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Research article

Right-way fire in Australia's spinifex deserts: An approach for measuring management success when fire activity varies substantially through space and time

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ABSTRACT

Indigenous Australians used fire in spinifex deserts for millennia. These practices mostly ceased following European colonisation, but many contemporary Indigenous groups seek to restore 'right-way fire' practices, to meet inter-related social, economic, cultural and biodiversity objectives. However, measuring and reporting on the fire pattern outcomes of management is challenging, because the spatio-temporal patterns of right-way fire are not clearly defined, and because spatio-temporal variability in rainfall makes fire occurrence highly variable in these desert environments. We present an approach for measuring and reporting on fire management outcomes to account for spatio-temporal rainfall variability. The purpose is to support Indigenous groups to assess performance against their management targets, and lay the groundwork for developing an accredited method for valuing combined social, cultural and biodiversity outcomes. We reviewed fire management plans of desert Indigenous groups to identify spatial fire pattern indicators for right-way fire in spinifex deserts. We integrated annual rainfall surfaces with time-since fire mapping (using Landsat imagery) to create a new spatial dataset of accumulated rainfall-since-last-fire, that better represents post-fire vegetation recovery as categorised by local Indigenous people. The fire pattern indicators were merged into a single score using an environmental accounting approach. To strengthen interpretation, we developed an approach for identifying a control area with matching vegetation and fire history, up to the point of management. We applied these methods to a 125,000 ha case study area: Durba Hills, managed by the Martu people of Western Australia. Using a 20-year time series, we show that since right-way fire management at Durba Hills was re-introduced (2009), the fire pattern indicators have improved compared to those in the matched control area, and the composite result is closer to the fine-scaled mosaic of right-way fire pattern targets. Our approach could be used by Indigenous groups to track performance, and inform annual fire management planning. As the indicators are standardised for rainfall variation, results from multiple sites can be aggregated to track changes in performance at larger scales. Finally, our approach could be adapted for other fire-prone areas, both in Australia and internationally with high spatio-temporal rainfall variability, to improve management planning and evaluation.

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1. Introduction

Australia is the world's driest inhabited continent, with over 70% of the land area classed as desert (Stafford Smith and Morton, 1990). The Australian deserts are the most sparsely populated of global deserts (UNEP, 2006), yet include one of the largest networks of Indigenous-managed land in the world, harbouring a high proportion of Australia's biodiversity (Renwick et al. 2017; Garnett et al. 2018; O'Bryan et al. 2021). Supporting Indigenous-led management is critical for social, economic and biodiversity outcomes in these landscapes (Davies and Holcombe, 2009; Campbell, 2011; United Nations, 2015; Garnett et al. 2018).

Within Australian deserts, spinifex grasslands are the most extensive vegetation formation (Allan et al., 2002). Spinifex grasslands experience high rates of fire disturbance (~3–30 years), because spinifex is volatile, perennial, and decomposes at very slow rates (Allan et al., 2002). Spinifex biomass, and thus fire occurrence, is closely related to accumulated rainfall since the last fire (Turner et al. 2008; Nano et al. 2012). Desert fire ignitions arise from lightning strike or, in more recent evolutionary time, from people (Edwards et al. 2008).

For thousands of years, Indigenous peoples of Australia's desert country applied fire to the landscape for a variety of purposes including ceremony, signalling, hunting, and to promote certain plant food resources (Gould, 1971; Kimber, 1983; Burrows and Christensen, 1990; Pike, 2008). Following European colonisation, Indigenous people moved into missions, settled communities and regional centres. The depopulation of the deserts resulted in a shift in fire patterns, from a fine-scaled seral mosaic created by multiple anthropogenic ignitions, to a wildfire-dominated regime of extensive, high severity fires (Allan et al., 2002; Burrows et al. 2006; Bliege Bird et al. 2018; Blackwood et al. 2021; Greenwood et al. 2022). Fire patterns caused by traditional practices were probably more pronounced in some areas and habitats, especially those used more intensively by people, and probably less evident after very heavy, extended rainfall that occurs infrequently in Australian deserts (Kimber and Friedel, 2015; Wright et al. 2021).

Altered fire regimes in Australian deserts are implicated in the contemporaneous declines of many plant, bird, and reptile species (Allan et al., 2002; Ward et al. 2014; Moore et al. 2015; Murphy et al. 2018). The most profound declines occurred in small to medium-sized mammals: approximately 60% of desert mammal species have become extinct in the past 250 years, and the distributional ranges of many other species have been reduced (Woinarski et al. 2015). The shift from fine-scale fire mosaics to a wildfire-dominated system may have reduced habitat quality for some species, and increased the vulnerability of ground-dwelling mammals (and other taxa) to predation by introduced cats (*Felis catus*) and foxes (*Vulpes vulpes*) (Short and Turner, 1994; Leahy et al. 2016). Indigenous people identify the loss of traditional fire practices as a key factor in biodiversity decline (e.g. Burrows et al. 2004), and consider that reinstating these practices is fundamental to improving cultural and environmental health (see Table S1).

Over the past 20 years, the economic, social, cultural and biodiversity benefits of reinvigorating traditional land management, including burning practices, have been more widely realised (Social Ventures Australia, 2016; Leiper et al. 2018; Paltridge et al. 2020; Robinson et al. 2020). For example, since 2007, the Australian and State Governments have funded Indigenous Rangers to deliver integrated cultural and conservation management, including fire management, on various conservation-designated areas including Indigenous Protected Areas (Putnis et al. 2021). Such management is guided by 'Healthy Country Plans' or equivalent planning documents, with objectives that combine social, cultural and biodiversity values articulated by the Indigenous landholders. Fire management objectives typically aim to restore right-way fire, or the fire patterns characteristic of the pre-European traditional fire practices, with related biodiversity and cultural benefits.

Fire management across Indigenous-managed land in the tropical savannas of northern Australia has been substantially supplemented by access to the carbon markets, because managed fire results in avoided greenhouse gas emissions that can be traded as carbon credits (Russell-Smith et al. 2009b; Ansell and Evans, 2019). This opportunity has greatly transformed the scale and complexity of management delivery, and the sophistication of management evaluation and reporting (Edwards et al. 2021). The same opportunity to use avoided emissions to support more fire management is not currently available to desert Indigenous groups. Desert average rainfall, and thus fire activity, is much lower, with lower emissions abatement possible. More importantly, rainfall is highly variable across time and space (Van Etten, 2009), which means that fire activity and abatement potential are also highly temporally and spatially variable (Edwards et al. 2008), and standardising annual outcome evaluation is more difficult than it is in the tropics (Russell-Smith et al. 2009a). However, there is still scope to develop approaches to measuring fire management outcomes, and potentially combine these with cultural, biodiversity and other co-benefits, for voluntary national and international markets (reference correction).

In this study, we present a method to measure whether fire management in spinifex deserts is achieving the spatial fire pattern targets of right-way fire as commonly described by desert Healthy Country Plans. In developing a framework to evaluate whether these targets are being met, we also seek to 1) address the challenge of standardising reporting when rainfall has high temporal and spatial variability, by creating fire pattern indicators that are based on accumulated rainfall since the last fire at any location rather than time since fire; and 2) integrate multiple fire pattern indicators into a single value, using an environmental accounting approach developed by Accounting for Nature (Steinfeld and Cosier, 2018). The purpose of this study is to support Indigenous groups to evaluate the success of their management and report against goals in Healthy Country Plans and equivalent documents. The approach could also be incorporated into the calculation of a combined cultural-biodiversity, or 'Healthy Country Credit', for transactions in voluntary markets for integrated social, cultural and biodiversity outcomes (Garnett et al. 2009; 10 10 Deserts, 2021).

2. Methods

2.1. Study area

Spinifex grasslands are the dominant vegetation group in the Australian deserts (≫75% of the combined area of the Great Victoria, Great Sandy, Little Sandy, Gibson, Simpson, Strzelecki, and Tanami Deserts (Thackway and Cresswell, 1995). Annual rainfall averages 550 mm in the north (defined as north of 27° parallel) to 250 mm in the south; rainfall in the north mostly falls in the warmer months (December to March) (Van Etten, 2009).

