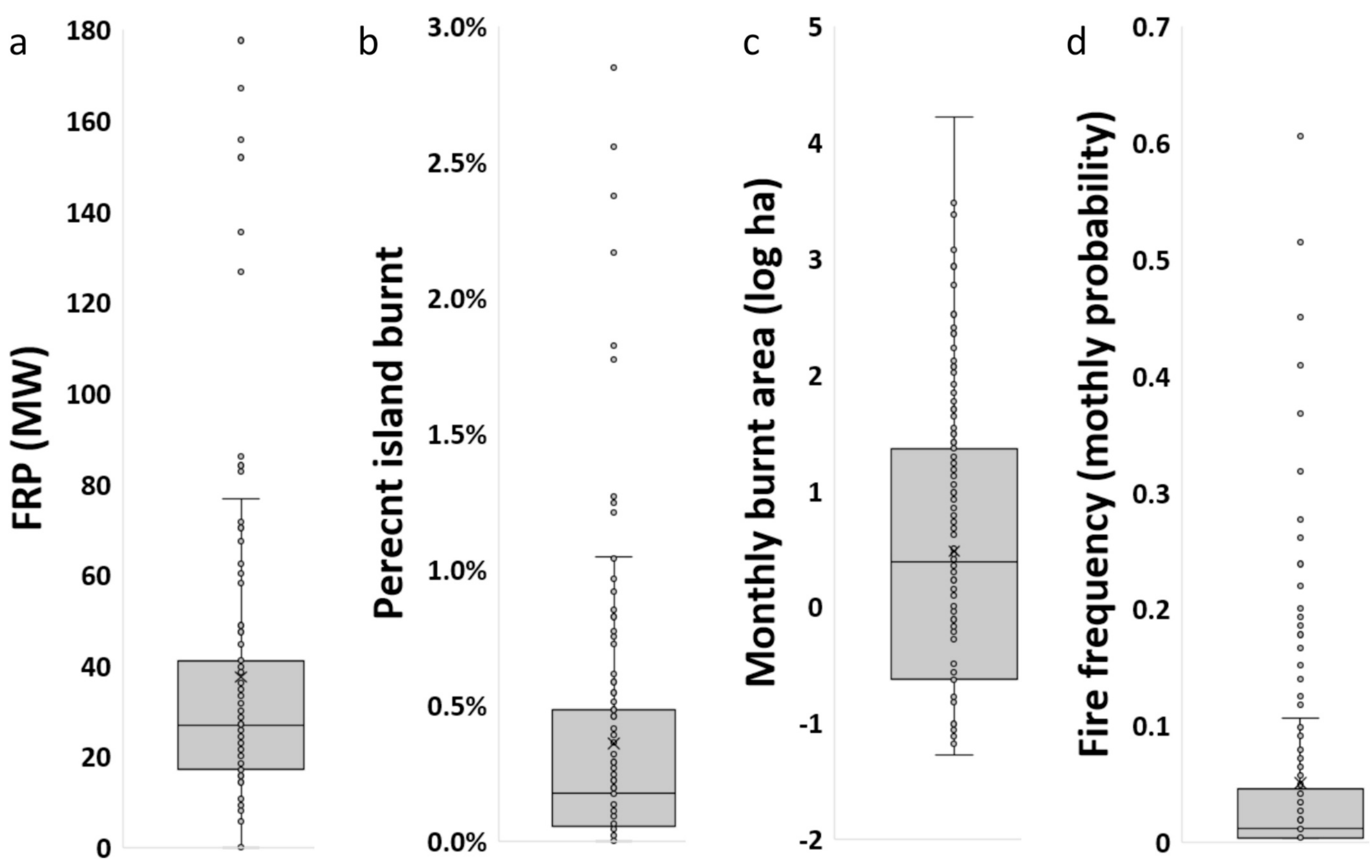

Fig. 2. Box plots showing for Australian islands the mean values for the following variables at the island spatial scale: a. Mean fire intensity (MW), b. Mean percent island area burnt, c. Mean fire size (log ha) and d. Mean fire frequency (percentage of months with fires; e.g., a value of 0.5 signifies that on average, there were six months with fires every year).

