RESEARCH REPORT

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Pirra Jungku: Comparison of traditional and contemporary fire practices on Karajarri Country, Western Australia

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Summary Traditional fire practices in Australia's deserts may have created mosaics of post-fire seral stages that benefitted some plants and animals. Managing fire to emulate the patterns produced by traditional burning practices is a common objective in contemporary conservation planning in Australia's deserts. However, the extent to which traditional burning in deserts affected fire regimes across space and time is contested. We aim to contribute to knowledge about the impacts of traditional burning on fire patterns in the Great Sandy Desert, northwest Australia. Our study covered the traditional lands of the Karajarri people, where some families were living a traditional lifestyle on Country until the 1960s. We analysed high-quality aerial photographs taken over 18,000 km^2 of Karajarri Country in the 1940s. Fire footprints up to several years old were mapped from these images, and their spatial characteristics were compared to those of contemporary fire regimes over the same area, visualised using high-resolution Sentinel satellite imagery. Fires in the 1940s (considered traditional) were more numerous but much smaller than contemporary (2016–2020) fires. The areal extent of recently burnt areas was smaller and the fire frequency was lower in the 1940s. Contemporary fire patterns around cultural sites differed little from fire patterns elsewhere in the landscape, possibly because people were burning over large areas rather than only at localised sites. Our study suggests that Karajarri influenced fire patterns at a landscape scale in the Great Sandy Desert, at least during periods of average rainfall. The findings are helping Karajarri refine fire management goals, for example, by informing the size and dispersion of future burns, and supporting community discussion about fire and culture. Fire management outcomes for plants and animals are being tracked with a biodiversity monitoring program.

Key words: *Contemporary fire management, Desert, Fiire spatial patterns, GIS mapping, Indigenous fire management, Traditional burning.*

Implications for Managers

- Traditional fire practices in the Great Sandy Desert in the 1940s included smaller fires and lower fire frequencies, than what occurs today.
- Recent changes in fire patterns may have contributed to declines in some plants and animals.
- Contemporary large-scale fire management using aerial ignition could be combined with small-scale on-ground burning to emulate traditional practices in key areas.
- Biodiversity monitoring programs will provide information about fire management, so Traditional Owners and rangers can report on management outcomes.

Introduction

Fire has played a dominant role in shaping many of Australia's ecosystems throughout evolutionary time (Bowman *et al*. 2012). Australia's deserts are characterised by low and variable annual rainfall, with irregular episodes of widespread, heavy rain driven by monsoonal activity (Greenville *et al*. 2009; Morton *et al*. 2011). Fires can occur when accumulated rainfall has caused the biomass of the dominant grass vegetation of Australia's deserts to increase so that fires can carry between adjacent perennial grass clumps; fire can also occur when heavy rain stimulates growth of annual grasses that carries fire between perennial grass clumps even if these are widely spaced (Allan & Southgate 2002; Greenville *et al*. 2009; Verhoeven *et al*. 2020). Desert fire ignitions arise from lightning strike or, in more recent evolutionary time, from people (Latz 1995).

Indigenous Australians used fire in the deserts for thousands of years, for reasons such as hunting and easing access (Lowe 2002; Bird *et al*. 2008; Pike 2008). However, whether this burning affected desert fire regimes at landscape scales, and the effect of this burning on desert ecosystems, remains unclear (Allan & Phillips 2003; Enright and Thomas 2008; Pastro & Dickman 2011; Kimber & Friedel 2015). Reconstructing the influence of traditional fire practices on landscape-scale fire regimes is challenging. Three lines of evidence have been used to infer the nature and scale of traditional burning: first- and second-hand accounts of Indigenous people, information in European explorers' diaries and analysis of aerial imagery from the 1940s to 1960s. Each has its own interpretational constraints. First-hand knowledge of Indigenous people is available from localised areas or can be incomplete (Lowe 2002; Burrows *et al*. 2006; Bird *et al*. 2016). Observations by explorers lack context on the purpose of fires and were not always systematically made (Kimber 1983; Kimber & Friedel 2015; Wright *et al*. 2021). Archived aerial imagery of remote Australian deserts was collected intermittently, often after the development of settlements and over a short window (Burrows & Christensen 1990; Burrows *et al*. 2006; Burrows & Chapman 2018; Bird *et al*. 2020).

Despite the limitations of each line of evidence about the outcomes of traditional burning practices, taken together they suggest that Indigenous burning promoted a diversity of seral stages (Lowe 2002; Burrows *et al*. 2006; Bird *et al*. 2016, 2020). However, there is disagreement over the scale at which traditional practices affected large-scale fire patterns. Some authors argue that fine-scale seral mosaics were present at landscape scales, and that they prevented the spread of large wildfires (Burrows & Christensen 1990; Bowman 1998; Burrows *et al*. 2006; Gammage 2011). Others argue that traditional fire practices were localised in space, focused on areas of key resource use and thus had little effect on landscape-scale fire regimes (Kimber & Friedel 2015). In an intermediate position, traditional burning could have affected the dispersion of seral stages at landscape scales in average rainfall years, but after widespread, heavy rainfall, extensive wildfires could have burnt through all but the most recently burnt patches (Allan *et al*. 2003; Enright & Thomas 2008; Wright *et al*. 2021). Resolving these issues is important for understanding the impact of cultural practices on desert biodiversity, because changes in fire regimes are a potential contributor to the recent biodiversity losses in the desert (Allan & Southgate 2002; Burrows *et al*. 2006).

