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# The sum of small parts: changing landscape fire regimes across multiple small landholdings in north-western Australia with collaborative fire management

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**Abstract.** Fire is a natural process in tropical savannas, but contemporary cycles of recurrent, extensive, severe fires threaten biodiversity and other values. In northern Australia, prescribed burning to reduce wildfire incidence is incentivised through a regulated emissions abatement program. However, only certain vegetation types are eligible; also, managers of small land parcels are disadvantaged by the program's transaction costs and interannual variability in management outcomes. Both impediments apply to landholders of the Dampier Peninsula, north-west Australia. Nevertheless, Indigenous rangers, pastoralists and other stakeholders have collaborated for 5 years to manage fire across their small holdings (300–2060 km$^2$). We used remote sensing imagery to examine the project's performance against seven fire regime targets related to biodiversity, cultural and pastoral values. At the scale both of individual landholders and the entire Peninsula (18 500 km$^2$), the project significantly reduced the extent of annual fire, high-severity fire, mid-late dry season fire, fire frequency and severe fire frequency. The project significantly increased the graininess of burnt and unburnt areas and the extent unburnt for 3+ years more than tripled. The project demonstrates that cross-tenure collaboration can overcome the challenges of managing fire on small land parcels. However, this project's sustainability depends on securing ongoing funding.

**Keywords:** fire management, traditional fire management, tropical savanna, carbon emissions, emissions abatement, Indigenous fire management, pindan woodlands, biocultural indicators.

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## Introduction

Fire is a pervasive disturbance for many terrestrial ecosystems (Bowman *et al.* 2009; Pausas and Keeley 2009) and an important landscape management tool used by humans for millennia (Pyne 1997; Bowman *et al.* 2011; Huffman 2013). Both natural and anthropogenic burning affect ecosystem structure and composition worldwide (Archibald *et al.* 2012; McLauchlan *et al.* 2020). In modern times, large wildfires are increasingly impacting terrestrial ecosystems and threatening human health, safety and livelihoods, posing immense challenges for land

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managers (Krawchuk *et al.* 2009; Boer *et al.* 2020). The controlled application of fire, such as through prescribed burning, is commonly used to reduce fuel loads or enhance fire breaks to protect specific tracts of land and limit the spread of wildfire. While there is considerable debate over the efficacy of prescribed burning in different biomes, its application can reduce the impacts of fire in some contexts (Fernandes and Botelho 2003; Penman *et al.* 2011).

In the tropical savannas of northern Australia, fire has been a natural disturbance agent for tens of millions of years (Bowman *et al.* 2010). This region has a monsoonal climate: wet season rains (November to April) stimulate profuse grass growth, which cures during the dry season (May to October), becoming susceptible to ignition from lighting strike in the lead-up to the subsequent monsoon (Russell-Smith *et al.* 2003). Prior to human occupation, fire in northern Australia was characterised by infrequent, high-intensity fires at the end of the dry season (Bowman 2002).

Following their arrival on the continent (*c.* 65 000 years ago; Clarkson *et al.* 2017), Aboriginal people began using fire for various purposes including to promote forage for game species, increase availability of food plants, facilitate travel across country or communicate over large distances (Gammage 2013). Fires were ignited through the dry season, resulting in a finer-grained mosaic of fire age classes across the landscape and across time (Vigilante 2001; Bowman *et al.* 2004; Blackwood *et al.* 2021). Following colonisation, the spread of pastoralism displaced Aboriginal communities from their lands (Reynolds 1987). In north-western Australia, the displacement accelerated in the 1960s following equal wage legislation, changes in technology that made the skills of the Indigenous stockman obsolete (e.g. the use of fencing, and motor vehicles for mustering), and the Australian government's policy of assimilation (Anthony 2007). These changes removed traditional fire management from much of northern Australia, although components of traditional burning continued in some locations (Yibarbuk *et al.* 2001; Russell-Smith *et al.* 2003).

Contemporary fire regimes in northern Australia became dominated by large (i.e. $10^2$–$10^4$ km$^2$), high-intensity (>2500 kW m$^{-1}$), mid-to-late season wildfires, re-occurring every 1–3 years over the same area of land (Fisher *et al.* 2003; Russell-Smith *et al.* 2003). The new fire regimes have contributed to contemporary changes to the structure and composition of woodlands, losses in key shelter and food resources for animals, and declines in fire-sensitive plants, ecological communities and animal guilds including small–medium-sized ground-dwelling mammals and birds, seed-eating birds and riparian birds (citations in Table 1).

Frequent wildfires also negatively affect the social, cultural and economic values of northern Australia. Such fires threaten the safety of remote communities and outstations and incur high emergency response costs. For Aboriginal communities, re-occurring wildfires threaten sacred sites, food and medicine plants and game species, and reduce the capacity for healthy country management (Vigilante *et al.* 2017; Ansell and Evans 2020). For pastoralists, wildfires cause substantial economic costs from lost production when pasture is burnt, and repairs when infrastructure (fences, bores) is destroyed (Drucker *et al.* 2008; Skroblin *et al.* 2014). Wildfires also threaten the regional tourism industry that relies on access to natural environments and outdoor activities (Axford and Legge 2008; Blanch 2008; Russell-Smith and Whitehead 2015). Finally, wildfires in the tropical savannas are a significant contributor to global annual greenhouse gas emissions (Russell-Smith *et al.* 2009).

Modern fire management in northern Australia relies on early dry season prescribed burning to strategically reduce fuel loads and thus limit the extent and severity of wildfires burning later in the dry season. Increasingly, such fire management is promoting the restoration of Indigenous burning practices modified by the use of modern technology (e.g. helicopters, satellite mapping, four-wheel-drive vehicles) to achieve benefits for people, culture, biodiversity and emissions abatement (Ansell and Evans 2020; McKemey *et al.* 2020). In northern Australia, fire management has been incentivised since 2012 (Commonwealth of Australia 2013) through a regulated program that allows registered savanna burning projects to sell carbon offsets that are accrued by reducing the extent of late dry season wildfires, and thus reducing annual greenhouse gas emissions (Russell-Smith *et al.* 2009). Currently, 76 registered savanna burning projects are managing fire over 25% of the tropical savanna region, achieving landscape-scale changes in fire regimes (Corey *et al.* 2020; Edwards *et al.* 2021). However, not all managers in northern Australia can access this incentive: the transaction costs of project registration, annual reporting and auditing, and the interannual variability in fire management outcomes disadvantage managers of small land parcels from participating because of diminishing and less certain returns at smaller scales (Russell-Smith *et al.* 2015). Hence, the average parcel size of registered projects is 4040 km$^2$ (Edwards *et al.* 2021). In addition, the emissions abatement calculations are specific to defined vegetation types, so land parcels with vegetation types that are not recognised by the approved method for estimating emissions abatement are ineligible.

The Dampier Peninsula in the western Kimberley region of Western Australia supports high biodiversity and economic values, in a unique landscape with enduring Aboriginal cultures. In recent decades, these values have been threatened by regular, extensive and severe wildfires. Land managers of the Peninsula cannot access the emissions abatement market of Australia's tropical savannas because the dominant vegetation (pindan woodland) is currently excluded from the approved method (Lynch *et al.* 2018). In addition, land parcels on the Peninsula include fairly small areas (smallest is 300 km$^2$; average is 2620 km$^2$), limiting the effectiveness of individual fire management efforts. In spite of these impediments, Indigenous ranger groups, pastoralists, fire managers and other stakeholders responded to widespread community concern about the prevailing fire regime, and have collaborated since 2016 to improve fire regimes on the Peninsula by coordinating fire management across tenures. In this paper, we describe the objectives and targets for the fire regime change set by the group and assess whether the coordinated fire management has allowed the group to meet those targets. We discuss the potential benefits of the managed fire regime for biodiversity and people on the Peninsula, the lessons for collaborative management and the challenges for a coordinated fire management program that lacks access to ongoing funding, such as the regulated carbon market.