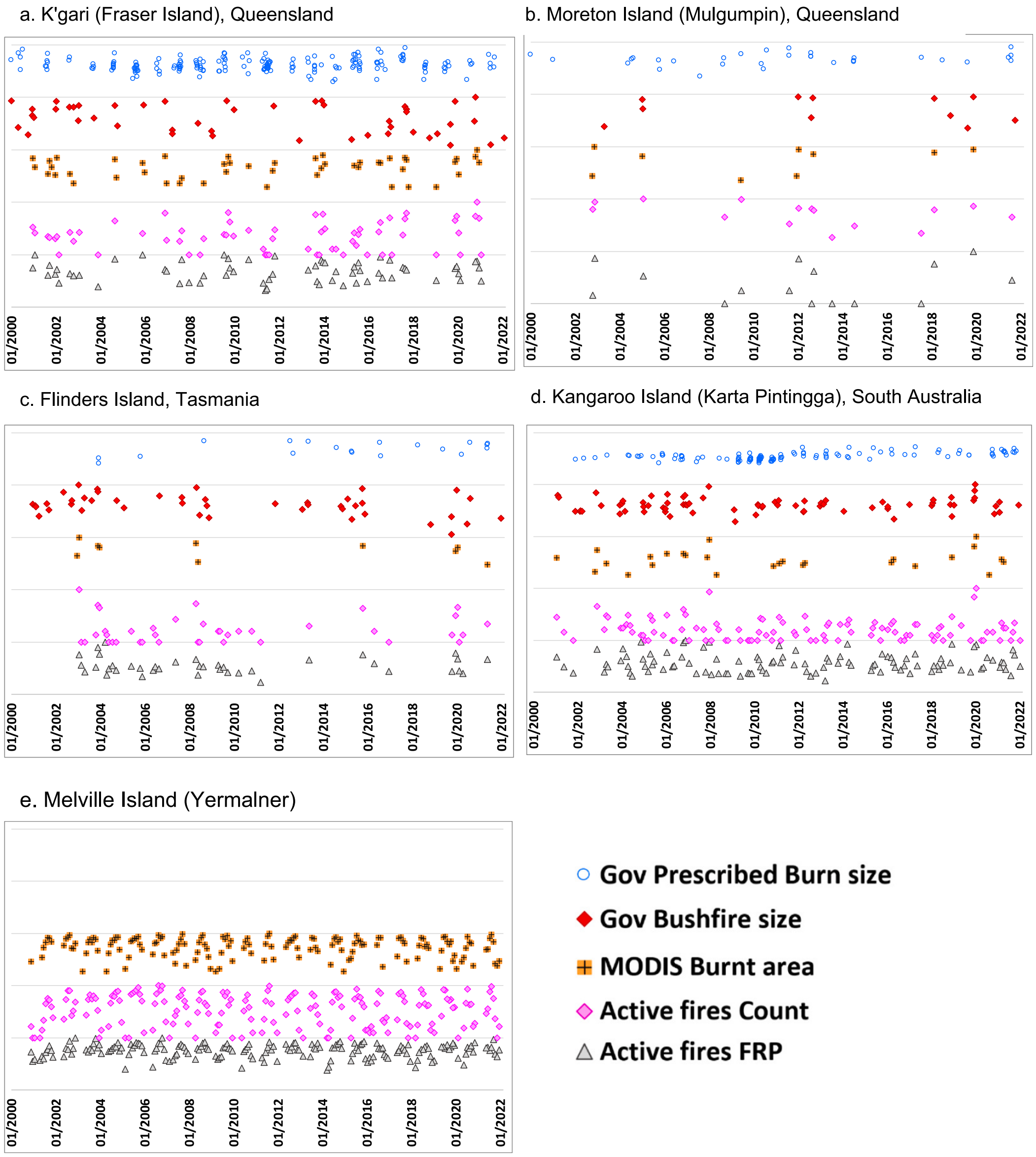

Fig. 3. Case study islands: Monthly temporal fire patterns between November 2000 to February 2022, including fire size, MODIS active point count, and fire radiative power (MW), for a. K'gari (Fraser Island; 1661 km^2), b. Moreton Island (Mulgumpin; 171 km^2), c. Flinders Island (1359 km^2), d. Kangaroo Island (Karta Pintingga; 4416 km^2) and e. Melville Island (Yermalner; 5785 km^2). All variables were normalized (after a logarithmic transformation) between their respective minimum and maximum within each island for visualizing their temporal variability. Governmental derived fire sizes were both normalized to the same maximum.

remote sensing using satellites such as MODIS allowed global mapping of wildfires (Fig. S4b).

Examining fire patterns between the years 2000 and 2022 as a function of island size, we found that in both the governmental dataset and MODIS data, the larger an island, the more likely it was to experience more fires (Fig. S6a). The average size of fires on islands expressed as a percentage of island size, decreased with island size – on islands smaller than 10 km^2 in size, both wildfires and prescribed fires often burnt >50 % of an island's area (Fig. S6b).