The western and north-western deserts of Australia provide an opportunity to describe fire patterns arising from traditional practices, and to contribute to this discussion. Indigenous Australians from this region left their Country relatively late compared to the rest of the continent. Pintupi people left the Gibson Desert by 1985 (Burrows & Christensen 1990). Martu people (Gibson Desert, Little Sandy Desert) and the Walmajarri and Karajarri people (Great Sandy Desert, Tanami Desert) moved off Country to coastal missions and pastoral stations between the 1900s and 1960s (Lowe 2002; Bagshaw 2003; Bird *et al*. 2008). In these regions, aerial imagery and personal accounts are potentially most useful for describing fire patterns arising from traditional burning. Additionally, some Traditional Owners from these areas continue to use traditional practices to manage fire in local areas (Bird *et al*. 2008; Paltridge *et al*. 2020). Current burning in the deserts is concentrated around communities, outstations and on some pastoral tenures, usually close to roads and favoured hunting areas (Edwards *et al*. 2008; Bird *et al*. 2016; Paltridge *et al*. 2020). There are increasing efforts to extend the spatial scale of planned burns over larger sections of the deserts, facilitated partly by the growth of the Indigenous Protected Area and associated ranger programs, as well as by projects, such as 10 Deserts (https://10deserts.org/). However, implementing prescribed burning over such vast and remote areas is logistically challenging and costly, and refinement of fire management objectives could help target investment.

This study focusses on the traditional lands of the Karajarri people, in the north-western deserts, and was instigated by the Karajarri rangers, with oversight from senior cultural advisors. It aims to support Karajarri's fire management goals by describing Jungku (fire patterns) in the Pirra and Marangurru (inland pindan and desert) when people were still living on Country. The study also aimed to contribute to knowledge about the role of Indigenous people in shaping fire regimes in desert ecosystems more broadly. We used archived aerial imagery from the late 1940s to describe fire patterns at landscape scales and compared these historical fire patterns to contemporary fire patterns, described using high-resolution satellite imagery. If Karajarri people were using fire intensively and this influenced landscape-scale fire patterns, we expected to find differences in a range of fire pattern metrics between the 1940s and today. We also explored whether traditional fire practices were focussed on localised areas rather than occurring across the landscape, by examining fire pattern metrics near and far from sites of cultural significance.

Methods

Study site

The study was undertaken over 18,100 km^2 of the Karajarri Native Title Determination (ca. 30,000 km^2), south of Broome, Western Australia, and extending from the coast into the Great Sandy Desert (Fig. 1a). Most of the study area overlapped with the Karajarri Indigenous Protected Area. Native Title was determined in 2002, and the Karajarri Indigenous Protected Area (IPA) was declared over the majority of the Determination in 2014. A ranger team employed by the Karajarri Traditional Lands Association delivers the management goals set out in the Karajarri Healthy Country Plan (Karajarri Traditional Lands Association 2014).

A key part of the ranger's work program is to manage fire (Fig. 2) (Karajarri Traditional Lands Association 2014). In the past, fires were mostly lit during Parrkana, the cool months of the dry season, for many reasons, by Elders on their own Country and were small in size (Lowe 2002; Pike 2008; Willing 2014). In contrast, *Yura* (wildfires) burned later in the dry season, which is considered 'wrong time'. The danger of fire in the wrong season is taught through *Pukarri* (Dreaming) stories, such as:

> *Bluetongue was told that his son will be going through the sacred ceremony so he said to the tribe 'Wait - I will go get more food'. So he went hunting. When he came back he saw that they had already put his son through the ceremony without him being there. Bluetongue was really angry, so he started a fire at this Yilpi. He made a huge fire that burnt the whole Country, burning the people who had disrespected him.* (Pukarri story for Yilpi area; Mervyn Mulat Mulardy, Karajarri cultural leader)

Now that Karajarri people are living on the coast, rangers use aerial incendiary to introduce *Jungku Minjanakuwiku* (prescribed burns) over the vast inland areas of the IPA in the late wet season and early dry season (February to April), under the guidance of cultural advisors. A key objective is to limit the spread of *Yura* in the late dry season (July to December). Thus, Karajarri fire management is undergoing a shift in scale from local to landscape and cultural to operational delivery (from Elders on the ground, to rangers in the air), although elders insist that some ground burning must be maintained for the rangers to understand changes to the Country. This scale and delivery transition has also been experienced by Traditional Owner groups in other regions (Russell-Smith 2001; Perry *et al.* 2018). To help navigate this shift, in 2018, the Karajarri Rangers and cultural advisors began a project to support cultural knowledge transfer and understand the biodiversity outcomes of