2.2. Durba Hills case study area

We applied our method to a case study area: Durba Hills, in the Little Sandy Desert of Western Australia (Fig. 1). This region is comprised of red dune-fields with outcrops of sandstone, and is dominated by spinifex grasslands. The annual rainfall averages 260 mm, falling mostly in summer between December and March (Bureau of Meteorology, Marymia, weather station ID 7180; 120.01°E, 25.04°S, 1974–2020). Interannual rainfall variability is high (10–90% range: 146–435 mm). The Durba Hills fire management zone is a circular area of 20 km radius (125,000 ha); 85% of its extent consists of spinifex grasslands. A control area, matched for vegetation and fire history, was identified 197 km away (from centre to centre; see below for description of control area selection).

Durba Hills and surrounding areas have special cultural significance for the Martu people. Kanyirninpa Jukurrpa (KJ) is a Martu organisation working to support Martu culture and heritage, build sustainable communities and provide healthy pathways for their young people (htt

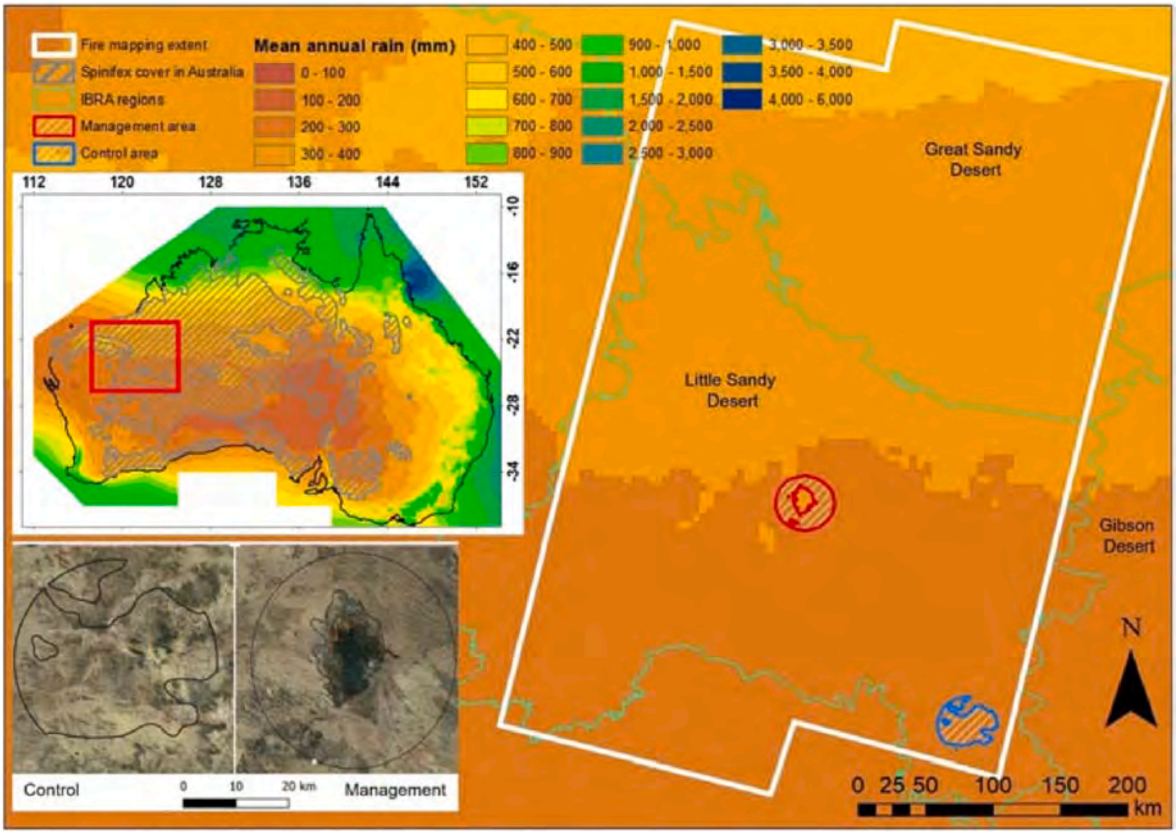

Fig. 1. Location of the Durba Hills fire management zone and the control area within the Little Sandy Desert in Western Australia (WA). The white outline shows the extent of the Landsat imagery used for fire mapping purposes (1997–2019), and cyan lines show the bioregional boundaries of the Interim Biogeographic Regionalisation for Australia (Thackway and Cresswell 1995). The map of the Australian mainland shows rainfall isohyets (Bureau of Meteorology, http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp), spinifex cover in Australia (adapted from Reid and Hill, 2013), and the zoomed-in extent (in red outline). Map at the bottom left shows the fire management zone and the control area. The interior areas delineated in black within the 20 km radius circles were not included in the study as they are not classed as spinifex grasslands.

ps://www.kj.org.au/). Since 2009, KJ (specifically the Jigalong Ranger team) have led fire management operations in the Durba Hills area. During the cold months (June–August) rangers use aerial incendiaries, drip torches and fire sticks to selectively burn country, with the goals of protecting people, infrastructure and cultural sites, and enhancing habitat conditions for native species (e.g. a reintroduced population of the nationally Endangered Black-flanked Rock-wallaby (*Petrogale lateralis lateralis*) and the nationally Vulnerable Greater Bilby (*Macrotis lagotis*)).

2.3. Vegetation mapping

The spatial extent of spinifex grasslands in Western Australia has been mapped by the Department of Biodiversity, Conservation and Attractions (DBCA, Government of Western Australia). It is based on 1:3,000,000 pre-European vegetation mapping (Beard et al. 2013) comprising eight Vegetation groups (details in Supplementary Information), clipped to red soils.

2.4. Fire scar mapping

To map annual fire scars from 1997 to 2019, Landsat imagery was used covering six adjacent scenes of the western deserts (335 km by 560 km), downloaded from the United States Geological Survey (https://earthexplorer.usgs.gov/) and further corrected to top-of-atmosphere using coefficients in the image report file, scene parameters and pixel-based values such as solar zenith (https://ieeexplore.ieee.org/document/978120). Fire scar mapping was conducted by the Remote Sensing and Spatial Analysis division at DBCA. Fire scars were mapped by creating annual difference images, comparing images taken in late March-early April of two consecutive years, with the exact date of images depending on cloud-free imagery availability. Burnt areas were identified through the Normalized Burn Ratio index (NBR = (Near Infrared – Short wave Infrared)/(Near Infrared + Short wave Infrared) (Key and Benson, 1999), and the near infrared band (dB4 = Band 4 in Landsat 5 and 7). Difference images (dNBR and dB4) were segmented through an object-based image analysis process using eCognition software (Trimble Germany GmbH). The mean dNBR or dB4 difference value per segment was used to classify areas of change through a threshold value manually set for each fire, which were selected and exported. This fire mapping method has been shown to have low omission errors (where a burnt area is mapped as unburned, around 3% on average) and low commission errors (where an unburnt area is mapped as burned, around 8% on average) in desert environments, when compared to 10 m resolution Sentinel-2 fire scars, in contrast with large omission errors observed for MODIS-derived fire scars (Ruscalleda-Alvarez et al. 2021). Landsat spatial resolution enables detection of fires as small as one pixel (900 m^2). Imagery was available for all years except 2007.

2.5. Rainfall data

Daily rainfall data were downloaded from the European Centre for Medium-Range Weather Forecasts (https://cds.climate.copernicus.eu/). Specifically, we used the *ERA5-Land hourly data from 1981 to present* dataset (with 10 km ground resolution), covering the same area as fire scar mapping extent. Data were processed in the R environment (R Development Core Team, 2020) to generate annual rainfall layers to match the fire scar data timing, so that annual rainfall layers covered the period from April 1st to March 31st of the following year. We used April to March rather than January to December so that the rainfall for the year (which falls mostly from December to March) falls after the fires for that year (which occur mostly from April to December. All rainfall layers were resampled to match the fire scar spatial resolution and stacked in single raster files.

2.6. Rainfall since last burn (RSLB)

Fires occur when spinifex cover has increased sufficiently that fires can carry between adjacent, free-standing hummocks (noting that fire can also occur when heavy rain stimulates a ground cover of annual grasses that carries fire between spinifex hummocks even if these are widely spaced, but this occurs infrequently) (Allan et al., 2002; Burrows et al. 2018; Verhoeven et al. 2020). Multiple studies, across a range of locations with large differences in average rainfall, have shown that

Table 1
Seral stages, what they represent in terms of vegetation recovery, and what they correspond to in terms of fire spread behaviour, the approximate time-since-fire, and accumulated rainfall. This information is based on discussions with Martu and other Indigenous groups, and on accounts in Bliege-Bird et al. (2018) and Southgate and Carthew (2007). The classifications were ground-truthed at five sites where accumulated rainfall and time-since-fire information were available (Yilka, Kuduarra in Ngurrura Country; Uluru; Yilpi and Kulgara on Karajarri Country; see Table S2 for sample photographs).