The correlation between MODIS fire frequency on Australian islands and fire frequency as recorded in the governmental dataset, was higher for wildfires ($R^2 = 0.36$) than for prescribed fires ($R^2 = 0.22$) (Fig. S7a). The size of the maximum burnt area of a fire event on an island, was positively correlated with wildfires ($R^2 = 0.32$) and not with prescribed fires (Fig. S7b).

3.3. *Fire regime and seasonality analysis*

Four main fire regimes covered most of the islands ($n = 105$), (Fig. S8). The assigned island fire seasons (seasons when the majority of fire occurred) varied around Australia, particularly in the tropical north and northeast (Fig. S5). Islands with a summer fire season were mostly found along the south and the east coast of Australia. Mackenzie Island, North Stradbroke Island (Minjerribah), Flinders Island and Kangaroo Island (Karta Pintingga) all falling under a summer fire season. Autumn fire seasons occurred only in islands along the northern parts of Australia, while winter and spring fire seasons both occurred on islands off northern and eastern Australia (Fig. S5).

3.4. *Multivariate model for fire metrics*

The multiple linear regression model was able to significantly explain log mean fire intensity (Adjusted R^2 of 0.533), with fire regime, population and % residential area entering the model (Table 3). The

Table 2
Summary of monthly temporal fire patterns between the year 2000 and 2022 on nine large Australian islands (see Fig. 2 for temporal variability of fires on five of these islands, and Fig. 5 for the spatial patterns of fires on four of those islands).

			Dirk Hartog Island (Wirruwana)	Melville Island (Yermalner)	Magnetic Island	K'gari (Fraser Island)	Moreton Island (Mulgumpin)	North Stradbroke Island (Minjerribah)	Flinders Island	Bruny Island	Kangaroo Island (Karta Pintingga)
		State/Territory	Western Australia	Northern Territory	Queensland				Tasmania		South Australia
		Island area (km^2)	628	5785	51	1661	171	269.5	1359	355	4416
Monthly fire properties from remote sensing	Largest fire event on island	Month	–	Aug 2011	Jul 2002*	Nov 2020	Nov 2002	Jan 2014	Jan 2003	Mar 2007*	Jan 2020
		Area (km^2)	No fires detected	1621	19*	515	67	107	150	28*	1753
		% burnt area	–	28	37*	31	39	40	11	8*	40
	Overall mean	Mean fire intensity (MW)	–	47.44	14.35	82.7	60.23	49.18	135.4	84.1	155.8
		Mean fire frequency (months with fires / year)	–	7.1	0.4	2.4	0.41	0.864	0.456	0.05	1.18
		Mean % burnt area	–	2.85 %	–	0.55 %	0.49 %	0.33 %	0.097 %	0.065 %	0.27 %
		Mean fire size area (km^2)	–	164.84	–	9.16	0.84	0.89	1.32	0.23	11.79
Gov. data	No. years with fires*	Bushfires	–	No data for the Northern Territory	5	21	7	4	18	16	20
		Prescribed fires	–		17	23	18	8	9	8	22
	Mean annual % burnt area*	Bushfires	–		1.7	7.5	18.3	5.4	1.6	0.8	3.7
		Prescribed fires	–		7.1	2.9	2.1	1.6	0.1	0.3	0.05

* Data from Australian governmental layer of "Historical bushfire extents".

models for the other three fire response variables had a weak and significant explanatory power (Adjusted $R^2 < 0.15$) (Table 3).

3.5. Threatened species and fires on islands

Threatened species richness across all Australian islands included in this study showed correspondence with several fire patterns, particularly fire intensity and fire size. The total number of threatened species on an island had a strong positive correlation with fire intensity ($r_s = 0.49$, $p < 0.001$). A similar result was also found for threatened species within specific taxonomic groups (except for plants and reptiles; Table 4), showing a strong positive correlation with fire intensity. When analysed by threat categories (IUCN and EPBC), all threat classes (except 'Near threatened') had positive correlations ($r_s > 0.4$, $p < 0.001$) with fire intensity. The threat classes 'Vulnerable' and 'Endangered' under EPBCA also had a positive correlation with fire size ($r_s > 0.32$, $p < 0.01$) (Table 5). We did not find an increase in the correlations between fire variables and the number of threatened species as a function of threat level (Table 5). The multivariate stepwise regression model ($n = 54$ islands) for the number of threatened species on islands, was able to explain 64.8 % (adjusted R^2) of the variability, using the variables of log of island area (standardized coefficient of 0.72, $p < 0.0001$), fire radiative power (standardized coefficient of 0.257, $p = 0.008$), and the percent area of the island that was burnt (standardized coefficient of -0.194, $p = 0.043$).