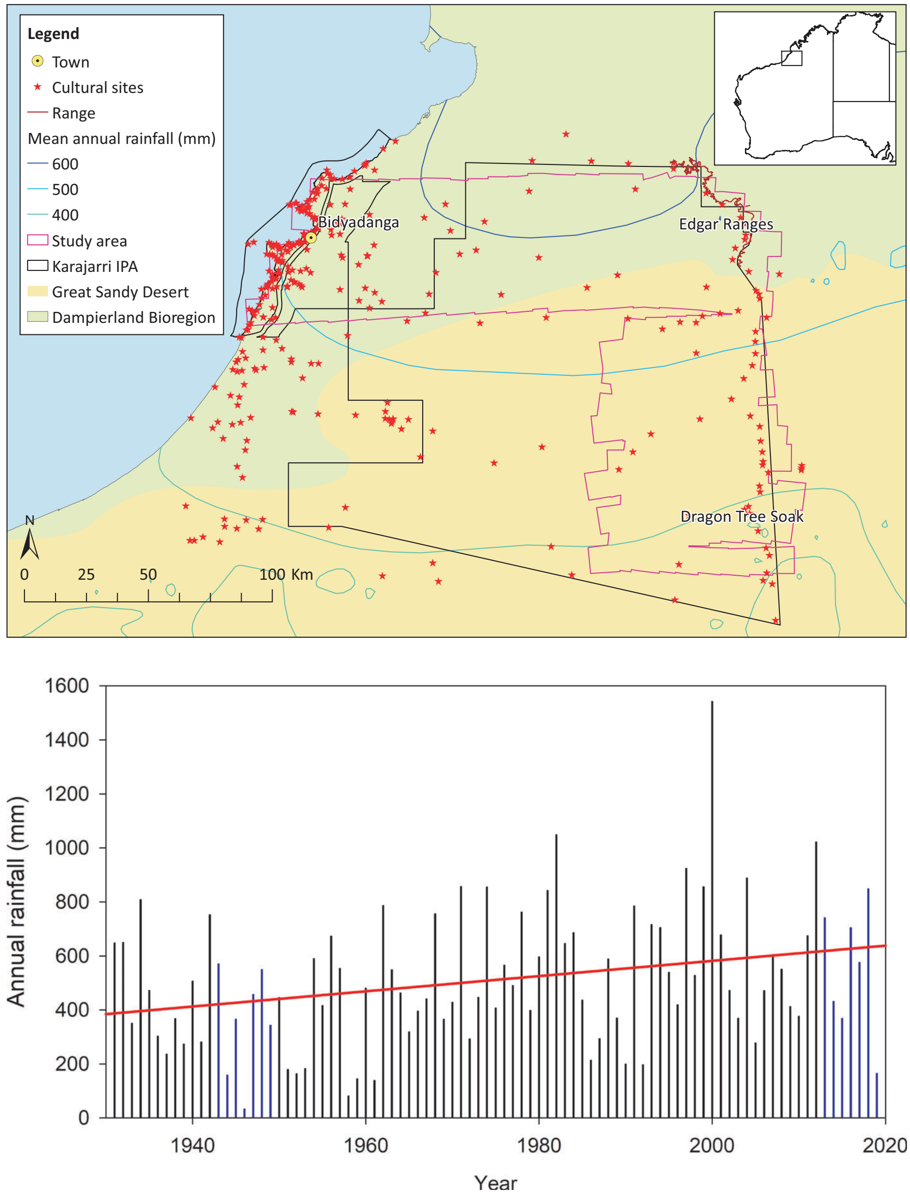

Figure 1. (a) Map of Karajarri IPA and study area, showing the IPA boundary, the boundary of the study area and the location of cultural sites. Mapping data obtained from Geoscience Australia, The Bureau of Meteorology, the Department of Agriculture, Water and the Environment and the Karajarri Lands Trust Association. (b) Annual rainfall (bars) at Bidyadanga community from 1930 to 2020, showing an increasing trend (red line). The trend is based on a linear regression between year and rainfall. Blue bars represent years where interpolated rainfall data for the whole study area were downloaded for use in analysis. Data were obtained from the Bureau of Meteorology website (www.bom.gov.au).

their fire management. The study reported here is part of this larger initiative. Specifically, Karajarri want to investigate the landscape-scale fire patterns that their ancestors created, and use that information to support discussion about cultural fire practices, and refine their contemporary fire management goals.

Fire pattern characterisation

The vegetation of the IPA is fire-prone, comprised mostly of *Pirra* near the coast (pindan woodlands with a sparse tree layer, thicker shrub layer dominated by *Acacia spp.*, understorey of tussock and hummock grasses) grading into *Marrangurru* inland

Figure 2. The Karajarri Rangers undertaking fire management on Karajarri IPA. Photos by Jesse Ala'i.

(spinifex *Triodia* spp. dune fields and plains).

Most rain falls on Karajarri Country from December to March when the monsoon is active, but rainfall is highly variable between years, and there is a rainfall gradient from north to south (Willing 2014; Bureau of Meteorology 2021). Annual rainfall has increased over the past decades (Fig. 1b). Since rainfall influences fire patterns, we needed to account for temporal and spatial variation in rainfall when considering any differences in fire patterns. We sourced interpolated gridded rainfall surfaces (5 km × 5km) from the Bureau of Meteorology (http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp). We downloaded the monthly rainfall data for July 1943 to June 1949, and July 2013 to June 2020, and created an annual total for each fiscal year (July to June) within those date ranges. We used fiscal years because the wet season occurs across calendar years (December to March).