**Table 1. Objectives and targets for improving the Dampier Peninsula fire regime identified by the Working Group before collaborative fire management. Includes the metrics used in the analysis and their rationale**

| Objective | Target | Rationale | Metric |
|---|---|---|---|
| (1) Reduce the extent of fires occurring in the mid-late dry season (July–December) | (1.1) The annual fire extent should be similar or lower compared with baseline (2004–15) | Previous studies have found that annual fire extent varies little with management, being influenced mainly by rainfall (Edwards *et al.* 2021). However, this metric is a key component of metrics (1.2) and (1.3) | Annual fire extent = percentage of total area burnt over a given year |
| | (1.2) By 2020, the percentage of annual fire extent caused by late dry season fires should decrease by more than 30% compared with baseline (2004–15) | Late dry season fires are typically of higher severity than early dry season fires, leaving less fine-scale unburnt patches within the fire footprint (Russell-Smith and Edwards 2006; Oliveira *et al.* 2015). These fires threaten pastoral livelihoods (Drucker *et al.* 2008; Skroblin *et al.* 2014), tourism enterprises (Axford and Legge 2008), Aboriginal biocultural values (Prober *et al.* 2011), fire-sensitive vegetation (Russell-Smith *et al.* 2012), native mammal assemblages (Radford *et al.* 2015), seed-eating birds (Legge *et al.* 2015*b*), riparian birds (Skroblin and Legge 2010) | Fire seasonality = percentage of the annual fire extent that burned in the late dry season |
| | (1.3) By 2021, the percentage of annual fire that is high severity should decrease compared with baseline (2004–15) | | Annual high severity fire = percentage of total area burnt severely, where severe fire is defined as ≥50% pixel burnt |
| (2) Reduce the frequency of fires, including high-severity fires | (2.1) By 2021, fire frequency should decrease (added in 2020) | High fire frequencies amplify the threats listed in the row above, especially so for obligate seeding plants (Russell-Smith *et al.* 2012), small mammals (Griffiths *et al.* 2015; Legge *et al.* 2019). High severe fire frequency changes woodland structure (Williams *et al.* 1999) and woody resources (Woolley *et al.* 2018) | High fire frequency = percentage of total area burnt ≥3 times over the prior 6-year period |
| | (2.2) By 2021, the frequency of high-severity fires should decrease (added in 2020) | | High severe fire frequency = percentage of total area burnt ≥3 times with severe fire (i.e. with ≥50% pixel burnt) over the prior 6-year period |
| (3) Reduce the distance to unburnt patches | (3.1) By end of 2019, the average distance from burnt areas to unburnt areas should decrease compared with baseline (2004–15) | Extensive, high-severity fires increase distance from burnt to unburnt patches, impacting fauna with restricted home ranges and plants lacking long-range dispersal mechanisms (Murphy *et al.* 2010; Lawes *et al.* 2015; Shaw *et al.* 2021) | Distance to unburnt = average distance from each burnt pixel to nearest unburnt pixel |
| (4) Increase the extent of long unburnt habitat patches | (4.1) By end of 2021, the extent of long unburnt vegetation (i.e. 3+ years old) increases compared with baseline (2009–15) | Long-unburnt patches increase habitat heterogeneity and structural complexity, especially at the ground layer, which is vital for many small mammals, reptiles and birds (Andersen *et al.* 2005; Woinarski and Legge 2013; Legge *et al.* 2015*a*; Radford *et al.* 2015; Radford *et al.* 2020) | Extent of long unburnt habitat = percentage of total area with vegetation unburnt for 3 or more years |

## Methods

### *Study area*

The project occurred in the Dampierland biogeographic region of northern Western Australia and comprised native title determinations, Indigenous Protected Areas, pastoral leases and Unallocated Crown Land, covering 18 500 $km^2$ (Fig. 1). The climate is tropical monsoonal. Traditional Owner groups recognise six seasons. Most rain falls in Man-gala (Yawuru and Bardi Jawi languages) (wet season, December–March), averaging between 627 mm (Broome airport) and 954 mm (Country Downs station) annually (http://www.bom.gov.au/climate/data) (Supplementary Fig. S1*a*). Prescribed burning mostly occurs in Wirralburu (Yawuru)/Iralbu (Bardi Jawi) (early dry season, May–June), and wildfires can occur in Barrgana and Wirlburu (Yawuru)/Bargana and Djalalayi (Bardi Jawi) (mid-late dry season, July–November) (http://www.bom.gov.au/iwk/calendars/yawuru.shtml).

The primary vegetation type is pindan woodland or shrubland dominated by a mid-storey of often thicket-forming *Acacia* (*A. tumida*, *A. eriopoda*), a sparse overstorey of trees including eucalypts (*Eucalyptus tectifica*, *E. polycarpa*, *Corymbia grandifolia*) and a sparse ground cover of hummock or bunch grasses (Kenneally *et al.* 1996). Monsoon vine thickets, a fire-sensitive dry rainforest recognised as a nationally endangered ecological community, occupy a small portion of the Peninsula (>0.01%) but contribute greatly to its biodiversity and are an important source of traditional medicine and food plants for Aboriginal people of the region (Ondei *et al.* 2017; Kenneally 2018; Lemon 2020). Wetlands, rocky outcrops, saline grasslands, saltwater paperbark thickets and sandplains are scattered

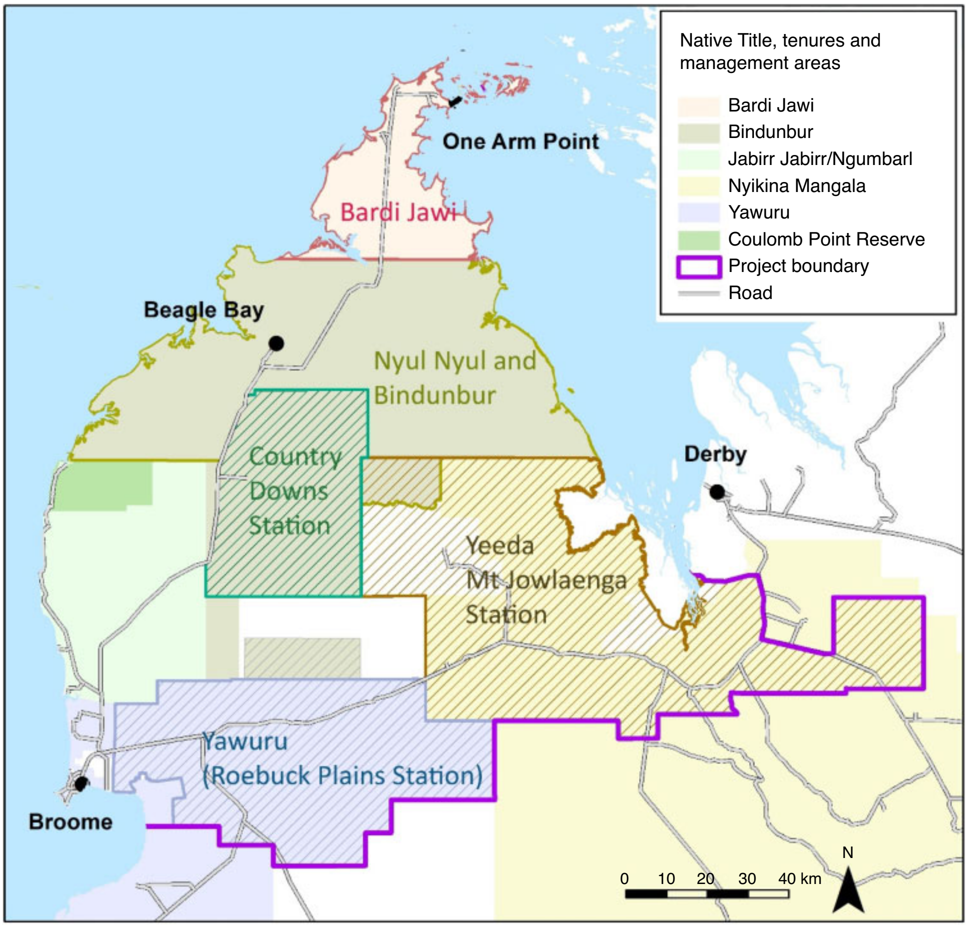


**Fig. 1.** Map of the project area, showing the Native Title Determinations (solid shading) and the pastoral leases (hatching). The management areas in the modelling analyses are labelled on the map.

throughout the study area in small proportions (Kenneally *et al.* 1996). In addition to managed cattle on active pastoral leases, unmanaged or feral cattle, horses and donkeys are present throughout the study area.