4. Discussion

Fire can have many impacts on native biodiversity and ecosystems. This can be especially true for island systems, some of which were shown in this study to be prone to fires burning very large areas of the island. Using the database of fire patterns across all Australian islands created in this study, we found that fire regimes vary widely across Australia's different islands. Human population was found to be an important fire intensity, and fire intensity was found to be associated with larger numbers of threatened species.

4.1. Fire regimes and fire properties on Australian islands

Fire patterns have been shown to vary temporally and spatially across the Australian mainland (Murphy et al., 2013). This study suggests that this is also the case for Australia's islands, which have been emphasized as being vulnerable to environmental changes (Laurance et al., 2011). The Australian continent had 22 described fire regimes ranging from tropical rainforest regimes to temperate eucalypt woodland regimes (Murphy et al., 2013) that vary widely in the intensity and frequency of fires. While the characterization provided by (Murphy et al., 2013) (Table 6) was approximated, in our analysis we show that fire regimes and fire properties can be quantified using remote sensing.

A fire characteristic that varies substantially between the different regions of Australia is fire intensity. In particular, fire patterns in temperate regions of Australia, such as Tasmania and Victoria's tall eucalypt forest, consist of multidecadal fire frequencies (Bradstock 2010, Murphy et al., 2013), allowing for the accumulation of fuel loads that, when burnt, cause high-intensity fires (Bradstock et al., 2002). Our analysis supported this, suggesting that islands classified under temperate regimes (e.g. temperate tall eucalypt forest) had higher fire intensities (Table 6). This trend is analogous to patterns of fire intensity across the Australian mainland (Murphy et al., 2013).

Across the southern temperate regions of Australia, there is increasing evidence that fire events are becoming more intense over time, and posing a threat to biodiversity (Tran et al., 2020). Further