Historical fire patterns

To describe historical fire patterns in the study area, we used archived aerial imagery from June/July of 1947 and 1949 taken by the Royal Australian Air Force, sourced from the National Library of Australia (scale of 1:50,000, spatial resolution of 25 m). We broadly followed the methods of Burrows and Christensen (1990) and Burrows *et al*. (2006) to georeference, mosaic, then manually digitise the fire scars in ArcGIS (further detail in Supporting Information). Each digitised fire scar was categorised into the following time-since-fire classes, based upon the relative brightness of each scar and clarity of the fire scar perimeter (Fig. 3):

Class 1: Very recently burnt, estimated 0–1 year since fire (1-year period, July to June), very high brightness with strong contrast against surrounding vegetation, 100% of the perimeter distinct.

Class 2: Recently burnt, estimated 2–3 years since fire (2-year period, July to June), high brightness with heavy contrast against surrounding vegetation, 90–95% perimeter distinct.

Class 3: Burnt, estimated 4+ years since fire, medium–low brightness with a medium contrast against surrounding vegetation, 75–85% perimeter distinct.

Unclassified: These areas lacked clear boundaries and a consistent brightness because they were areas of multiple overlapping fire scars, all of which occurred at least 4 years before the image. Unclassified areas

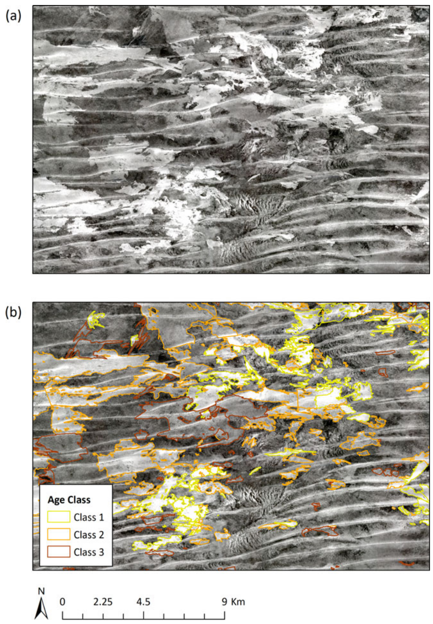

Figure 3. Example of the mapping of 1940s fire patterns using archived aerial imagery. (a) Part of a tile of the imagery with patches of varying post-fire age visible. (b) The same view, with patches outlined and assigned into post-fire age classes.

Table 1. Post-fire vegetation age of each fire class for historical and contemporary imagery, and the analyses they were included in

	1940s imagery	Contemporary imagery	Analysis
Class 1	0–1 year since burnt	0–1 year since burnt	• Patch number, patch size, patch dispersion • Areal extent of post-fire vegetation age, fire frequency • Patch number and size around cultural sites
Class 2	2–3 years since burnt	2–3 years since burnt	• Patch number, patch size, patch dispersion • Areal extent of post-fire vegetation age, fire frequency • Patch number and size around cultural sites
Class 3	4+ years since burnt	4 years since burnt	• Patch number • Areal extent of post-fire vegetation age, fire frequency (merged with Unclassified)
Unclassified	4+ years since burnt	5+ years since burnt	• Areal extent of post-fire vegetation age, fire frequency (merged with class 3)

could not be used in analyses of patch metrics, but they could be used in calculations for the areal extent of different time-since-fire classes, as they were all at least 4 years since the last fire (Table 1). They were, therefore, merged with class 3 for the areal extent and fire frequency calculations. Further justification for the age classification is available in Supporting Information.

Contemporary fire patterns

Contemporary fire patterns were mapped using Sentinel-2 satellite imagery obtained from the Copernicus Open Access Hub. This imagery is only available from 2016 on, but has a high ground spatial resolution (20 m), making it the most suitable readily available imagery for comparing with the historical photography. See Supporting Information for detail on imagery manipulation. Fire scars in the final image of June 2020 were categorised into class 1 (0–1 year post fire), class 2 (2–3 years post fire) and class 3 (4 years since fire); all other areas of the image were 5+ years since fire, and called unclassified (Table 1).

Analysis of differences in fire patterns

Mapped fire scars in the historical (1940s) and contemporary (2016–2020) imagery were attributed with the average fiscal-year rainfall over the preceding 4 years for their locations, by using the join function in ArcGIS. If a fire scar intersected rainfall grid cells with different values, the rainfall values were averaged across all grid cells. We chose the preceding 4 years to calculate rainfall leading up to fire, as it is the current average fire interval on Karajarri Country (Crowley 2019). For class 2, which spanned 2 years, we calculated the antecedent rainfall to the midpoint of those years.

Spatial characteristics of burnt patches from the 1940s were compared with those of contemporary times, in the 18,000 km^2 study area where the historical aerial imagery was available (Fig. 1a). Specifically, using patches in classes 1 and 2 only, we compared the number, size and dispersion of burnt patches of similar post-fire ages (Table 1). We omitted class 3 patches from these analyses, because they related to slightly different ages across the imagery (class 3 was 4+ years since fire in the 1940s imagery, but 4 years since fire in the contemporary imagery); also, class 3 patches were incompletely identified and mapped in both time periods, but more so in the 1940s imagery, where light flares and image degradation affect quality. In ArcGIS, we calculated patch size (ha) and the distance (m) between neighbouring patches of the same post-fire age class, using the near tool to find shortest distance between nearest boundaries. In R studio, we used linear regression to examine differences in patch metrics between the historical and contemporary imagery, by fitting time period (1940s, contemporary), antecedent rainfall (average annual over the preceding 4 years) and their interaction (RStudio Team 2020, package: ggplot2). Patch size and interpatch distance were transformed using natural log to meet the requirements of normal error distributions.