Seral stage	Description of vegetation; and fire spread	Time-since-fire (years)	Accumulated rainfall (mm)
	Recently burnt areas, no plant biomass or very little. Unable to carry fire.	Weeks to 1 year (although can be longer)	0–300 mm
	Plants beginning to recover. Unable to carry fire.	1–3 years	300–600 mm
	Forbs and small shrubs producing fruit/flowers, some grasses seeding. Unlikely to carry fire.	3–5 years	600–1200 mm
	Spinifex beginning to dominate, with larger shrubs. Can carry fire, but hot windy conditions needed at the lower end of accumulated rainfall.	5–10 years	1200–2400 mm
	Mature and long-unburnt spinifex, spinifex begins to senesce, or is senescing, in the middle of hummock. Fire spreads very easily.	>8 years	>2400 mm

spinifex cover depends on the accumulated rainfall since the last fire, and that biomass attrition between rainfall events is minimal. The area that burns is therefore also closely related to the accumulated rainfall (Allan et al., 2002; Southgate and Carthew, 2007; Turner et al. 2008; Nano et al. 2012; Burrows et al. 2018). We checked this relationship by ground-truthing spinifex recovery versus accumulated rainfall at five sites with contrasting average rainfall totals in the northern and north-western deserts (see Table 1, and Table S2 for sample photographs). Since rainfall in deserts is spatially and temporally variable, time-since-fire can be a poor proxy for describing post-fire seral stages, especially if working across large areas (Fig. S1). Therefore, we developed new spatial layers based on accumulated *rainfall since last burn* (RSLB), by integrating fire scar and rainfall datasets.

We first generated a *years-since-last-burn* (YSLB) raster for each year of the study, with each pixel (in each annual layer) attributed with the number of years since it last burnt. Unburnt areas were assigned the same age as the oldest burnt areas. For each annual YSLB layer, we then created a mask for each time since fire age. From the stack of annual rainfall rasters, we selected layers (years) to correspond to each time since fire, and calculated the accumulated rainfall for that period, for each raster cell. The mask from the YSLB raster was used to crop the accumulated rainfall layer. This raster layer was exported and subsequently merged with the other accumulated rainfall layers for each time since fire class in that YSLB layer, to generate a rainfall since last burn (RSLB) layer for each year in the study (Fig. 2). A step-by-step description of the method for generating the YSLB layers is provided in the SM, and the R code to carry out this process automatically is available from the Indigenous Desert Alliance.

We then categorised the RSLB data to align with five stages of spinifex recovery post-fire, corresponding to categories commonly used by Indigenous groups of the western and north-western deserts, including Martu (Table 1). The categories were identified during discussions with rangers and Traditional Owners, then ground-truthed at five sites with varying annual rainfall averages, where accumulated rainfall and time-since-fire information were available (Yilka, Kuduarra in Ngurrura County; Uluru; Yilpi and Kulgara on Karajarri Country). The composite RSLB map is analogous to a traditional 'time-since-fire' map, but more closely represents the recovery of spinifex grasslands, and the capacity of spinifex to carry fire.

2.7. Fire pattern indicators

We reviewed management plans of 20 desert groups to derive a description for right-way (and wrong-way) fire patterns, and to identify the values that fire management aimed to protect (Table S1). These typically include interlinked cultural and knowledge transfer, bush tucker and medicine, and biodiversity values. Right-way fire is most consistently described as small fires of varying intensity every year, resulting in a fine-scale mosaic of spinifex at different seral stages, and including mature and long-unburnt spinifex. Conversely, wrong-way fire is characterised by extensive, high intensity fire, a landscape lacking seral heterogeneity at a fine scale, and lacking mature and long-unburnt vegetation. We specified a suite of spatial indicators that would collectively show a shift from wrong-way fire (a wildfire-dominated fire regime) to right-way fire (a managed fire regime). The selection of spatial indicators was also justified by links between them and biodiversity outcomes as evidenced in the scientific literature (Table S3). The fire pattern indicators, and their method of calculation, are shown in Table 2.

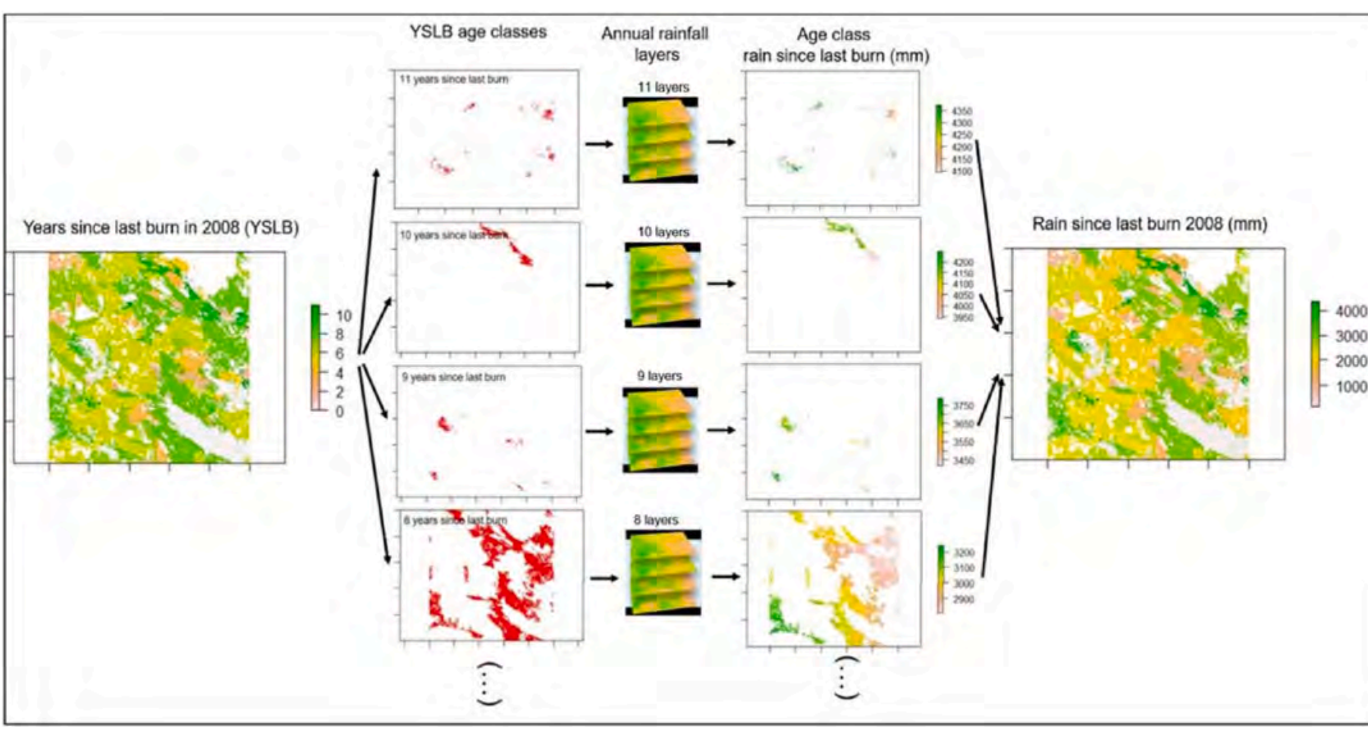

Fig. 2. Process followed to generate a *rain since last burn* (RSLB) layer for 2008 (as an example of what was done for each year of the study). For legibility, only four of the 11 layers needed (from 1997 to 2008) are included in this figure (hence the (…) symbol in the lower part of the figure).

Table 2
Right-way fire, as described in Indigenous management plans, and as represented by spatial fire pattern indicators, with their method of calculation. Reference condition values for each fire pattern indicator, showing the direction that management aims to shift the indicator towards, are given in the final column. These are based either on values from studies of traditional fire practices reported in the literature, or with reference to the baseline data.