## *The Dampier Peninsula Fire Working Group*

The Dampier Peninsula Fire Working Group (hereafter the Group) was formed in 2016, and brings together Traditional Owners, Indigenous ranger groups, government agencies, regional conservation groups, non-profit organisations, the pastoral and natural resources industries, and scientific experts to work collaboratively to improve fire management on the Dampier Peninsula through coordinated training, skills-sharing, communications and prescribed burning delivery (Table 2, Fig. 1).

During a series of facilitated planning workshops structured using the Open Standards for the Practice of Conservation Framework (to align with Healthy Country Plans that are routinely developed by Indigenous rangers to manage country; Carr *et al.* 2017), the Group identified the biodiversity, cultural, pastoral and human safety and livelihood values threatened by a wildfire-dominated fire regime. The Group then set four medium-term objectives with seven measurable targets outlining the specific fire regime changes they wanted to achieve on the Peninsula in order to support those values (Table 1).

## *Coordinating prescribed burning*

Before each burning season (April–June, Wirralburu, Iralbu), each landholder developed their own property burn plan to suit their individual objectives (Table 2). These plans were then compiled for the entire Peninsula and reviewed by the Group to identify any operational 'gaps' where management was missing or weak, particularly in interstitial areas between the focal activity areas of each of the five to six (depending on year) landholders that managed the largest tracts of land. Opportunities to share equipment, resources or burning activities were discussed. Once prescribed burning was under way, the Group reviewed progress during fortnightly phone hook-ups, and made alterations to the burn plans as needed to target or re-prioritise areas for additional fire application.

Generally speaking, the consolidated burn plan aimed to use prescribed burns in the early dry season to create fuel-reduced buffers around high-value areas (e.g. monsoon vine thicket patches, important areas of pasture) and across the path of typical wildfire spread (known from local knowledge plus inspection of archived satellite imagery) in the mid-late dry

**Table 2. List of project partners and their primary fire management objectives, grouped by their roles in the Dampier Peninsula Fire Project. Landholders and managers and shown in grey shading**

| Project partner | Primary project objectives |
|---|---|
| Project coordination and support | |
| Rangelands NRM | Support project with coordination, communication |
| NESP Threatened Species Recovery Hub | Support project with scientific expertise |
| Conservation Management Pty Ltd | Support project with project planning and facilitation |
| Landholders: Traditional Owners and Indigenous rangers | |
| Bardi Jawi | Biocultural and community assets identified in Healthy Country Plans, IPA Management Plans, or similar management planning documents. These include fire-sensitive plants, ecological communities and animals that have conservation or cultural value |
| Nyul Nyul | |
| Yawuru | |
| Jabirr Jabirr | |
| Bindunbur–Ngumbarl | |
| Nyikina Mangala | |
| Landholders: pastoralists | |
| Roebuck Plains Station | Protect small areas of irrigated agriculture and natural pasture from fire in order to retain fodder for cattle through the dry season, and protect infrastructure from high-severity fire |
| Yeeda–Mt Jowlaenga Station | |
| Country Downs station | |
| Kilto Station | |
| Land managers: industry | |
| Sheffield Resources | Protection of infrastructure and workforce |
| Landholders: state government | |
| WA Dept of Biodiversity, Conservation and Attractions | Conservation of species and communities |
| WA Department of Planning, Lands and Heritage | Support Indigenous rangers with funding |
| State government agencies | |
| WA Dept of Fire and Emergency Services | Protection of life and property, regulatory compliance |
| Western Australia Main Roads | Protection of infrastructure and workforce |
| Regulators | |
| Shire of Broome | Protection of life and property, regulatory compliance |
| Shire of Derby–West Kimberley | |
| Funders and supplementary support | |
| Kimberley Land Council | Support rangers with funding, training, expertise |
| World Wildlife Fund for Nature (WWF) | Support rangers with funding, expertise |
| Environs Kimberley | Support rangers with biocultural monitoring |
| All West Australians Reducing Emergencies program | Support project with funding |
| WA Government's Natural Resource Management Program | Support project with funding |

season (July–December; Barrgana to Wirlburu; Bargana to Djalalayi), and to break up any large patches (e.g. >10 km$^2$) of the same fire age into smaller patches, so wildfires were less likely to consume the whole original patch area. Because of the scale, remoteness and limited access across the project area, much of the prescribed burning was carried out through the use of aerial incendiaries deployed by helicopter. Where feasible, ground burning ignited by drip torch was also conducted.

### Fire regime metrics

We described annual fire patterns (2004–20) using MODIS (Moderate Resolution Imaging Spectroradiometer; 250-m resolution) vector data available from the North Australia Fire Information service (http://firenorth.org.au). Each year's fire scars are attributed to a month. Fire severity, or the amount of above ground vegetation consumed by the fire, is related to the fraction burnt of each pixel affected by fire; we estimated this using a linear spectral unmixing approach. We used raw data from MODIS on both satellite platforms, Aqua and Terra (Barnes *et al.* 1998, Justice *et al.* 1998, Salomonson *et al.* 2006), downloaded from the Ocean Biology Processing Group (OBPG) Distributed Active Archive Center at NASA's Goddard Space Flight Center (https://oceandata.sci.gsfc.nasa.gov). Raw data were processed to L1b (radiometrically and geometrically calibrated) using the MODIS L1b processor of the SeaDAS software package (https://seadas.gsfc.nasa.gov). Pre-processing, including atmosphere correction, geocoding and observation geometry correction, followed Maier (2010). The fraction of the pixel burnt was estimated using linear spectral unmixing of the bottom-of-atmosphere reflectances of MODIS channels 1–5 and 7 using two end members, *unburnt* and *burnt*. Results from individual satellite overpasses were aggregated to monthly maps for further analysis.

We used several metrics to characterise fire patterns, based on Legge *et al.* (2011, 2015*b*) (Table 1), and calculated them for the baseline 'control' period before the Group began peninsula-wide collaborative fire management (2004–15) as well as the 5-year 'treatment' period (2016–20) over which collaboration occurred. Fire metrics were calculated for the whole project area, as well as separately for five constituent management areas that had been managed by the same partner over the project period, because managers wanted to know whether the collaboration was improving fire patterns at a smaller scale, on their own land, as well as across the Peninsula (Fig. 1). These five management areas (Bardi Jawi, Nyul Nyul–Bindunbur, Country

Downs Station, Yeeda–Mt Jowlaenga Station, Yawuru) comprised 80% of the project area. The remaining 20% was managed by different partners over a period in which Jabirr Jabirr Native Title was being determined, and was not included in this analysis.