We examined the areal extents of post-fire age classes in both the historical and contemporary imagery. For this analysis, class 3 areas were merged with unclassified areas and attributed with a post-fire vegetation age of 4+ years. This was necessary because, again, class 3 referred to slightly different age brackets across the imagery sets (Table 1). To find the average fire frequency across the study area for each time period, we assigned a mid-point age for each age class (class 1 = 1 year post fire, class 2 = 3 years post fire, class 3 and unclassified = 6 years post fire), multiplied these mid-point ages by the percentage of the study area covered by that vegetation age, summed these values to find the average post-fire vegetation age and inverted this (1/average age) to find the average fire frequency for each time period. Differences in the areal extents of post-fire vegetation age classes, and fire frequencies, were examined using Chi-squared heterogeneity tests.

To examine whether burning activities were focussed in localised areas or occurred across the landscape, we compared the fire pattern around 60 cultural sites and 60 random control points. Knowledge about the extent and intensity of use of each site is now very limited in living memories. We, therefore, did not attempt to discriminate between types of cultural sites, such as water places (soaks and wetlands), sacred sites (gender specific and ceremony) or food harvesting sites, although the use of fire would have differed depending on the site. We created a sample area of 1-km radius around each point and counted the number of class 1 and 2 patches either within, or intersecting the edge of the sample area. We also calculated the average size of these patches. In R Studio (package: ggplot2), we used linear regression to compare the size (natural log-transformed) of fire scar patches around cultural sites versus those around control points; and generalised linear regression with Poisson error distribution to compare the number of patches around cultural sites versus control sites.

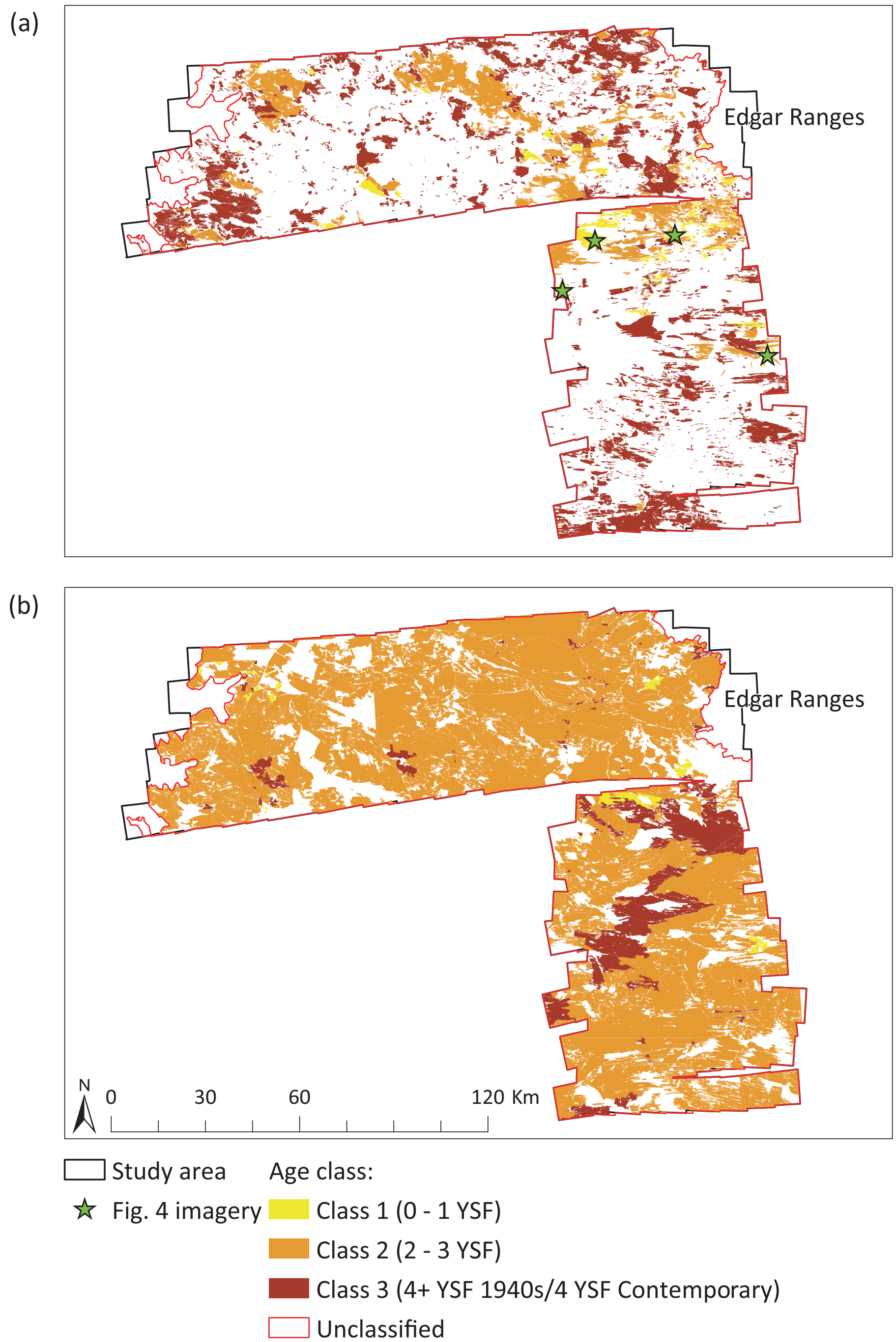

Figure 4. Mapped fire scars shown by their post-fire age class from the (a) 1940s and (b) contemporary periods. YSF is Years since fire. White areas of the maps are unclassified; they are (a) 4+ years for historical imagery and (b) 5+ years since fire for contemporary imagery; discrete patches could not be mapped in these areas.