Descriptions of right-way fire in Indigenous management plans (from Table S1)	Fire pattern indicator and method of calculation	Reference condition value
Recently burnt patch size and area		
Right-way fire: • Many, small fires, of varying intensity. Wrong-way fire: • Few, but large, high intensity fires.	**Patch size** (median; ha) Median area of all recently burnt patches, in the RSLB category of <600 mm. Median is used as patch sizes have a skewed distribution. **Recently burnt area** (% of study area) Proportion of study area in the RSLB category of <600 mm (area with <600 mm within spinifex grasslands divided by total extent of spinifex grassland within each area; <600 mm is ¬ <2 years since fire).	4.9 ha average of medians from six studies: (Burrows et al. 1991, 2006; Bird et al. 2005; Burrows and Chapman, 2018; Bliege Bird et al. 2020; Blackwood et al. 2021). 5% No published evidence available to set reference value. Given the paucity of data on this indicator, we set a reference value that signifies an improvement over baseline, which is half of the average values from the management zone and control area in the baseline period (2004–08).
Availability of unburnt habitat		
Right-way fire: • Protect mature and long-unburnt areas and fire-sensitive plants and animal species. Wrong-way fire: • Mature and long-unburnt habitat is rare; fire sensitive species and communities burnt.	**Area of mature and long-unburnt vegetation** (% of study area) Proportion of the area in the RSLB category of >2400 mm (area with >2400 mm within spinifex grasslands divided by total extent of spinifex grassland within each area; >2400 mm is ~>8 years since fire).	66% No published evidence available to set reference value. Given the paucity of data on this indicator, we set a reference value that signifies an improvement over baseline, by doubling the average values from the management zone and control area in the baseline period (2004–08).
Right-way fire: • If fires are small, unburnt habitat is always nearby. Wrong-way fire: • Fires are large and intense leaving no unburned vegetation across big areas.	**Mean distance to unburnt habitat** (m) Average value of pixel-based distance between all recently burnt areas (i.e., patch with RSLF <600 mm) and a patch of unburnt vegetation of at least 10 ha (where unburnt is defined as >1200 mm of accumulated rain). Buffers of 20 km were added to the perimeters of the management zone and control areas, because the nearest unburnt areas could lie outside these areas (R package *raster*, function *distance*).	154 m No published evidence available to set reference value. We therefore set a reference value that signifies an improvement over the baseline years by calculating the minimum of all values recorded during 2004–08 in both the management zone and control area and reducing this by 25%.
Heterogeneity (pyrodiversity)		
Right-way fire: • A fine-scale mosaic of vegetation at different seral stages. Wrong-way fire: • Extensive areas of vegetation of the same seral stage.	**Edge density** (m/ha) Higher edge densities are expected from fine-scale application of planned fire. Density (length per unit area) of edge or boundary between any 2 different RSLB categories within the study area (R package landscapemetrics, function lsm_l_ed). **Fire Mosaic Index** (%) The number of RLSB categories in each 5 km by 5 km grid cell is calculated. The indicator is the % of grid cells where the most recently burnt (0–300 mm), the mature (>2400 mm) and at least one intermediate RLSB category are all present.	26 m/ha No published evidence available to set reference value. We therefore set a reference value that signifies an improvement over the baseline years by finding the maximum of all values recorded during 2004–08 in both the management zone and control area, and increasing this by 25%. 53% No published evidence available to set reference value. Given the paucity of data on this indicator, we set a reference value that signifies an improvement over baseline, by doubling the maximum value from the management zone and control area in the baseline period (2004–08). A 5 km by 5 km cell size was chosen to align with observations of movements by small mammal and reptile fauna (of a few hundred meters to several km), over days to weeks (Dickman et al. 1995; Letnic, 2001; Koertner et al. 2007; Cross et al. 2020; Riley, 2020). To explore the effect of varying the scale of the Index, we calculated the indicator for 2019 using different grid resolutions (1 km, 2 km, 10 km) (Fig. S2; Table S4).

2.8. Integrating the fire indicators into an environmental account

The fire pattern indicators are co-correlated (Fig. S3). For example, as the number of fires in a given area increases, their size reduces, the edge density increases, the distance from burnt to unburnt habitat decreases, and the fire mosaic index increases. We therefore integrated the indicators into a single reporting tool using an existing framework for environmental accounts. The *Accounting for Nature* (AfN) framework guides the development of robust methods for measuring the condition of 'environmental assets', as estimated by a single value, called the Econd™ (Steinfeld and Cosier, 2018). The Econd™ is an index between 0 and 100, where 100 describes the 'ideal' reference condition of the environmental asset; the current value of the asset is measured against that reference condition. Econds™ can be calculated based on combining multiple indicators, each with their own reference condition, into a single index value. Projects registered under the AfN scheme can produce an accredited environmental account that is subject to an independent audit and verification process, to track changes in an Econd™ value through time, and potentially also to a counterfactual value. In our study, most simply, the environmental asset is the spinifex grasslands, and the indicators are the fire pattern indicators.

In the case of one indicator (fire patch size), we used evidence from the literature to set the reference condition values that approximates right-way fire patterns (Table 2). For other indicators, reference values were not available in the literature, so we used the values available in the imagery baseline time series (2004–2008) to set directional targets that would represent improvements in those indicators (Table 2). This comparison of each indicator with a reference value resulted in an indicator condition score value from 0 to 100 for all indicators, representing the similarity of the observed value to the reference value. For all observed indicators listed in Table 2, indicator condition scores are calculated as shown in Table 3where ICS stands for Indicator Condition Score. In years where no fires were recorded for a particular area, the *median fire area* was set as zero, and the *mean distance to unburnt habitat* was set as the value from the previous year.

Table 3

Formulas for the calculation of indicator condition scores for each fire pattern indicator. OBS is the measured metric, and REF is the reference value. The scores indicate how close the indicator value is to the reference value. When management aims to reduce the indicator (i.e. patch size, recently burnt area, distance to unburnt), the scores are calculated with reference to maximum indicator values for the time series (rather than the reference value), to generate appropriate relationships between the indicator values and scores (Fig. S4).

Econd" = average (ICSNumber of Fires + ICSFire size + ICSEdge Density + ICSMature habitat area + ICSMean dist.10ha + ICSFire Mosaic Index)

Indicator	Indicator condition score (all values multiplied by 100)
Median patch size (ha)	1-abs((ln(OBS)-ln(REF))/7.9) (where 7.9 is the ln_max value from any year over the time series)
Recently burnt area (%)	1-abs(OBS-REF)/50) (where 50 is the max value from any year over the time series)
Mature and long unburnt area (%)	1-(abs(OBS-REF)/REF)
Mean distance to 10 ha of unburnt habitat (m)	1-(abs((ln(OBS)-ln(REF))/800) (where 800 is the max value from any year over the time series)
Edge density (m/ha)	1-abs(OBS-REF)/REF
Fire Mosaic Index (%)	1-abs(OBS-REF)/REF

Indicator condition scores are then averaged to create a single value between 0 and 100:

2.9. Examining change in indicators at the case study area

We used a BACI (Before-After, Control-Impact) approach to examine indicator changes. The Durba Hills fire management zone is circular, with radius 20 km. We identified a same-sized (20 km radius) control area with similar vegetation and fire history characteristics to the fire management zone. We generated a RLSB category distribution (in the form of a histogram) for every possible 20 km radius circular area, with centres placed in a 2 km by 2 km grid of points, and selected the 20 km radius area (with a spinifex grassland cover of at least 70%) with a RSLB distribution that most closely matched that of the Management Zone at the end of the baseline period. The identified control area, where fire is unmanaged, is 197 km SE (measured from centre to centre of the two zones) from the Durba Hills fire management zone. Although here we selected the control area based on RSLB distribution match alone, it would be possible to include other factors to guide the selection of the control area from the best candidate set, such as proximity to the management zone, access, topographical and ecological features. Annual values for all indicators were compiled for the fire management zone and the control zone, for the years 2004–19 (with years defined as Apr to Mar), with annual values up to and including 2008 assigned as baseline, and from 2009 on as management. We used indicator scores from 2004 onwards, because three indicators (the fire mosaic index, the extent of mature and long-unburnt spinifex, and the density of edges between seral stages), need a minimum mapping time series of ~8 years to derive values.