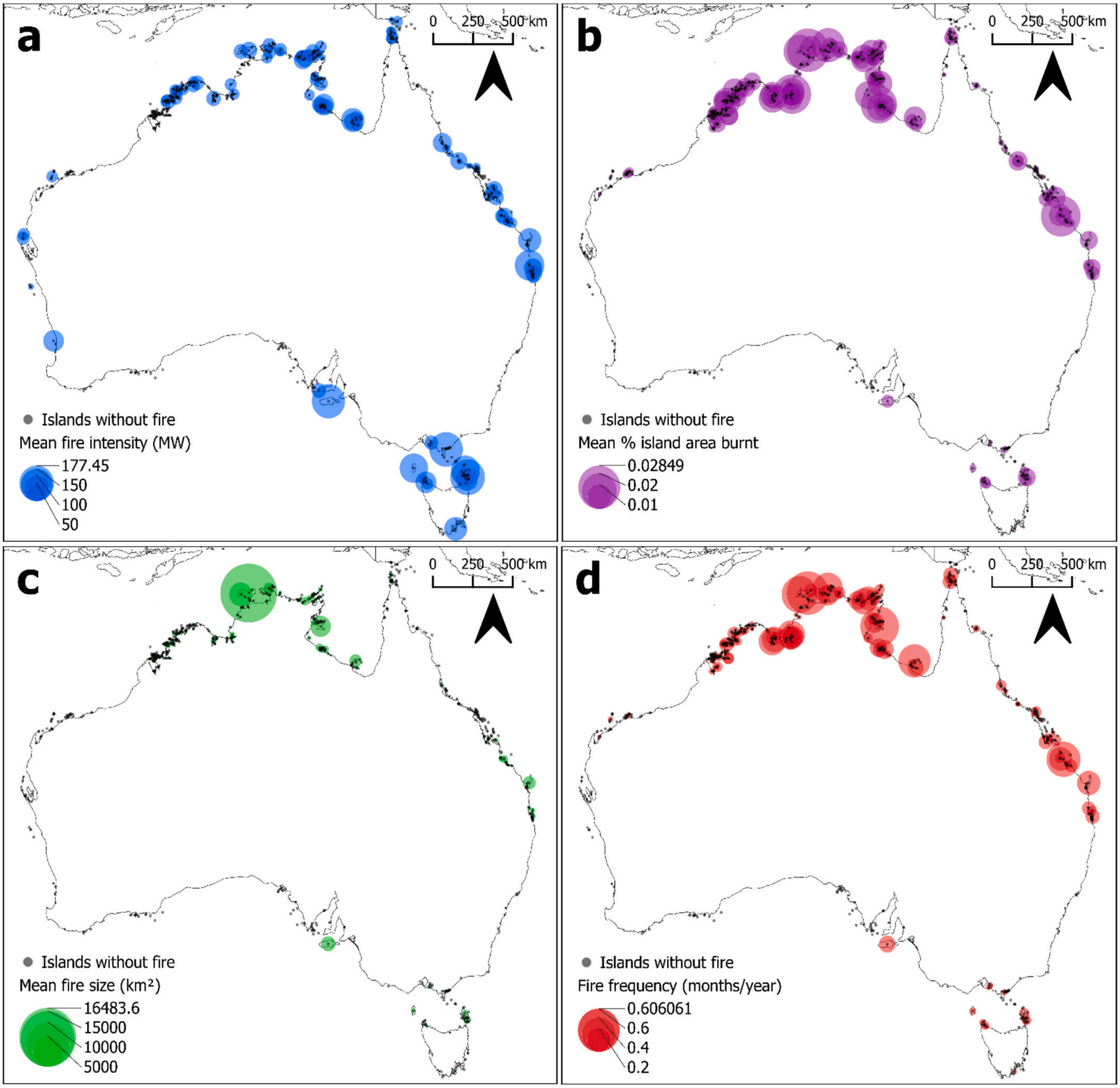

Fig. 4. Maps showing the: a. Mean fire intensity for Australian islands; b. Mean percent island area burnt; c. Mean fire size and d. Fire frequency (% of months with fire events) across Australian islands over 1 sq. km ($n = 704$).

studies found that the 2019/2020 Black Summer bushfires severely burnt a greater spatial extent than ever recorded for temperate and subtropical regions (Collins et al., 2021). Despite this, our analysis found limited evidence of increases in fire intensity through time in temperate region islands (probably because of the relative short time frame of our study, two decades), with islands such as Flinders Island and Kangaroo Island (Karta Pintingga) showing sporadic peaks without clear trends. However, on Kangaroo Island (Karta Pintingga) these sporadic peaks (particularly during the 2019/2020 bushfires), showed the most severe and extensive fires in 30 years (Bonney et al., 2020). While the governmental dataset extends further backward in time in comparison with MODIS data, based on our temporal analysis it is incomplete, and cannot be relied on to examine multi-decadal trends in fire frequency.

While on most islands the mean monthly percent of the island burnt was below 0.5 % (Fig. 2), in most of the islands the maximum monthly fire events burnt >10 % of an island. These are very high values, especially when compared to annual burned area percentages for forest biomes (Boer et al., 2020). Islands smaller than 10 km^2 were found to be at higher risk of stochastic events of fires burning >50 % of their area, however even on large islands (>100 km^2) there were fire events that burnt >25 % of their area. These findings have implications for in situ threatened species and translocated species, where burning major sections of habitat has been found to reduce available forage and allowing for increased invasion of invasive species (Pastro et al., 2011; Kark et al., 2022), and informs the selection of larger islands for refuge and safe haven projects rather than small islands.

Lightning is a major ignition source for wildfires across Australia and globally (Latham and Williams, 2001; Dowdy et al., 2017). In some