Results

Fire scar patch metrics

Fire scar patches of classes 1 and 2 were mapped over 11% of the 1940s imagery (Fig. 4). The remaining 89% was 4+ years since fire (Class 3 and Unclassified; Table 1). In the contemporary imagery (2016–2020), classes 1 and 2 made up 70% of the study area, with the remaining 30% aged at 4+ years post fire (Class 3 and Unclassified, Table 1). More fire scar patches across post-fire age classes 1 and 2 were mapped in the 1940's imagery compared with the contemporary imagery (Table 2). There were also more class 3 patches in the 1940s imagery, but the more limited time series of contemporary

Table 2. The number of patches of different post-fire ages mapped in the 1940s and contemporary imagery

	Contemporary	1940s
Class 1 (0–1 year since fire)	58	682
Class 2 (2–3 years since fire)	1892	2631
Class 3 (4+ years since fire in 1940s; 4 years since fire in contemporary)	72	6146

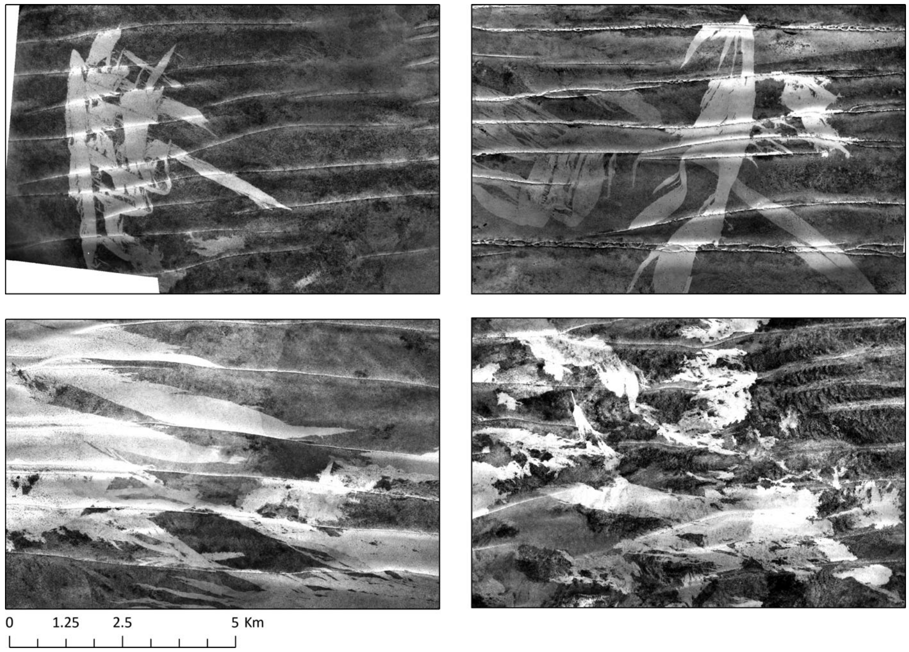

Figure 5. Examples of the visual signs of anthropogenic burning across the study site. Locations of the imagery are shown as stars in Fig. 4 above. All images taken in June/July 1949.

imagery likely reduced the number of mappable patches of class 3 vegetation, making this comparison problematic.

Visual inspection of the archived aerial imagery showed evidence of fine-scaled anthropogenic burning across the study area (Fig. 5). These were characterised by several overlapping patches heading in different directions, as the wind direction changed between ignitions. These are likely to have occurred in the same season. While these examples were observed across the study area, they appeared to be concentrated around the Edgar Ranges in the central west and further south, where fire patterns were most intensive (Fig. 4a).

Fire scar patches (of classes 1 and 2) were much smaller in the 1940s than they are now ($F_1 = 112$; $P < 0.001$; Fig. 6a). The average fire scar patch size in the 1940s imagery was 49.4 ha with a maximum of 6420 ha; the average from contemporary imagery was 581 ha with a maximum size of 63 700 ha. There was a significant interaction between time period and rainfall ($F_1 = 12.0$; $P = 0.005$; Fig. 6a), where fire scar patch size increased with increasing rainfall in the 1940s period, but slightly decreased with higher rainfall in the contemporary period. Fire scar patches of the same age class were further apart in contemporary imagery than in the 1940s imagery ($F_1 = 11.9$; $P = 0.0006$, Fig. 6b). The mean distance between same-aged fire scar patches in the 1940s was 366 m (max 12,970 m); in the contemporary period, it was 555 m (max 34,600 m). Neither rainfall, nor its interaction with time period, significantly affected the distance between patches (Fig. 6b). Overall, the analyses of patch size and dispersion show that patches were smaller but more aggregated 70 years ago.