3. Results

In 2008, the spatial arrangement of different rain since last burn

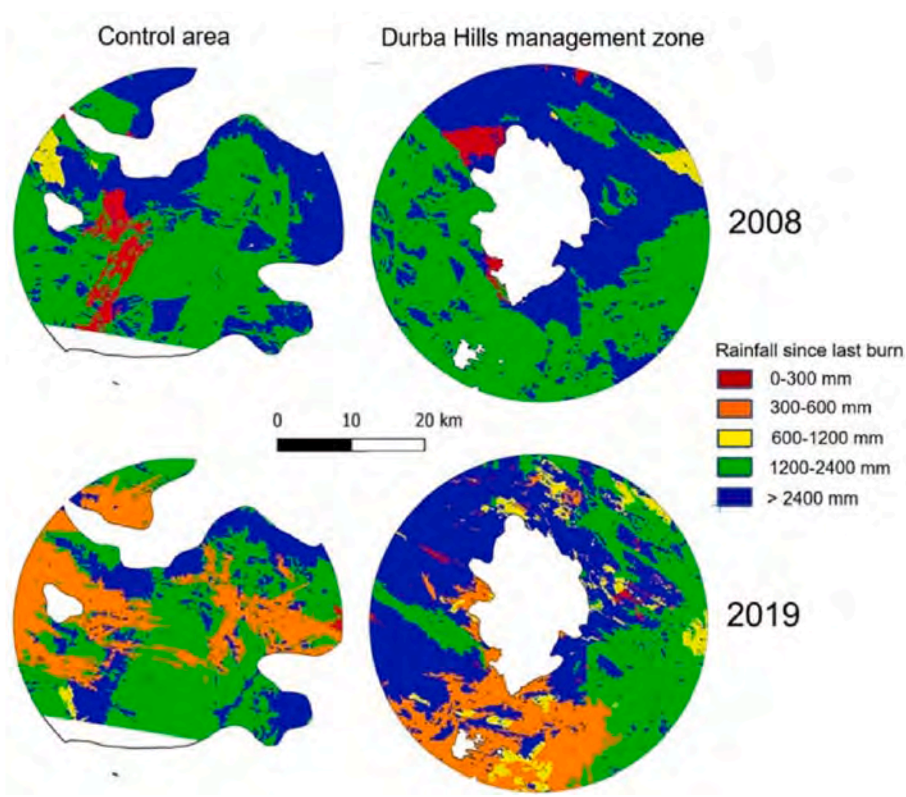

Fig. 3. Spatial distribution of rain since last burn (RSLB) categories in 2008 (before management) and in 2019 (after 10 years of management) in the Durba Hills fire management zone (right) and in the selected control area (left).

(RSLB) categories in the management zone and control area was similar (Fig. 3). In 2019, after 10 years of fire management, the management area shows a finer-scaled patterning of RSLB categories, particularly in the north-eastern part, where most fire management action has focused (D. Johanson, former KJ Fire Officer, pers. comm.). There are still large areas of long unburnt spinifex in the western sector, where some recent prescribed burns (thin and long linear fire scars) can be observed.

From 2009 when management began, the fire pattern indicators moved closer to the reference values in the management zone, whilst the values in the control area did not consistently improve (Fig. 4). In the

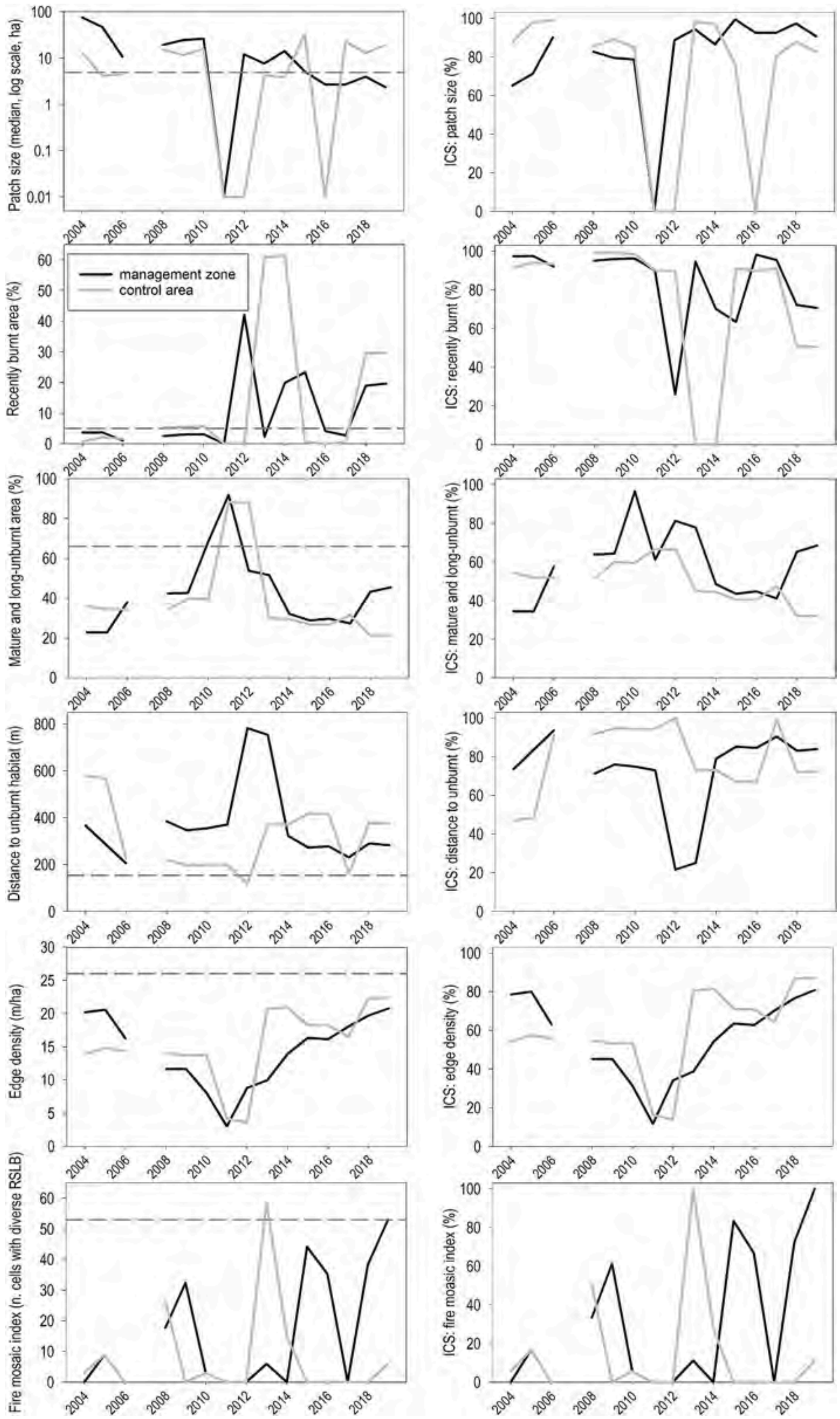

Fig. 4. Change in the raw indicator values and corresponding indicator condition scores for all fire pattern indicators explored in this study, from 2004 to 2019, in the Durba Hills fire management zone and the control area. Grey dashed lines on the indicator raw value plots show the reference values. Note logarithmic scale on the y-axis of the patch size indicator raw value. No data available for 2007.

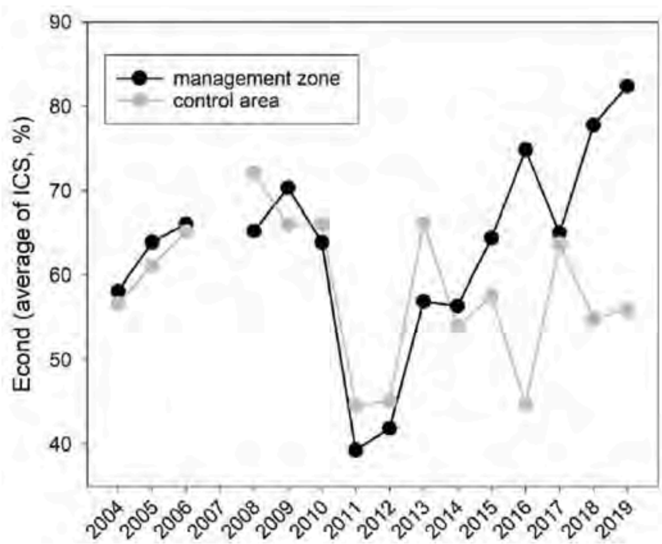

Fig. 5. Change of Econd™ values from 2004 to 2019, in the Durba Hills fire management zone and the control area. No data available for 2007.

management zone, the edge density, area of mature spinifex and the fire mosaic index all increased towards their reference values, while the median patch size and the distance to unburnt habitat decreased towards their reference values. The area of recently burnt spinifex appears to be stabilising nearer to the reference condition. In 2012 a very large, fragmented wildfire burnt through the control area, improving indicators such as edge density and the fire mosaic index for two subsequent years, but at the expense of other indictors especially the areas of recently burnt, and of mature spinifex. The relationship between raw values and scores for each indicator is available in Fig. S4.