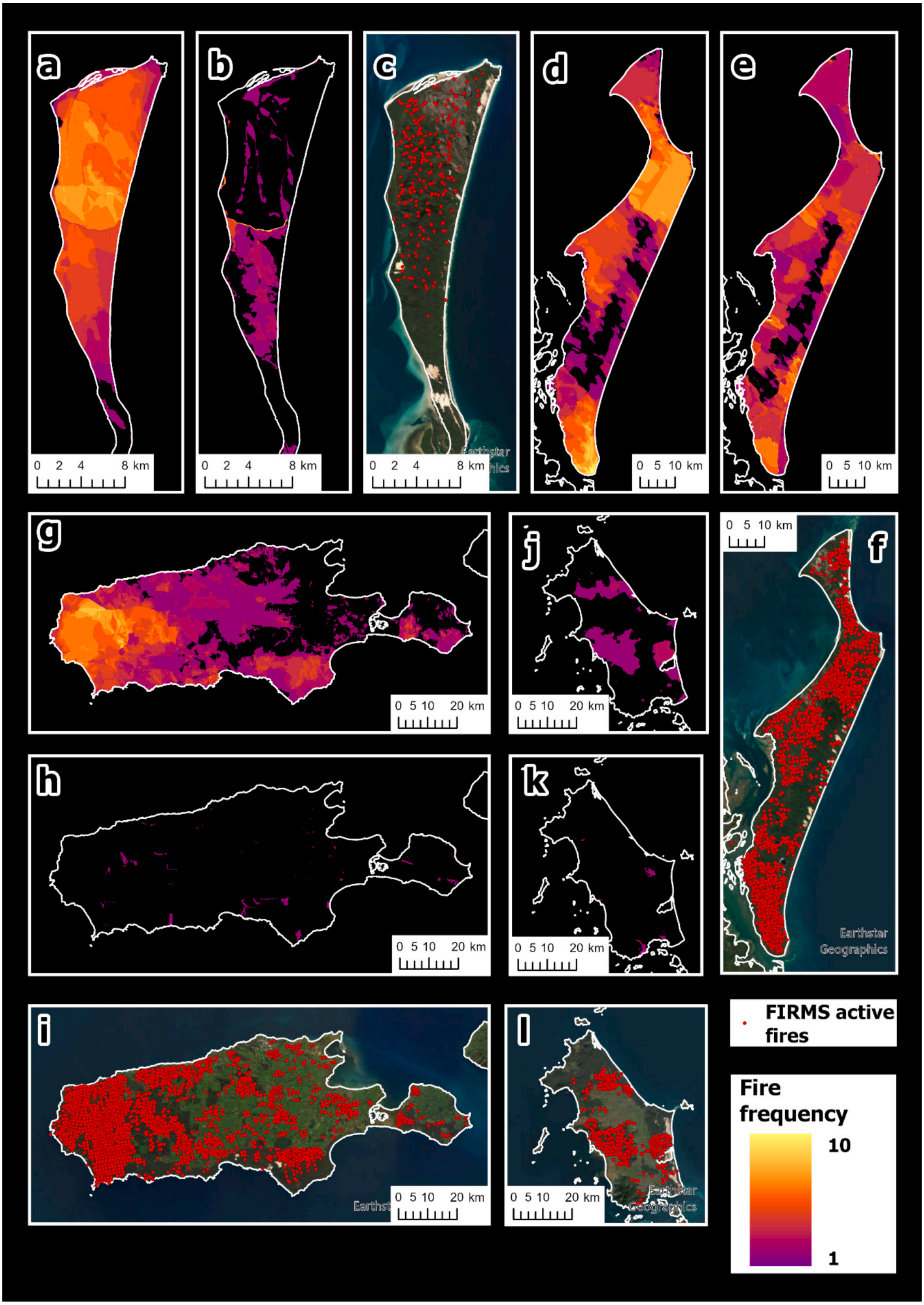

Fig. 5. Spatial patterns of fire frequency (number of fires recorded within grid cells of 25 m for the entire governmental dataset) on case study islands based on the governmental dataset of historical bushfires, and the FIRMS dataset of active fires (shown as red points with a satellite image in the background). Moreton Island (Mulgumpin): bushfires (a), prescribed fires (b), FIRMS active points (c). K'gari (Fraser Island): bushfires (d), prescribed fires (e), FIRMS active points (f). Kangaroo Island (Karta Pintingga): bushfires (g), prescribed fires (h), FIRMS active points (i). Flinders Island: bushfires (j), prescribed fires (k), FIRMS active points (l). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
General Linear Model analysis examining the statistical influence of explanatory variables on response variables (n = 167 islands). The explanatory variables are sorted by the order they entered the stepwise regression model.

Response variable	Adjusted R^2	Explanatory variables	t	Pr > |t|
Log Mean fire intensity (MW)	0.533	Fire regime		
		Acacia shrubland (mulga) (semi-arid/arid)	−3.126	0.003
		Eucalypt forest and woodland (tropical)	−2.343	0.024
		Eucalypt savanna woodland (monsoon tropical)	−2.835	0.007
		Hummock grassland (semi-arid/arid)	−2.161	0.036
		Population	3.836	0.000
		% Residential area	−2.550	0.014
Log mean fire size (km^2)	0.136	Fire regime		
		Eucalypt forest (temperate)	2.651	0.010
		Eucalypt savanna woodland (monsoon tropical)	2.112	0.039
		Heath (temperate)	2.424	0.018
		Mallee (temperate)	2.789	0.007
Log fire frequency	0.063	Log Lightning	−2.464	0.015
		Population	2.188	0.031
Log percent Island area burnt	–	–	–	–

regions of Australia, lightning is highly abundant and closely linked to season, in tropical and arid regions such as Darwin and Alice Springs (Northern Territory), respectively (Kuleshov et al., 2002). Conversely, in other climate regions, such as those around Perth (Western Australia) and Strahan (Tasmania), lightning occurs throughout the year, uninfluenced by season and at lower strike frequencies (Kuleshov et al., 2002). We did not find a significant correlation between lightning strikes and the frequency of fires on Australian islands.