Areal extent of post-fire vegetation ages

The areal extent of post-fire vegetation ages was skewed towards older ages in the 1940s compared to contemporary imagery. The most extensive post-fire age in the 1940s was 4+ years (class 3 and unclassified combined, 90% of study area), compared with 2–3 years in the contemporary imagery (69% of study area) (Heterogeneity test $\chi^2_2 = 14.4$; $p < 0.001$, Fig. 6c). Given the differences in areal extents of post-fire vegetation age, the fire frequency also differed between time periods: the average post-fire vegetation age in the 1940s imagery was 5.7 years, indicating an average fire frequency of 0.18, or less than once every 5 years. In the contemporary imagery, the average post-fire vegetation age was 3.9 years, indicating an average fire frequency of 0.26, or once every 4 years, a 46% increase over the two periods. Note that we may have overestimated the fire frequency in both time periods because we were unable to age vegetation patches of increasing age, but the relative difference between the fire periods remains plausible.

Fire patterns around cultural sites

On average, class 1 and 2 patches within 1 km of cultural sites were smaller in the 1940s imagery ($\overline{X} = 321$ ha) than class 1 and 2 patches within 1 km of control sites ($\overline{X} = 1109$ ha). However, the distribution of patch sizes had a long tail, and when the data were transformed using natural log, the size difference between patches near cultural versus control sites was not significant ($F_1 = 0.09$; $P = 0.76$). The number of class 1 and 2 patches within 1 km of cultural sites ($\overline{X} = 1.68$) was marginally greater than the number of patches around control sites ($\overline{X} = 1.28$) (GLM, Poisson error distribution: $\chi^2_1 = 3.25$; $P = 0.072$; Fig. 6d).

Discussion

Our study shows that the fire patterns on Karajarri Country in the 1940s comprised smaller fires that were closer

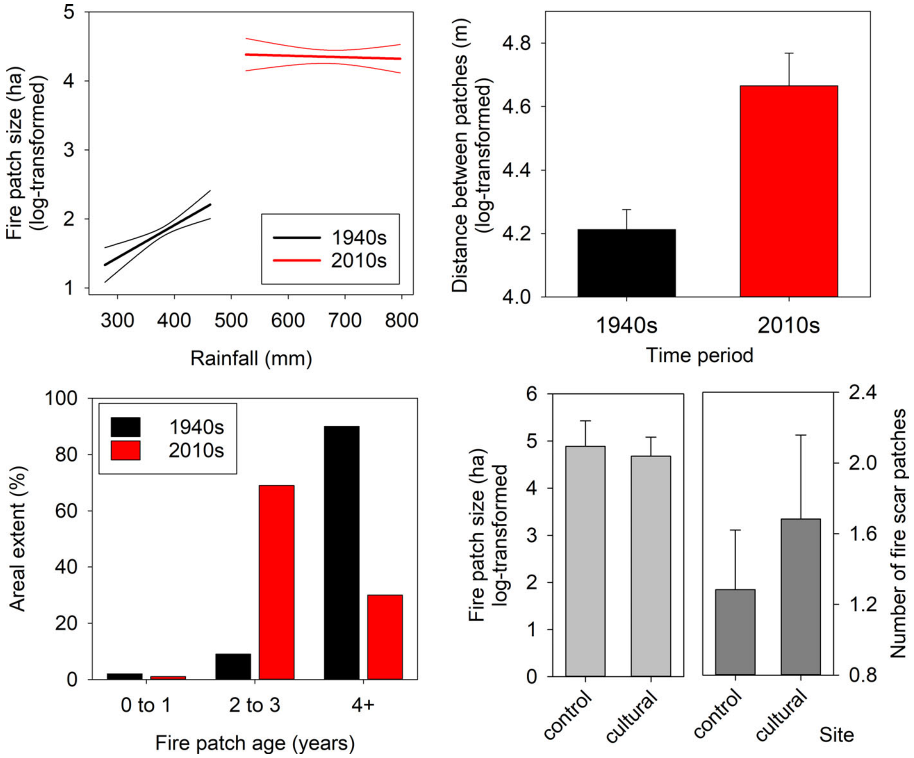

Figure 6. Fire pattern differences between the 1940s and contemporary times. (a) Fire patch size (transformed by natural log) against rainfall, for the 1940s and the contemporary periods; lines show data with the 95% confidence bounds. (b) Distance between neighbouring patches of the same age class (transformed by natural log), for the 1940s and contemporary periods; bars show means of data and their standard errors. (c) Areal extent (% of study area) of mapped fire patches of 0–1 year post fire (class 1), 2–3 years post fire (class 2) and 4+ years post fire (class 3 and unclassified, merged) from the 1940s and contemporary imagery. (d) Size (log-transformed) and count of class 1 and 2 fire patches from the 1940s within or intersecting a 1-km radius sample area around cultural and control sites. Data for cultural and control sites are shown separately.

together than those in 2016–2020. Fire frequency was lower and the modal post-fire vegetation age was 4+ years, compared to 2–3 years in contemporary times. The differences in fire patch size and spacing were evident even after taking variation in rainfall into account, suggesting that Traditional Owners were influencing landscape-scale fire patterns in the 1940s. The 1940s imagery clearly shows areas with human ignition (Fig. 5), but the number and size of fire scars immediately around cultural sites did not clearly differ from those around random control points. Below, we discuss the change in fire patterns over 70 years and consider why fire patterns were not clearly different at cultural sites. Then, we discuss the implications of our study for contemporary fire management in the deserts.