The Econd™ score (average of six fire pattern indicator condition scores) improved in the management zone from 2009, and especially so from 2015, coincident with an increase in prescribed burning effort including the introduction of aerial incendiary operations (G. Catt) (Fig. 5). The Econd™ value in the control area fluctuated from 2009 but without any improving trend. These results suggest that management successfully changed the fire pattern indicators over five years; continued monitoring will reveal if these differences are sustained.

4. Discussion

The goal of fire management in the spinifex desert by Indigenous groups is typically to reinstate traditional fire practices in order to maintain culture and knowledge, protect bush tucker and medicine, and restore biodiversity more broadly (Table S1). The specific fire pattern indicators of right-way fire are described in planning documents like Healthy Country Plans, and these indicators can be mapped, with varying confidence, onto biodiversity outcomes evidenced in the scientific literature (Table S3). We recognise that pre-European fire regimes probably varied through time and across space (Kimber and Friedel, 2015; Wright et al. 2021), and that any fire regime advantages some species and disadvantages others (Andersen et al. 2014). However, it is plausible that shifting the fire pattern in spinifex deserts towards the pre-European regime will benefit biodiversity (Table S3). Restoring traditional fire practices is of intense cultural importance to desert Indigenous groups, and supporting people to manage fire on Country has substantial social co-benefits (Social Ventures Australia, 2016). We therefore suggest that measuring changes in fire pattern indicators is a reasonable first step towards a more comprehensive reporting system that could include measuring biodiversity and cultural indicators directly.

The precedent of using annual fire pattern indicators based on time-since-fire for reporting, from Indigenous fire management in northern Australia (Ansell and Evans, 2019; Edwards et al. 2021), cannot be easily transplanted to the spinifex deserts, where rainfall is low and very variable across time and space (Van Etten, 2009), and intervals between fires consequently vary between 3 and 30 years (Allan et al., 2002). We developed an approach to calculating fire pattern indicators that integrates rainfall and fire, and that aligns with seral stage categorisations used by Indigenous groups. This approach provides a more meaningful and standardised way of comparing fire patterns over time and between areas. Below, we discuss this integrated fire-rainfall approach, the choice of fire pattern indicators and their reference values, and the advantages/disadvantages of using an environmental accounting approach for reporting.

4.1. Integrating rainfall and fire data

Previous studies have characterised fire spatial patterns in deserts based on time-since-fire (e.g. Bliege Bird et al. 2018; Ruscalleda-Alvarez et al. 2021). In water-limited, spinifex deserts, the occurrence of fire is closely linked to vegetation biomass, which is itself closely linked to accumulated rainfall since the last fire event (Southgate and Carthew, 2007; Turner et al. 2008; Nano et al. 2012). However, inter-annual variability in rainfall is higher in Australia's spinifex deserts than in most other deserts worldwide (Van Etten, 2009), making time-since-fire a poor proxy for biomass gain. By using increments of accumulated rainfall rather than calendar time to define seral stages, we aimed to enable more standardised comparisons over time and across space. With this approach, the fire management outcomes after a low rainfall year can be compared more fairly with outcomes after a high rainfall year. At our study area, although the mean annual rainfall is 260 mm, the 10–90% range is 146–435 mm, a threefold difference. We further strengthened the approach by including a comparison between a fire-managed with a nearby, unmanaged area (control), where the control was selected to most closely match the management area in terms of fire patterns until the point where management began. As well as improving reporting on fire management outcomes, incorporating rainfall into time-since-fire informs annual fire management planning, such as the areal extent to aim for in prescribed burns, because it helps to predict when and where fires will next spread.

In principle, our integrated rainfall and fire data layer could be used across the entire extent of the spinifex deserts, with an average annual rainfall gradient of 250–550 mm. For example, our final rainfall category (>2400 mm) would take an average of 9.2 calendar years to accumulate at our case study area. At the northern extreme of the spinifex deserts, where the average annual rainfall is 600 mm, this final category could be reached in 4 years (which accords with the average fire return interval reported there, Blackwood et al. 2021). In contrast, the average annual rainfall in the Great Victoria Desert is 200 mm, and an accumulated total of 2400 mm would be reached in 12 years. We note that the interpolated rainfall surface used here is based on a limited number of weather stations across the deserts, but we consider incorporating rainfall into the firescar analysis represents an improvement over not using it at all.

We defined categories to align with the seral stages recognised by Indigenous people of the case study area, with three stages before an area will carry fire, and two stages after that point. We set thresholds of accumulated rainfall for these categories based on observations of rainfall, spinifex biomass and fire spread in north-western spinifex deserts, where rain mostly falls in the warmer months. The rainfall thresholds could be adjusted, but this is unlikely to make a substantive difference to the analysis, as the RSLB categories are a tool for looking at the distribution of seral stages across space and time in a consistent way, given rainfall variability. However, with increasing latitude, rainfall in the cooler months becomes increasingly likely (Larsen and Nicholls, 2009), which could mean that spinifex biomass gain is reduced and fire return intervals may be longer for the same accumulated rainfall (Nano et al. 2012). The accumulation of rainfall needed to allow fires to carry may also be greater if the distance between spinifex hummocks increases. Fire management programs in the southern spinifex deserts may therefore opt to use different accumulated rainfall categories. In addition, if programs are particularly interested in protecting very long unburnt spinifex, they may prefer to adapt the categorisations to allow them to measure changes in those later seral stages.

4.2. Fire pattern indictors and reference values

The goal of fire management as set out in management plans (Table S1) is to shift fire pattern from wrong-way fire (a wildfire-dominated system of extensive, intense fires) to right-way fire (a managed system with many smaller fires of variable intensity, and increased seral heterogeneity, including areas that have not burnt for many years). The specific fire pattern indicators most relevant to components of biodiversity are not always clear, but the extent and proximity of unburnt, especially mature and long-unburnt, vegetation is a recurring indicator of importance to some species (Table S3). Different projects may consider particular indicators more informative than others, and may prefer a specific indicator mix that differs from the one chosen here. Since fire pattern indicators tend to be correlated (Fig. S3, Edwards et al. 2021; Wysong et al. 2022), shuffling indicators should be acceptable, as long as the set includes indicators related to the extent of mature and long-unburnt vegetation, seral heterogeneity, and fire size and dispersion. Using a suite of indicators that covers these attributes is useful because idiosyncratic changes in any one indicator are somewhat dampened by changes in the other indicators.

The indicator condition scores were calculated in relation to a reference condition, which we aimed to set as the pre-European values for the indicators, or values closer to those fire patterns. We recognise that our knowledge of pre-European fire patterns is poor, but the reference condition functions as a benchmark against which to measure change, and can be revised if new data comes to light. The use of a control area with similar characteristics to the management zone prior to management also helps to isolate the effects of management on fire patterns. Note that if key data sources were changed, the reference condition values could need adjusting. For example, if lower resolution imagery were used to describe fire patterns, then the reference value for patch size used here, which is based on aerial photography, could be set well below the scale of the satellite imagery. Likewise, if higher resolution or more accurate rainfall datasets become available, then the time series of RSLB layers and fire pattern indicators should be reproduced, to avoid introducing indicator changes due to methodological change.