Remotely sensed derived data and governmental datasets complement each other for fire mapping and conservation purposes (Guk et al., 2023). While remote sensing may be more reliable and consistent, governmental datasets are also important as they allow for descriptive differences to be drawn between prescribed fire and wildfire, and show the presence of prescribed fire even if the data is incomplete.

4.2. Human influence and fire

In recent history (post-European settlement) fire suppression practices have increased (Santos et al., 2022). The concern associated with fire suppression is the long term effects of increased occurrence of highly intense, widespread fires (Turner et al., 2003). Particularly with growing populations and urban areas, there is an increased need for fire management and mitigation to protect human life and assets (Driscoll et al., 2010). In our study, we identified that on Australian islands, population positively influenced both fire intensity and fire frequency, suggesting that as human populations increased per island, so did the occurrence of fires and of more intense fires. These findings are supported by the literature (Turner et al., 2003; Laming et al., 2022; Santos et al., 2022). However, due to data limitations regarding controlled burns and wildfire across Australia (no data for the Northern Territory on whether a fire was a wildfire or a prescribed fire), it was difficult to understand (in our study) what about increased populations data is causing increased intensity and area burnt. A possible explanation may be related to increased visitation pressures on populated islands, which may lead to more fires that are ignited accidentally by visitors, or which are related to other anthropogenic activities (Bradstock, 2010). A relevant report found that urban vegetation fires in places such as the Northern Territory, Queensland and Victoria were deliberately lit 27 %, 40–50 % and 21–32 % of the time, respectively (Bryant, 2008).

Land tenure was hypothesized to influence all fire characteristics, as different land tenure types (such as Indigenous land tenure and protected area tenure) often have different fire management techniques (Burr, 2013). However, evidence of these two land tenure types showed no influence on fire on Australian islands. It is plausible that these management types could be influencing fire on a scale undetectable in this analysis due to the absence of controlled fire versus wildfire data. Understanding how different land tenures influence fire characteristics is difficult, as fire management within protected areas is continuously changing. Some conservation areas are implementing Indigenous burning techniques (Fletcher et al., 2021), while fire management techniques within some Indigenous protected areas have decreased due to changes in community distributions (Woinarski et al., 2011).

Table 4
Matrix of correlation coefficients (Spearman's rank) between fire characteristics variables (rows), versus total threatened species and different taxonomic groups across Australian islands (columns; number of species from each group found on each island) (n = 79 islands).

	Total Threatened Species	Fish	Frogs	Invertebrates	Land birds	Mammals	Plants	Reptiles	Seabirds
Fire intensity (MW)	0.495***	0.306*	0.453***	0.416***	0.349**	0.499***	0.182	0.149	0.321**
% Island burnt	0.063	−0.089	−0.112	0.064	−0.060	0.165	0.043	0.189	−0.227
Fire size (km^2)	0.362**	0.168	0.185	0.268*	0.205	0.361**	0.310**	0.224	0.020
Fire frequency (months/years)	0.249*	−0.031	0.117	0.150	0.152	0.169	0.306*	0.202	−0.046

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Table 5
Spearman's rank correlation matrix between fire variables were and threatened species and different IUCN and EPBC threat categories across Australian islands (n = 79 islands).

	Total threatened species	Least concern	Near Threatened	Vulnerable	Endangered	Critically endangered	Extinct
Fire intensity (MW)	0.495***	0.425***	0.264*	0.428***	0.535***	0.461***	0.431***
% Island burnt	0.063	0.025	−0.243*	0.034	0.131	−0.073	0.095
Fire size (km^2)	0.362**	0.214	0.008	0.350**	0.324**	0.219	0.302*
Fire frequency (months/years)	0.249*	0.041	−0.060	0.280*	0.208	0.095	0.070

* p < 0.05.
** p < 0.01.
*** p < 0.001.

Table 6
A comparison of fire properties (intensity, frequency and season) in the analysis undertaken in this paper at the island level compared with the properties estimated by the fire regime niche analysis of Murphy et al. (2013) ($n = 105$; see Table 1).