Changes in fire regimes

The change in fire patterns in the Great Sandy Desert over 70 years is consistent with that reported for deserts to the south, by Burrows and Christensen (1990), Burrows *et al.* (2006), Bird *et al.* (2016, 2020) and Burrows and Chapman (2018). Specifically, Karajarri Traditional Owners created a fine-grained mosaic of many small fires across the landscape that has now been replaced by a larger grained mosaic of fewer, larger fires re-occurring at shorter intervals, with the effect of lowering the average post-fire vegetation age. An analysis of fire patterns from 2000 to 2019 on Karajarri IPA using MODIS imagery (Crowley 2019) showed that the fire frequency over this period was about once every 3 or 4 years, similar to the fire frequency we estimated here, using Sentinel imagery over a shorter period, of once every 3.9 years. In contrast, the fire frequency in the 1940s was once every 5.7 years. This suggests that the Karajarri fire practices in the 1940s caused fire intervals to lengthen, an outcome also documented by Bird *et al.* (2012) who suggested that by introducing many small fires, people reduced the extent of large wildfires, and thus lowered the overall amount of fire in the landscape.

Other factors may have influenced fire pattern changes from the 1940s to now. For example, populations of feral herbivores (cattle, camels) may have increased, with their grazing reducing overall fuel loads (Liedloff *et al.* 2001). If this was the case, fire pattern changes would be opposite to what we observed. Another influence on fire regimes is rainfall, which has increased over the past three or four decades in the northern deserts (Fig. 1b). We incorporated the antecedent rainfall into our analyses of fire patch size and spacing, but were unable to do so in the tabulation of areal extents of post-fire ages across the whole study area, because of the limited historical time series. It is possible that the dominance of post-fire vegetation in the 2- to 3-year class in contemporary times was partly driven by high rainfall in the 2017–2018 wet season, which led to increased fire extents in the 2018 season.

Our results suggest that rainfall affected components of the fire regime differently in the 1940s versus today. During the 1940s, patch size was larger and the inter-patch distance was smaller in higher rainfall areas nearer the coast. This pattern disappears, or is slightly reversed, in the contemporary period. This change may be due to a spatial shift in human activity: people are now concentrated near the coast, in Bidyadanga, the outstations and on the pastoral leases. These areas likely experience more intensive prescribed burning and fire suppression activities (Edwards *et al.* 2008). Conversely, large wildfires are more able to spread across the remote desert regions (Vaarzon-Morel & Gabrys 2009).

Both the historical and the contemporary imagery were taken after a decade of fairly average rainfall (although the average rainfall in the more recent decade was higher). It remains unclear whether the seral mosaic present in the 1940s would inhibit the spread of wildfires following extensive, heavy rainfall events, such as that experienced in 2010-11. To resolve this issue on Karajarri Country, we would need to examine historical fire patterns immediately after extensive rain, but aerial photography was conducted infrequently in the 1940s and 1950s, and there is no imagery of this desert landscape, after rain, during the period when Karajarri Traditional Owners were still on Country. Instead, it may be better to focus on whether Karajarri's contemporary fire management limits the spread of large wildfires after substantial rain (Burrows *et al*. 2013; Paltridge *et al*. 2020).

Fire regimes at cultural sites

Fire scar patches around cultural sites tended to be smaller and more numerous than around random control points, but the differences were not significant, suggesting that burning activities were not intensively concentrated around cultural sites. However, the analysis had several limitations. First, our cultural site mapping is incomplete, meaning that some control points could have been close to unmapped cultural sites. Second, the locations of some cultural sites are approximate, and up to several km off. Finally, while fire may have been used at some cultural sites often, it may have been rarely used at other sites. Knowledge about the intensity of use of each site is limited in living memories (Karajarri, pers comm), but our study may help improve the documented evidence about cultural sites:

> *We can show this map to our old people, and where there was a lot of burning in the past, we can see if they can remember anything about these places. J. Shovellor, Traditional Owner, Head Woman Ranger*

Implications for management

Our study suggests that desert fire regimes, at least during periods of average rainfall, have changed since European colonisation. To investigate the influence of these changes on biodiversity, Karajarri are undertaking a biodiversity monitoring program to measure the outcomes of their fire management (Karajarri Rangers et al. 2021)

Our study supports Karajarri's fire management by describing traditional fire patterns that Rangers want to aim for. For example:

> *When I first saw those old photographs, I thought those old people probably did a better job, because they were on foot, they used to live out in the desert and walked, lighting fires that broke up the Country. The photographs are showing me how they used to burn smaller areas . . . to break up the Country. Braedon Taylor, Traditional Owner, Ranger Coordinator*

This study encourages us to combine landscape-scale with local-scale management approaches. Aerial incendiary could be used over most of the IPA, but at smaller trial areas, on-ground burning could aim to produce a finer-scaled mix of seral stages. The trial areas could be places with important plants and animals, cultural sites or places of high intensity use evident from the 1940s imagery (Fig. 4a). The relative performance of the management scales for inhibiting wildfire spread could be evaluated with high-resolution satellite imagery, and with our existing field surveys used to monitor the response of plants and animals.

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Supporting Information

Additional supporting information can be found in the following online files.
Appendix S1. Methods.