Spatial data manipulation was carried out using ArcGIS, with the Spatial Analyst extension. Data were projected to GDA94 MGA51 before area and distance calculations were made. We derived the fire metrics for the whole peninsula, and for the constituent management areas, as follows (and see Table 1). *Annual fire extent* was the proportion of the area (Peninsula-wide, or individual management areas) that burned in that year. *Fire seasonality*, or the extent of late season fires, was the proportion of the year's fires that occurred from July to December. *Annual high-severity fire* was the proportion of the project area that burned at high severity, where high severity was defined as >50% of a pixel being burnt (detailed methods in Supplementary file). Note that this metric is likely to correlate with fire seasonality, but not be the same, because some early dry season fires can burn severely, and conversely some late dry season fires can burn mildly. *Fire frequency* and *severe fire frequency* were calculated using a moving 6-year window leading up to each year analysed: we found the proportion of each management area that had burnt 0, 1, 2, 3, 4, 5 or 6 times in that preceding 6-year window and calculated the proportion burnt ≥3 times, which we defined as 'high frequency'. Likewise, we defined severe fire frequency as being burnt ≥3 times by a severe fire over the prior 6-year period. To derive the *distance to unburnt vegetation* metric, we buffered the project area by 200 km because unburnt vegetation outside the project boundary could potentially be closer to burnt areas near the boundary. We removed patches of less than 20 ha so that the metric represented the distance to the nearest unburnt patch of at least 20 ha. We converted the vector data to 250-m raster format, then calculated the straight-line distance from every burnt pixel to the nearest unburnt vegetation. Zonal statistics were used to display the data in a table format and the distances for each management area were averaged. Finally, we merged the annual fire mapping each year to create a composite time-since-last fire map, then calculated the *extent of long-unburnt vegetation*, defined as the proportion of each management area that had not burnt in 3, 4, 5 and 6 years or more.

### Data analysis

We evaluated the effect of coordinated collaborative fire management on the fire metrics of each management area, using generalised linear mixed effects models for six of the seven fire metrics (the average distance to unburnt vegetation excepted). Each of these six metrics is expressed as a proportion ranging between 0 and 1 and arises from continuous data (ha), so we fitted each model with a β distribution and logit link function (Douma and Weedon 2019) using the package 'glmmTMB' version 1.0.2.1 (Magnusson *et al.* 2020) in R version 4.0.5 (R Core Team 2021). Where necessary, we applied a data transformation, following Douma and Weedon (2019) to ensure that values for the response variables did not equal 0 or 1. The average distance to unburnt vegetation is a normally distributed continuous variable so we used linear mixed effects models in the package 'lmer4' version 1.1–27 (Bates *et al.* 2012) to evaluate the effect of coordinated fire management on this metric.

All models included management as a categorical variable with two levels: pre-management 'control' (2004–15) and post-management 'treatment' (2016–20). We also included rainfall in the preceding year (1 July–30 June) as a continuous covariate in the models because rainfall can have an important effect on productivity and in turn on annual fire metrics (Whitehead *et al.* 2014). Monthly rainfall data were sourced from the Australian Government Bureau of Meteorology online climate data portal (http://www.bom.gov.au/climate/data) and compiled for each of the five management areas from weather stations located on those parcels (Supplementary Fig. S1*b*). Where rainfall data were missing or incomplete for a management area, rainfall values were sourced from the next nearest station. Rainfall data were normalised between 0 and 1 using the rescale function in the package 'scales' version 1.1.1 (Wickham and Seidel 2020). We included management area as a random effect in the models in order to account for unexplained variation attributed to the land managers or places.

Since fire patterns are strongly influenced by rainfall, and rainfall was a covariate in the models, we did not also include year in the models for annual fire metrics (i.e. annual fire extent, fire seasonality, annual fire severity, distance to unburnt) to avoid collinearity issues. In contrast, we included year as a continuous variate in the models dealing with multi-year metrics (fire frequency, severe fire frequency, extent of long-unburnt vegetation) because the extent of collinearity between annual rainfall and a metric calculated over several years is reduced, and also because if management is effective, these metrics should improve progressively over time, and we therefore wanted to test for a time trend. Thus, for these three models, we included year as an interacting factor with management. Model fit was assessed using residual diagnostic plots generated by the package 'DHARMa' version 0.4.1 (Hartig and Hartig 2017).

## Results

For each of the seven fire metrics, we describe the change from baseline to project period for the whole Peninsula, and present the results of the mixed model analyses of metric changes across the constituent management areas.

### Annual fire extent, seasonality and severity

The overall annual fire extent over the baseline period (2004–15) averaged 43% (s.e. 5.2%; range 14–68%) and more than halved to an average of 19% (s.e. 5.9%; range 2.5–39%) during the project period (2016–20). The percentage of annual fires occurring in the late dry season decreased by 30% from a baseline average of 86% (s.e. 4.7%; range 40–100%) to a project average of 60% (s.e. 10%; range18–77%). The percentage of the Dampier Peninsula that burned in severe fires decreased from a baseline average of 28% (s.e. 3.5%; range 9.1–45%) to a project average of 9.8% (s.e. 3.1%; range 2.8–21%). The percentage of the annual fire extent burned in severe fires had a baseline average of 65% (s.e. 1.2%), while the project average was 62% (s.e.13%); the lack of change was driven by the results in 2016, where a very small area of the peninsula burned (2.5%) but did so with high severity (Fig. 2*a*–*d*; Fig. S2).