4.3. Environmental accounting

Environmental accounting is a structured, systematic way of organising data to track the change in value of the account subject or asset (e.g. a national park, an ecosystem or a measure of biodiversity) through time (Cosier, 2011). The environmental accounting approach used here has some advantages; first, it produces a simple, single value than can be readily used to communicate with Indigenous communities and external stakeholders whether the fire management is achieving spatial targets, and by proxy, cultural and biodiversity targets. Second, the environmental account is structured in a way that would make it easy to add (or subtract) other indicators, including direct measures of biodiversity change (e.g., from surveys), or of social and economic values, such as the number of people employed to deliver the fire management. Third, as the indicators are standardised for rainfall variation, changes in the environmental account of fire patterns in any one site can be aggregated with those from other sites. Ideally, biodiversity and cultural outcomes relevant to each site would also be measured directly, and combined with the fire pattern indicators. It should therefore be possible to develop a credit system of cultural and biodiversity outcomes that could be used to diversify funding streams, through sale in voluntary markets.

The environmental accounting approach we use here also has some potential disadvantages. In particular, reducing a complex fire pattern analysis to a single value means there is a risk of ignoring the detail and texture that lies under that figure, and which could provide important insight for understanding ecological changes to Country. It will be important to consider changes in the underlying fire pattern indicators carefully, without relying solely on changes in the final Econd™ value.

5. Conclusions

A consistent reporting approach for fire pattern outcomes from fire management in deserts has been challenging, because indicators of fire patterns that characterise right-way fire have not been defined; and because the high variability in rainfall, and thus fire intervals, across time and space have precluded a reporting approach that can be standardised. We selected fire pattern indicators that relate to descriptions of right-way fire shared across multiple desert Indigenous groups; then integrated rainfall into time-since-fire, and developed an approach to select a control area, so that comparisons in fire patterns across time and space can be more standardised. Our methods could be applied, with modification, to other fire-prone areas, in Australia or globally, with high spatio-temporal variability in rainfall, to improve annual reporting and to finesse annual fire management planning.

Author statement

JR-A: Conceptualization; Data curation; Formal analysis; original draft. HC: Conceptualization; Methodology; review and editing. GC: Conceptualization; Methodology; review and editing; supervision. JH: Conceptualization; Methodology; review and editing. AS: Methodology; review and editing. PS: Funding acquisition; Conceptualization; Methodology; review and editing; Supervision. NB: Conceptualization; Methodology; review and editing. RP: Conceptualization; Methodology; review and editing. JR-S: Conceptualization; Methodology; review and editing. SL: Conceptualization; Funding acquisition; Supervision; Methodology; original draft.

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.

Data availability

Code for processing spatial data is available from the Indigenous Desert Alliance

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117234.

References

10 Deserts, 2021. 10 Deserts Project: Healthy Country Credits. https://10deserts.org/wp-content/uploads/2021/04/202010-10DP-HCC-overview.pdf.

Allan, G., Southgate, R., 2002. Fire regimes in the spinifex landscapes of Australia. In: Bradstock, R., Williams, J., Gill, A. (Eds.), Flammable Australia: the Fire Regimes and Biodiversity of a Continent. Cambridge University Press, Cambridge, UK, pp. 145–176.

Andersen, A.N., Ribbons, R.R., Pettit, M., Parr, C.L., 2014. Burning for biodiversity: highly resilient ant communities respond only to strongly contrasting fire regimes in A ustralia's seasonal tropics. J. Appl. Ecol. 51, 1406–1413.

Ansell, J., Evans, J., 2019. Contemporary Aboriginal savanna burning projects in Arnhem Land: a regional description and analysis of the fire management aspirations of Traditional Owners. Int. J. Wildland Fire 29, 371–385.

Beard, J., Beeston, G., Harvey, J., Hopkins, A., Shepherd, D., 2013. The vegetation of Western Australia at the 1: 3,000,000 scale. Explanatory Memoir 9. *Conservation Science Western Australia*.

Bird, D.W., Bird, R.B., Parker, C.H., 2005. Aboriginal burning regimes and hunting strategies in Australia's Western Desert. Hum. Ecol. 33, 443–464.

Blackwood, E.M.J., Rangers, Karajarri, Bayley, S., Biljarni, H., Fensham, R., Lindsay, M., Noakes, E., Wemyss, J., Legge, S., 2021. Pirra Jungku: comparison of traditional and contemporary fire practices on Karajarri Country, Western Australia. Ecol. Manag. Restor. 23, 83–92.

Bliege Bird, R., Bird, D.W., Fernandez, L.E., Taylor, N., Taylor, W., Nimmo, D., 2018. Aboriginal burning promotes fine-scale pyrodiversity and native predators in Australia's Western Desert. Biol. Conserv. 219, 110–118.

Bliege Bird, R., McGuire, C., Bird, D.W., Price, M.H., Zeanah, D., Nimmo, D.G., 2020. Fire mosaics and habitat choice in nomadic foragers. Proc. Natl. Acad. Sci. USA 117, 12904–12914.

Burrows, N.D., Chapman, J., 2018. Traditional and Contemporary Fire Patterns in the Great Victoria Desert. Great Victoria Desert Biodiversity. Trust. Perth, Australia.

Burrows, N.D., Christensen, P., 1990. A survey of Aboriginal fire patterns in the Western Desert of Australia. In: Fire and the Environment: Ecological and Cultural Perspectives. Proceedings of an International Symposium, pp. 297–310. Knoxville, Tennessee.

Burrows, N., Ward, B., Robinson, A., 1991. Fire behaviour in spinifex fuels on the Gibson Desert nature reserve, Western Australia. J. Arid Environ. 20, 189–204.

Burrows, N., Burbidge, A., Fuller, P., 2004. Integrating Indigenous Knowledge of Wildland Fire and Western Technology to Conserve Biodiversity in an Australian Desert. In: Bridging Scales and Epistemologies: Linking Local Knowledge and Global Science in Multiscale Assessments Conference, pp. 1–20. Alexandria, Egypt.

Burrows, N.D., Burbidge, A.A., Fuller, P.J., Behn, G., 2006. Evidence of altered fire regimes in the Western Desert region of Australia. Conserv. Sci. West Aust. 5, 14.

Burrows, N., Gill, M., Sharples, J., 2018. Development and validation of a model for predicting fire behaviour in spinifex grasslands of arid Australia. Int. J. Wildland Fire 27, 271–279.

Campbell, D., 2011. Application of an integrated multidisciplinary economic welfare approach to improved wellbeing through Aboriginal Caring for Country. Rangel. J. 33, 365–372.

Cosier P (2011) Accounting for the condition of environmental assets. UN Committee of Experts on Environmental Accounting Technical Meeting on Ecosystem Accounts, London, December 2011, pp 1-18. Wentworth Group of Concerned Scientists, Sydney, Australia.

Cross, S.L., Tomlinson, S., Craig, M.D., Bateman, P.W., 2020. The Time Local Convex Hull method as a tool for assessing responses of fauna to habitat restoration: a case study using the perentie (*Varanus giganteus*: reptilia: Varanidae). Aust. J. Zool. 67, 27–37.

Davies, J., Holcombe, S., 2009. Desert knowledge: integrating knowledge and development in arid and semi-arid drylands. Geojournal 74, 363.

Dickman, C., Predavec, M., Downey, F., 1995. Long-range movements of small mammals in arid Australia: implications for land management. J. Arid Environ. 31, 441–452.

Edwards, G., Allan, G., Brock, C., Duguid, A., Gabrys, K., Vaarzon-Morel, P., 2008. Fire and its management in central Australia. Rangel. J. 30, 109–121.

Edwards, A., Archer, R., De Bruyn, P., Evans, J., Lewis, B., Vigilante, T., Whyte, S., Russell-Smith, J., 2021. Transforming fire management in northern Australia through successful implementation of savanna burning emissions reductions projects. J. Environ. Manag. 290, 112568.

Garnett, S.T., Sithole, B., Whitehead, P.J., Burgess, C.P., Johnston, F.H., Lea, T., 2009. Healthy country, healthy people: policy implications of links between Indigenous human health and environmental condition in tropical Australia. Aust. J. Publ. Adm. 68, 53–66.

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C. J., Watson, J.E., Zander, K.K., Austin, B., Brondizio, E.S., 2018. A spatial overview of the global importance of Indigenous lands for conservation. Nat. Sustain. 1, 369–374.

Gould, R.A., 1971. Uses and effects of fire among the Western Desert aborigines of Australia. Aust. J. Anthropol. 8, 14.

Greenwood, L., Bliege Bird, R., Nimmo, D., 2022. Indigenous burning shapes the structure of visible and invisible fire mosaics. Landsc. Ecol. 37, 811–827.