Fire regime niche analysis							Fire regime analysis (this study)* *Mean values at the island level			
Regime Name	Typical Intensity (kW/m)	Extreme intensity(kW/m)	Typical Interval (years)	Extreme Interval (years)	Dominant fire season	n	Observed Frequency (month/year)	Interval between fires (years)	Observed Intensity (kW)	Observed fire season
3. Temperate Eucalypt Forest	1000–5000	10,000–50,000	5–20	20–100	Spring–Summer	7	1.8	0.55	45,360	Spring-Summer
9. Tropical Eucalypt Forest and Woodland	1000–5000	5000–10,000	5–20	20–100	Spring	5	0.324	3	23,120	Summer
13. Monsoon Tropical Eucalypt savanna woodland	100–1000	5000–10,000	2–5	5–20	Winter–Spring	71	1.44	0.69	34,150	Winter-Spring
19. Semi-Arid/Arid Hummock grassland	1000–5000	5000–10,000	5–20	20–100	Spring	22	0.276	3.6	39,570	Autumn

4.3. Threatened species and fire on Australian islands

Despite the Australian mainland and its islands long history of fire, many of Australia's threatened species have 'inappropriate fire regime' listed as a threatening driver (Santos et al., 2022). While our study did not look at whether fire was a direct threatening process for threatened species on Australian islands, it did find that islands with high fire intensity and fire size also hosted more threatened species. More specifically, high fire intensity islands hosted more threatened fish, frogs, invertebrates, land and sea birds, mammals, and plants, whereas high fire size islands hosted more threatened plants. While our findings may not indicate that fire intensity is threatening species on Australian islands, it does highlight the importance of management on these islands due to their high conservation values and high potential for catastrophe, as was the case of the Black Summer fires on Kangaroo Island (Robinson, 2020) and for the 2020 fire on Fraser Island (Qi et al., 2021). Given that human population was an important predictor of fire intensity and fire frequency, and that human activities are often a source for threats to species (Wood et al., 2017), we highlight the need for better and more informed management of fire on islands.

Understanding how fire regimes differ between Australian islands and the mainland is important for conservation actions and the management of threatened species across Australia's islands. Australian islands and their endemic and threatened species are overwhelmingly susceptible to impacts of fire, disease and invasive species (Kirkwood and O'Connor, 2010; Woinarski et al., 2011). Examples of this have been seen far and wide across Australian islands, including 64 separate Australian island species extinctions related to invasive species (Woinarski et al., 2019), seabird populations extinguished by single fire events on a Tasmanian island, (Brothers and Harris, 1999) and two species of endemic Christmas Island rat species now extinct due to introduced disease (Green, 2014). Inappropriate fire regimes can also interact with other stressors such as disease and invasive species (Hradsky et al., 2017; Geary et al., 2022; Santos et al., 2022). Disease such as chytrid fungus affecting many amphibian species has been found to be exacerbated by megafire events (Geary et al., 2022), while invasive predators (e.g. foxes and cats) become nearly doubly effective in predating small to medium size mammals after a fire events (Hradsky et al., 2017).

Islands are the focus of many conservation projects that use islands as safe havens/refuges for threatened species from mainland Australia in addition to islands in situ threatened species (Legge et al., 2018; Eddie et al., in press). Melville island of the Northern Territory is an example of a refuge for threatened species, home to northern brown bandicoots, black footed tree-rat, and brush tailed rabbit-rat (Davies et al., 2018). This island was identified in this study as having frequent and disproportionately broad scale fires, and has shown significant declines in the above listed species which have been found to correlate with both fire and cat populations (Davies et al., 2017; Davies et al., 2018). Another example is the endemic Kangaroo Island Dunnart, whose 324 km^2 home range was 98 % burnt in the 2019/2020 bushfires (Hohnen et al., 2019) combined with increased cat predation post-fire (Taggart et al., 2019), caused major concern for the species' persistence. These examples shed light on the importance of managing both fire and alongside other stressors such as invasive species to protect our islands refuges catastrophe. At a global level, islands hold a significant proportion of the world's biodiversity and endemic species (Courchamp et al., 2014). Understanding the role of fire and its interaction with species and ecosystems on islands should be at the forefront of future research to ensure the protection and conservation of this biodiversity. Critical to prioritising future conservation for islands and species, future research should include species-specific and fire-specific (wildfire versus prescribed) analyses as well as island specific investigations to better analyse suitability for conservation projects like safe havens or translocation sites. The synthesis of fire patterns and species richness across islands presented in this study sets a baseline for future research. Little is known about the impact of fire on invertebrates on islands, which is an important area to future examine.

This study highlights the need to better study and understand fire patterns and processes for future management and conservation action on islands, and their impacts on native species. While fire may be beneficial for some threatened species, large and intense fires may lead to further threats and decline in others (Santos et al., 2022). Further knowledge sharing between practitioners, Indigenous peoples, and other experts across islands can support the management of fires on islands to benefit both native biodiversity and humans.

CRediT authorship contribution statement

Alana O'Dwyer: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Salit Kark:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Noam Levin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111335.

Data availability

Data will be made available on request.

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