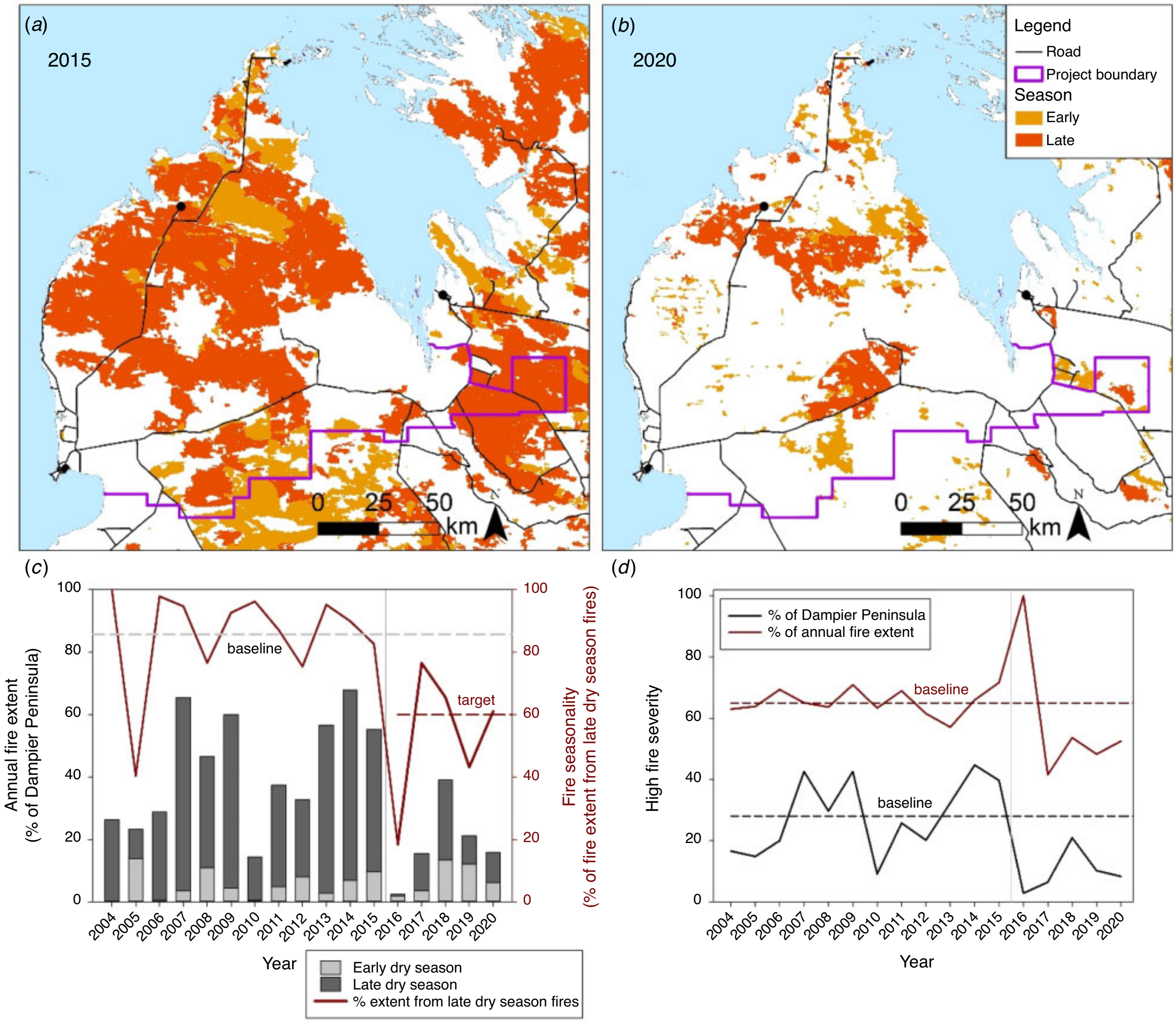


**Fig. 2.** Changes in the annual fire extent, seasonality and severity of fire. Maps of the project area, showing (*a*) the annual fire extent at the end of 2015 (an example year from the baseline period); and (*b*) 2020 (after 5 years of the project). Annual fire extent maps for the full series of years (2004–20) are available in the Supplementary material. Early dry season fires occurring from January to June are shaded orange; late dry season fires occurring from July to December are shaded red. (*c*) Annual fire extents, made up of early and late season fires, for baseline years (2004–15) and project years (2016–20). The proportion of each year's fires that are late season fires, the baseline average (86%), and the target for this metric (60%). (*d*) High-severity fires for baseline years (2004–15) and project years (2016–20), expressed as the proportion of the Dampier Peninsula project area (black line), and – for additional context – as the proportion of the annual fire extent (red line).

The analysis of changes in the constituent management areas showed that collaborative fire management significantly reduced the total annual fire extent, the proportion of fire occurring in the late dry season, and the proportion of annual fires that were severe. As expected, rainfall had a positive effect on all three metrics (Table 3; Fig. S3*a*–*c*).

### *Fire frequency and severe fire frequency*

Both fire frequency and severe fire frequency decreased across the Dampier Peninsula during the project years (2016–20) compared with the baseline (2009–15) (Fig. 3*a*–*c*). The modal fire frequency at the end of the baseline period was 3 times in 6 years; by 2020, the modal frequency had decreased to 2 times in 6 years. Additionally, the proportion of the Peninsula remaining unburnt or burnt only once in 6 years more than doubled while the proportion of habitat burnt 3 or more times in 6 years more than halved at the end of the project period (Fig. 3*d*). At the same time, the proportion of habitat not burnt in 6 years more than doubled while the proportion of habitat burnt 3 or more times in 6 years more than halved at the end of the project period. (Fig. 3*d*).

The analysis of changes in the constituent management areas showed a significant interaction between year and management for high-frequency fires, whereby the proportion of the

**Table 3. Estimates (β), standard error (s.e.) and statistical significance of variables used in mixed effects models to evaluate the effectiveness of collaborative fire management on the Dampier Peninsula, Western Australia, across seven fire metrics**

| Predictors | Annual fire extent | | Fire seasonality | | Annual high severity fire | | High fire frequency | | High severe fire frequency | | Distance to unburnt | | Extent of long-unburnt | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | β | s.e. | β | s.e. | β | s.e. | β | s.e. | β | s.e. | β | s.e. | β | s.e. |
| Fixed effects | | | | | | | | | | | | | | |
| Treatment | −0.78*** | 0.22 | −1.74*** | 0.26 | −0.88*** | 0.20 | 0.33 | 0.18 | 0.25 | 0.16 | −475.733*** | 85.87 | 0.21 | 0.26 |
| Rainfall | 1.68*** | 0.47 | 1.31* | 0.57 | 1.28** | 0.41 | 0.46 | 0.23 | 0.56* | 0.23 | 440.54* | 195.3 | 1.16** | 0.34 |
| Year | | | | | | | 0.06 | 0.03 | 0.04 | 0.03 | | | −0.06 | 0.05 |
| Treatment × year | | | | | | | −0.36*** | 0.06 | −0.46*** | 0.07 | | | 0.29** | 0.09 |
| *n* (observations) | | 85 | | 85 | | 85 | | 60 | | 60 | | 85 | | 60 |
| Random effects | | | | | | | | | | | | | | |
| Within subject variance ($\sigma^2$) | 0.12 | | −0.16 | | 0.24 | | 0 | | 0.06 | | 128 556 | | 0.11 | |
| Between subject variance ($\tau_{00}$) | 0.01 | | 0.00 | | 0.00 | | 0.43 | | 0.27 | | 14 383 | | 0.35 | |
| *n* (random) | 5 | | 5 | | 5 | | 5 | | 5 | | 5 | | 5 | |

***$P < 0.001$; **$0.01 < P < 0.001$; *$0.05 < P < 0.01$

Peninsula burnt 3 or more times in 6 years decreased over time in the project years, but not in the baseline years. We also found a significant interaction between year and management for high severe fire frequency, whereby the proportion of the peninsula burnt severely 3 or more times in in 6 years decreased over time in the project years, but not in the baseline years. Rainfall had a positive effect on both metrics (Table 3; Fig. S3*d*, *e*).

### *Distance to unburnt vegetation*

The mean distance (± s.e.) from burnt areas to the nearest unburnt vegetation (>20 ha) across the entire peninsula decreased from a baseline (2004–15) of 1420 ± 78.5 m (range 1050–1840 m) to 844 ± 82.9 m (range 413–821 m) over the period of collaborative fire management (2016–20) (Fig. 4). The analysis of changes in the constituent management areas showed that collaborative fire management significantly reduced the distance from burnt to unburnt vegetation. Rainfall had a positive effect on distance to unburnt vegetation (Table 3; Fig. S3*f*).

### *Extent of long-unburnt vegetation*

By the end of the project period (2020), the areal extents of different vegetation ages had shifted towards longer-unburnt relative to the end of the baseline period (2015) (Fig. 5*a*, *b*). The extent of vegetation unburnt for 3 or more years increased from 18% in 2015 to 65% in 2020 (Fig. 5*c*). In the analysis of changes in the constituent management areas, we found a significant interaction between year and management, whereby the proportion of the Peninsula that was long-unburnt (3 or more years) increased over time in the project years, but not in the baseline years. Rainfall also had a positive effect on the extent of long-unburnt vegetation (Table 3; Fig. S3*g*).

## Discussion

Our results demonstrate that the Dampier Peninsula Fire Working Group successfully changed the fire regime on several adjacent, fairly small (down to 300 km$^2$) land parcels by coordinating fire management across boundaries. To monitor their progress, the Group identified four broad objectives and seven specific targets with metrics against which the fire regime was measured. The objectives, metrics and targets were selected because they are related, by published evidence, to the biodiversity, pastoral, economic and cultural benefits sought (Table 1). Below, we discuss the changes in fire metrics and their implications for the range of values that the project sought to protect; we describe what made the partnership model successful, what its weaknesses are, and how these could be solved.