Key, C.H., Benson, N.C., 1999. Measuring and Remote Sensing of Burn Severity: the CBI and NBR. University of Idaho and International Association of Wildland Fire, Boise, ID, USA, pp. 5–17.

Kimber, R., 1983. Black lightning: Aborigines and fire in central Australia and the Western Desert. Archaeol. Ocean. 18, 38–45.

Kimber, R., Friedel, M., 2015. Challenging the concept of Aboriginal mosaic fire practices in the Lake Eyre basin. Rangel. J. 37, 623–630.

Koertner, G., Pavey, C., Geiser, F., 2007. Spatial ecology of the mulgara in arid Australia: impact of fire history on home range size and burrow use. J. Zool. 273, 350–357.

Larsen, S.H., Nicholls, N., 2009. Southern Australian rainfall and the subtropical ridge: variations, interrelationships, and trends. Geophys. Res. Lett. 36, 1-5.

Leahy, L., Legge, S., Tuft, K., McGregor, H.W., Barmuta, L.A., Jones, M.E., Johnson, C.N., 2016. Amplified predation after fire suppresses rodent populations in Australia's tropical savannas. Wildl. Res. 42, 705–716.

Leiper, I., Zander, K.K., Robinson, C.J., Carwadine, J., Moggridge, B.J., Garnett, S.T., 2018. Quantifying current and potential contributions of Australian indigenous peoples to threatened species management. Conserv. Biol. 32, 1038–1047.

Letnic, M., 2001. Long distance movements and the use of fire mosaics by small mammals in the Simpson Desert, central Australia. Aust. Mammal. 23, 125–134.

Moore, D., Kearney, M.R., Paltridge, R., McAlpin, S., Stow, A., 2015. Is fire a threatening process for *Liopholis kintorei*, a nationally listed threatened skink? Wildl. Res. 42, 207–216.

Murphy, S.A., Paltridge, R., Silcock, J., Murphy, R., Kutt, A.S., Read, J., 2018. Understanding and managing the threats to night parrots in south-western queensland. Emu-Austral Ornithology 118, 135–145.

Nano, C.E., Clarke, P., Pavey, C.R., 2012. Fire regimes in arid hummock grasslands and Acacia shrublands. In: Bradstock, R., Gill, A., Williams, R. (Eds.), Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World. Cambridge University Press, Cambridge, pp. 195–214.

O'Bryan, C.J., Garnett, S.T., Fa, J.E., Leiper, I., Rehbein, J.A., Fernández-Llamazares, Á., Jackson, M.V., Jonas, H.D., Brondizio, E.S., Burgess, N.D., 2021. The importance of indigenous peoples' lands for the conservation of terrestrial mammals. Conserv. Biol. 35, 1002–1008.

Paltridge, R., Ward, N.N., West, J.T., Crossing, K., 2020. Is cat hunting by Indigenous tracking experts an effective way to reduce cat impacts on threatened species? Wildl. Res. 47, 709–719.

Pike, J., 2008. The Art of Fire. Backroom Press, Broome, WA.

Putnis, A., O'Leary, P., Leach, A., Ings, E., See, P., 2021. Strong on Country: Sustaining Success in Indigenous Land and Sea Management in Australia. Country Needs People Limited, Canberra, Australia.

R Development Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. R Foundation for Statistical Computing, Austria.

Reid, N., Hill, S.M., 2013. Spinifex biogeochemistry across arid Australia: mineral exploration potential and chromium accumulation. Appl. Geochem. 29, 92–101.

Renwick, A.R., Robinson, C.J., Garnett, S.T., Leiper, I., Possingham, H.P., Carwardine, J., 2017. Mapping Indigenous land management for threatened species conservation: an Australian case-study. PLoS One 12, e0173876.

Riley, J.L., 2020. Spatial Ecology and Conservation Management of the Endangered Sandhill Dunnart, *Sminthopsis Psammophila*. PhD thesis. University of Bristol, Bristol, UK.

Robinson, C., Carwardine, J., Garnette, S., Skroblin, A., Duncan, T., van Leeuwen, S., Gore-Birch, C., Moggridge, B., Goolmeer, T., Costello, O., Turpin, G., Legge, S., 2020. Healing Country for Significant Species: A Synthesis of Supporting Materials Relevant to Partnerships that Empower Indigenous Leadership and Management of Significant Plant and Animals. University of Queensland, NESP TSR Hub, Brisbane, Australia.

Ruscalleda-Alvarez, J., Moro, D., Van Dongen, R., 2021. A multi-scale assessment of fire scar mapping in the Great Victoria Desert of Western Australia. Int. J. Wildland Fire 30, 886–898.

Russell-Smith, J., Murphy, B.P., Meyer, C.M., Cook, G.D., Maier, S., Edwards, A.C., Schatz, J., Brocklehurst, P., 2009a. Improving estimates of savanna burning emissions for greenhouse accounting in northern Australia: limitations, challenges, applications. Int. J. Wildland Fire 18, 1–18.

Russell-Smith, J., Whitehead, P., Cooke, P., 2009b. Culture, Ecology and Economy of Fire Management in North Australian Savannas: Rekindling the Wurrk Tradition. CSIRO Publishing.

Short, J., Turner, B., 1994. A test of the vegetation mosaic hypothesis: a hypothesis to explain the decline and extinction of Australian mammals. Conserv. Biol. 8, 439–449.

Social Ventures Australia, 2016. Consolidated Report on Indigenous Protected Areas Following Social Return on Investment Analyses. Department of the Prime Minister & Cabinet, Canberra.

Southgate, R., Carthew, S., 2007. Post-fire ephemerals and spinifex-fuelled fires: a decision model for bilby habitat management in the Tanami Desert, Australia. Int. J. Wildland Fire 16, 741–754.

Stafford Smith, D.M., Morton, S.R., 1990. A framework for the ecology of arid Australia. J. Arid Environ. 18, 255–278.

Steinfeld, C., Cosier, P., 2018. Private Sector Trials of Accounting for Nature, and Links with National Environmental Economic Accounts. (24th Meeting of the London Group on Environmental Accounting, 1 – 4 October 2018: Dublin, Ireland.

Thackway, R., Cresswell, I., 1995. An Interim Biogeographic Regionalisation for Australia: a framework for establishing the national system of reserves, Version 4.0. Australian Nature Conservation Agency, Canberra, Australia.

Turner, D., Ostendorf, B., Lewis, M., 2008. An introduction to patterns of fire in arid and semi-arid Australia, 1998–2004. Rangel. J. 30, 95–107.

UNEP, 2006. Global Deserts Outlook. United Nations Environment Programme, Nairobi, Kenya.

United Nations, 2015. Transforming Our World: 2030 Agenda for Sustainable Development. https://undocs.org/A/RES/70/1.

Van Etten, E.J., 2009. Inter-annual rainfall variability of arid Australia: greater than elsewhere? Aust. Geogr. 40, 109–120.

Verhoeven, E.M., Murray, B.R., Dickman, C.R., Wardle, G.M., Greenville, A.C., 2020. Fire and rain are one: extreme rainfall events predict wildfire extent in an arid grassland. Int. J. Wildland Fire 29, 702–711.

Ward, B.G., Bragg, T.B., Hayes, B.A., 2014. Relationship between fire-return interval and mulga (*Acacia aneura*) regeneration in the Gibson desert and gascoyne–murchison regions of western Australia. Int. J. Wildland Fire 23, 394–402.

Woinarski, J.C.Z., Burbidge, A.A., Harrison, P.L., 2015. The ongoing unravelling of a continental fauna: decline and extinction of Australian mammals since European settlement. Proc. Natl. Acad. Sci. USA 112, 4531–4540.

Wright, B.R., Laffineur, B., Roye, D., Armstrong, G., Fensham, R.J., 2021. Rainfall-linked megafires as innate fire regime elements in arid Australian spinifex (*Triodia* spp.) grasslands. Front. Ecol. Evol. 9, 296.

Wysong, M., Legge, S., Clarke, A., Maier, S., Bardi Jawi Rangers, Nyul Nyul Rangers, Yawuru Country Managers, Cowell, S., Mackay, G., 2022. The sum of small parts: changing landscape fire regimes across multiple small landholdings in north-western Australia with collaborative fire management. Int. J. Wildland Fire 31, 97–111.