### *Fire regime changes*

Over the 5 years of the Dampier Peninsula fire project, we observed significant changes in annual fire extent, fire seasonality, fire severity, fire frequency, severe fire frequency, the average distance to unburnt vegetation and the extent of long-unburnt vegetation, leading us to conclude that the Group was successful in achieving their fire management objectives (Table 1).

Previous studies have shown that management can be very effective at changing the seasonality of fires, and reducing the proportion of fires burning in the late dry season is a common

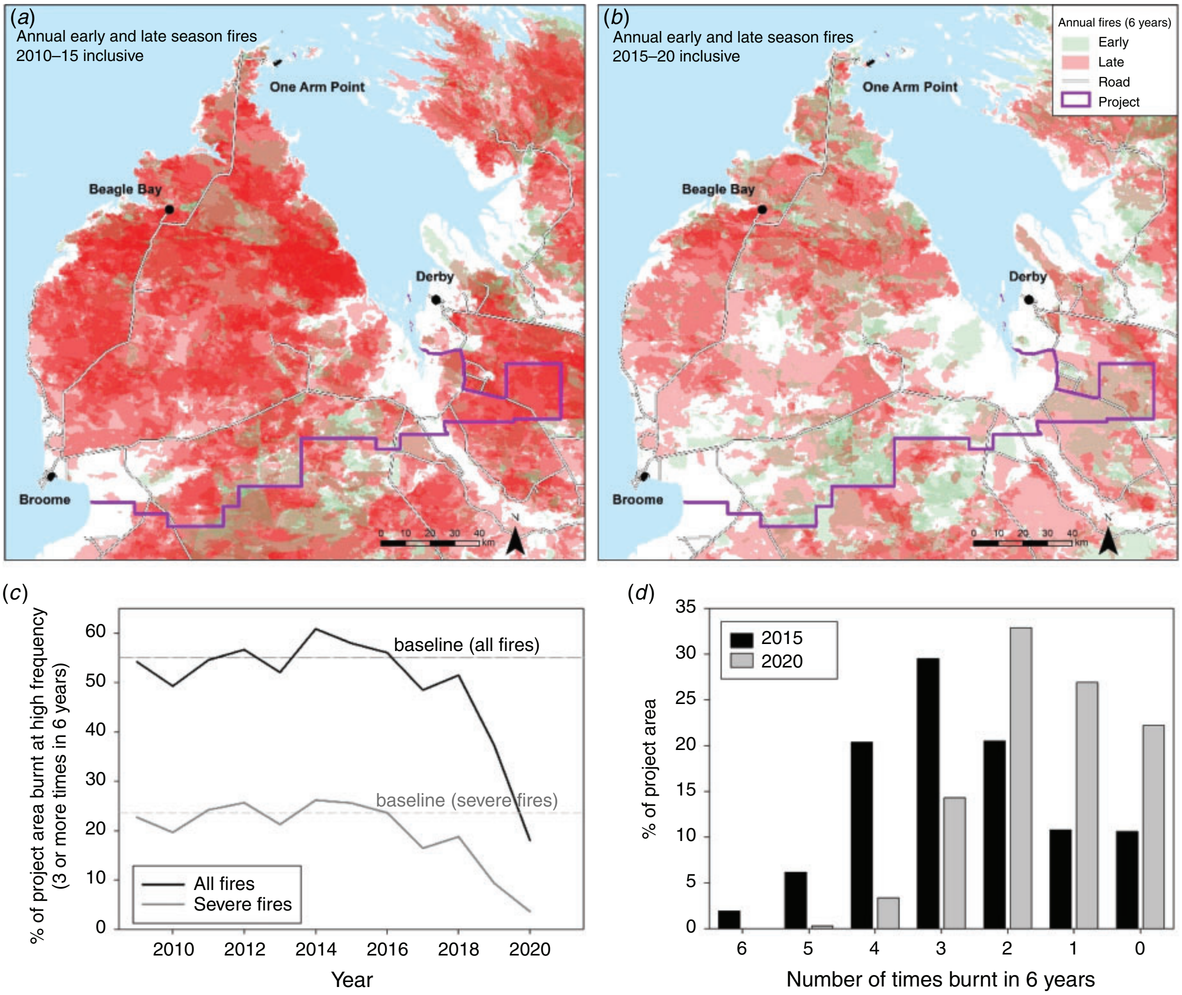


**Fig. 3.** Change in fire frequency over time: (*a*) 6-year fire frequency to the end of 2015; and (*b*) to the end of 2020. Each year's fire extent is shaded green (early dry season; January–June) and red (late dry season fires, July–December), and overlain with 70% transparency. The maps show a decline in fire frequency as well as a shift in fire seasonality from late to early dry season. (*c*) The percentage of the Dampier Peninsula that is burnt at high frequency (i.e. 3 times or more in 6 years) annually, for all fires and for severe fires, from 2009 to 2020. The baselines (dashed line) are the averages of the values from 2009 to 2015. The vertical line indicates when the collaborative fire project began. (*d*) The proportion of project area burnt at different frequencies, over the preceding 6 years, at the end of 2015 (baseline period) and the end of 2020 (after 5 project years).

target for wildfire abatement in tropical savanna ecosystems globally (Van Wilgen *et al.* 2004; Russell-Smith *et al.* 2015; Mistry *et al.* 2016; Evans and Russell-Smith 2020; Radford *et al.* 2020; Edwards *et al.* 2021). In northern Australia, the seasonality of fire is of particular interest, as late dry season fire is an indicator of wildfire extent and a key metric of the emissions abatement estimation. Our project in the Dampier Peninsula achieved a 30% reduction in the proportion of the annual fire extent caused by late dry season fires, decreasing it from an average over 12 years of 86% to an average over 5 years of 60% (Target 1.2, Table 1). The scale of this change is similar that of registered savanna burning projects elsewhere in northern Australia, where the proportion of the annual fire extent caused by late dry season fire has decreased by ~41% (from an average of 67% pre-project to 40% following implementation; Edwards *et al.* 2021). Although the baseline annual fire extents are similar (43% in the Dampier Peninsula, 46% in registered projects elsewhere in the savanna), and the scale of the fire seasonality change is comparable (30–40% reduction), the baseline proportion of the annual fire extent comprising late dry season fires was particularly high in the Dampier Peninsula (86% vs. 31% for registered projects), suggesting something about the social, vegetation and climate context predisposes the peninsula to late season fire. These contrasts also suggest there is potential to further reduce the proportion of mid-late dry season fire on the Dampier Peninsula.

The collaborative fire management reduced the annual fire extent by over half, from 43% to 19%, an unanticipated result. Reviews of fire management outcomes in Australia suggest that even when the extent of late season wildfires is reduced by prescribed burning, the net change in the overall fire extent is modest, including small increases (Penman *et al.* 2011), no

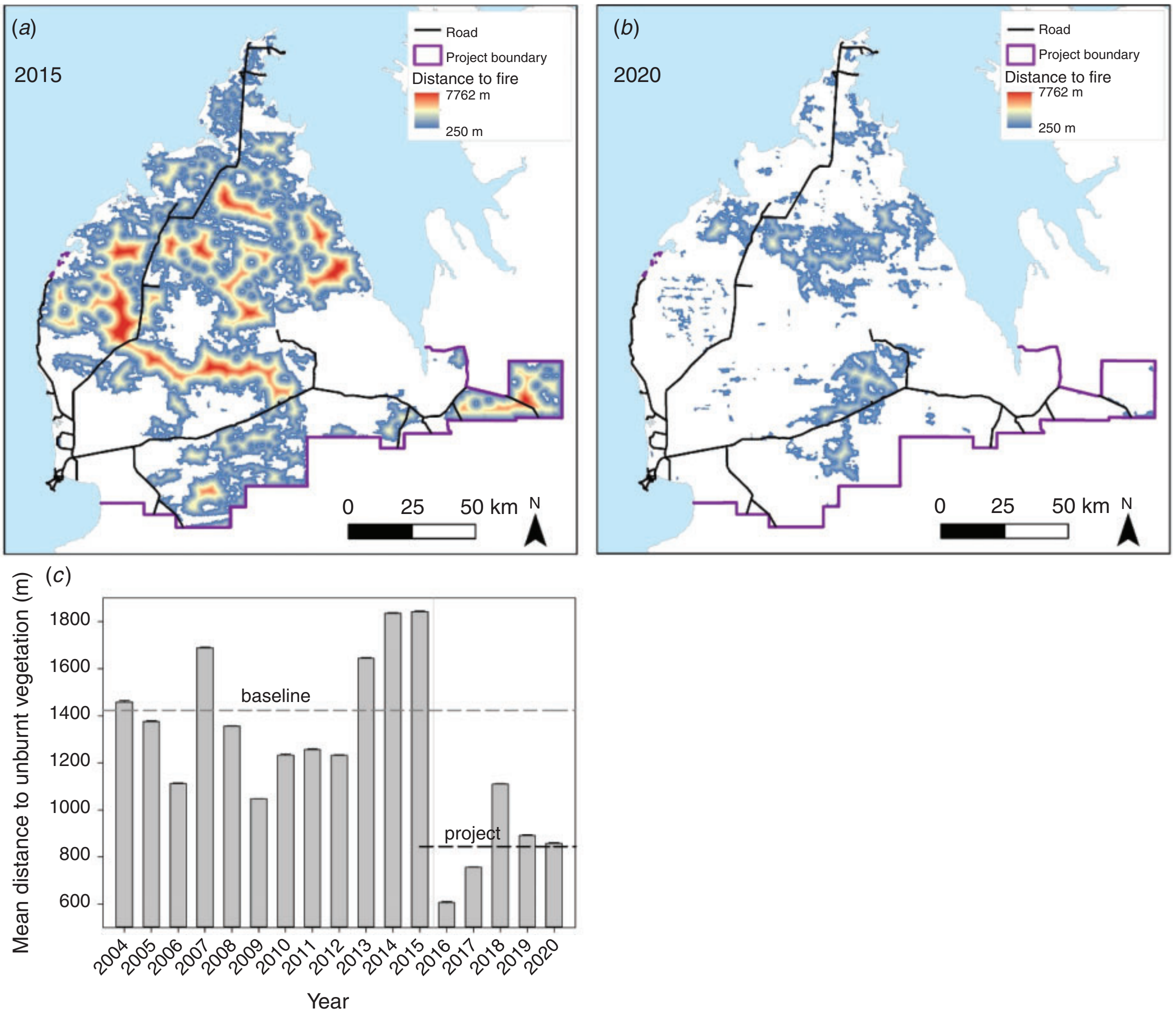


**Fig. 4.** The distance (mean and standard error) from burnt pixels to the nearest unburnt patch of at least 20 ha in size (*a*) at the end of 2015; and (*b*) the end of 2020. White areas of the map are unburnt vegetation; shaded areas are coloured to show the distance to the nearest unburnt vegetation. (*c*) The average distance to unburnt vegetation over time; the means of the baseline years (2009–15) and project years (2016–20) are shown with dotted lines.

change (Murphy *et al.* 2015; Evans and Russell-Smith 2020; Radford *et al.* 2020) or small decreases (Russell-Smith *et al.* 2013). Our project achieved a reduction in annual fire extent that considerably exceeds that of other prescribed burning projects in northern Australia (Russell-Smith *et al.* 2013; Murphy *et al.* 2015; Radford *et al.* 2020) (but see Legge *et al.* 2015*b*). One contributor to this discrepancy is the influence of the 2016 fire season, during which only 2.5% of the Peninsula burnt as a result of an unusually dry preceding monsoon season (with less than half the average rainfall, 312 mm), and very high annual fire extents in the previous 3 years (averaging 59.9% each year). Thus, low fuel availability contributed to the observed low fire extent in 2016. However, even if 2016 is excluded, the average annual fire extent in the project years 2017–20 was 23%, which is still much lower than the equivalent figure for the baseline years. The project stimulated constructive community conversation about managing fire and it is possible that this helped to reduce careless ignitions by residents on the Peninsula. We lack data to examine this, but note it takes very few ignitions late in the dry season to create extensive annual fire extents, and we doubt the change in fire patterns could be caused by changes in ignition patterns alone.

### *Impacts of the fire regime changes*

The high annual fire extent, high proportions of late dry season and severe fires, high fire frequency and high severe fire frequency in the baseline years of the project represent an extreme fire regime for pindan woodlands and shrublands, the prevalent vegetation type of the Peninsula. Pindan communities are dominated by obligate-seeder trees and shrubs that take 4–5 years (Radford and Fairman 2015) or 5–7 years (Kenneally *et al.* 1996) to recover from fire. Therefore, a minimum interval of 5–8 years between severe canopy-killing fires is needed to re-establish mature reproductive trees. Similarly, re-establishment of perennial hummock and tussock grass canopies typically takes 3 years following fire (Radford and Fairman 2015). Hence,

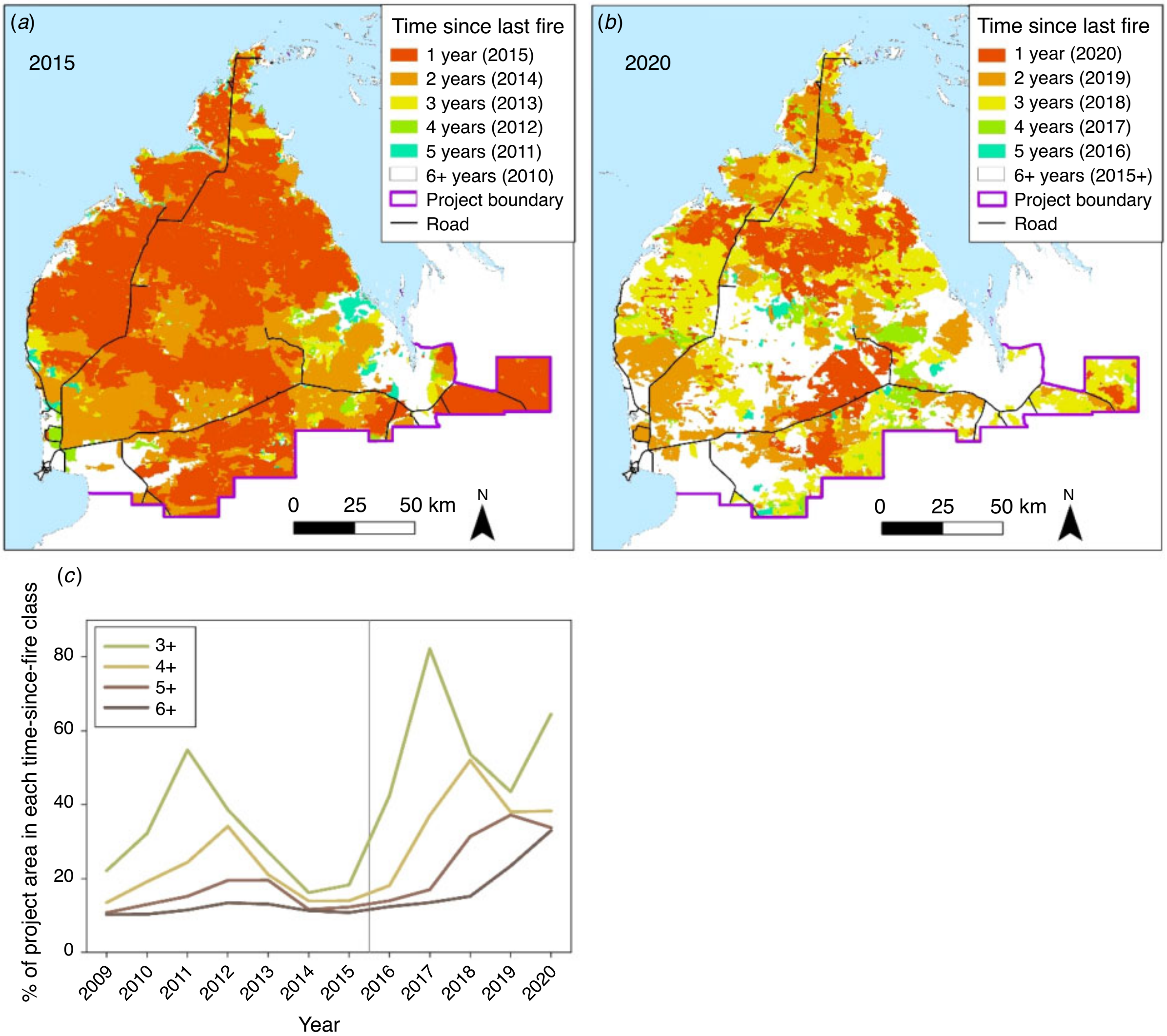


**Fig. 5.** Extent of different time-since-fire age classes across the Dampier Peninsula at (*a*) the end of the baseline period in 2015; and (*b*) at the end of the project period in 2020. (*c*) The percentage of the Dampier Peninsula that is long-unburnt (expressed as 3+, 4+, 5+ and 6+ years since fire) between 2009 and 2020. The vertical reference line shows the transition from the baseline years to the project years.

with frequent and severe fire, these communities may not reach climax ecological succession, but instead remain caught in a highly disturbed state, exacerbated by continual grazing (Legge *et al.* 2019). The fire regime of the baseline years is likely to favour epicormic re-sprouting trees and fast-growing forbs and annual grasses (Radford and Fairman 2015).

The fire regime being brought about by the project may cause the vegetation structure and species composition of the pindan communities to change. During a November 2020 workshop, the Group identified seven biocultural indicators that may respond to the fire regime change. These indicators represent assets previously identified in Healthy Country Plans, property management plans and regional planning documents (Watson *et al.* 2011; Oades and Meister 2013; Yawuru Registered Native Title Body Corporate 2014), and include nationally threatened species and ecological communities that are the subject of recovery plans and conservation advices (https://www.environment.gov.au/biodiversity/threatened). A key output of the workshop was the Dampier Peninsula Fire Project Monitoring Plan (DPFWG 2021), which outlines broad targets for each of the seven biocultural indicators and identifies costs associated with their monitoring. Securing funding to support partners to monitor these biocultural indicators on their tenures will be a key future priority of the Group.

While it may take years for the impacts of changing fire regimes to be understood, evidence suggests that improvements to these specific biocultural indicators are likely. The spectacled hare wallaby, *Lagorchestes conspicillatus*, and bilby, *Macrotis lagotis* – two rare medium-sized mammals on the Peninsula – require long-unburnt habitat for shelter from predators (McGregor *et al.* 2014; Leahy *et al.* 2015; Davies *et al.* 2020), close to recently burnt habitat for foraging (Southgate *et al.* 2007; Wysong *et al.* 2021). Hence, increased extent of long-unburnt habitat and reduced distance to unburnt vegetation are likely to benefit populations of these species. Spear wattle, *Acacia monticola*, an obligate-seeder tree that does not typically produce seed within 3 years of post-fire germination (Williams *et al.* 1999), is a culturally valued tree used by Aboriginal groups of the Dampier Peninsula to produce traditional artefacts such as clapping sticks, boomerangs and spears (Kenneally *et al.* 1996), now a source of income for Indigenous craft-makers. Reduced fire frequency, especially of severe fires, should benefit this species, and other culturally important, fire-intolerant species and ecological communities of the Peninsula, including the national endangered monsoon vine thickets (Vigilante *et al.* 2017; Lemon 2020).

### *The partnership – strengths and weakness*

The Group's success at changing fire regime changes on the Peninsula has been helped by some features of the collaborative partnership that was purposefully built around the Collective Impact approach to solving complex conservation problems outlined in the Open Standards for the Practice of Conservation (Carr *et al.* 2017). This approach describes five key features: a shared vision, coordinated action, accountability (the subject of the work presented here), communication, and project coordination and resourcing. The partnership was formed in recognition that the impediments to improved fire outcomes were social, rather than operational. The collaboration was structured to be thoroughly democratic: meetings before and after the burning season were facilitated, and expert technical advice was engaged, but there were no leaders, and differences in fire management objectives and operational delivery were respected. This format built trust among diverse partners and created a sense of shared ownership and co-development among individuals. Participants had different levels of prescribed burning experience and groups conducted fire operations on their own remote tenures, so these fora were important opportunities to learn from one another and to share skills, success and failures. The partnership also enabled local and state government agencies to work more efficiently across land tenures, rather than working with stakeholders separately. This allowed speedier, shared resolution for regulatory and operational barriers, and the efficiencies freed up more logistic and operational support for aerial and on-ground ignition, and related work such as creating mineral earth breaks. Regular communication among the group members was critical for maintaining cohesion. As well as the twice-yearly workshops, fortnightly conference calls during the burn season enabled members to stay connected, track overall progress across the Peninsula and adaptively respond to challenges on the ground.

The project's success was achieved despite significant challenges. The partnership formed around shared objectives, and built enough self-sustaining momentum to withstand challenges such as relying on year-to-year small grant funding to pay for coordination and communication, consultants to deliver planning workshops, external scientific expertise and to fill small funding gaps for critical operational components not covered in the participants' budgets. The project also survived turnover of key personnel who initiated and coordinated the project. The instability of funding and coordination poses ongoing uncertainty and risks to the project. Without a more secure source of funding for project coordination, planning and reporting, as well as operational delivery, even successful collaborative partnerships such as the Dampier Peninsula Fire Working Group are unstable and likely unsustainable.

## Conclusions

Prescribed burning across large land parcels in northern Australia is changing fire regimes by reducing the extent of wildfires (Legge *et al.* 2011; Murphy *et al.* 2015; Russell-Smith and Whitehead 2015; Corey *et al.* 2020; Evans and Russell-Smith 2020; Edwards *et al.* 2021). The emissions abatement opportunity that incentivises fire management has been a critical driver for these landscape improvements in fire regimes (Russell-Smith *et al.* 2009). In contrast, we achieved success across small land parcels managed by diverse interests without such incentive, but the project faces an ongoing risk of failure due to funding insecurity. To access emissions abatement funding, four enabling steps are needed. Pindan vegetation needs to be added as an eligible vegetation type in the approved methodology (Lynch *et al.* 2018). Second, the current rules stipulate that the baseline fire regime, against which the project performance is contrasted, is measured immediately before project registration. Hence, unless the baseline can be backdated, the Group's current success will work against them because their baseline would encompass project years with reduced late dry season fires, limiting the potential for further improvement and reducing carbon payments. Third, legislation in Western Australia means that the Minister of Lands needs to approve any new emission abatement projects on pastoral leases, but the process for doing so remains vexed. Finally, the Group would need to establish strong governance to manage the division of payments resulting from abatement across several landholders with varying baselines, operational capacities and objectives.

More fundamentally, the Group developed objectives and targets for fire regime changes designed to benefit biocultural and pastoral assets on the Peninsula. However, the emissions abatement scheme priorities greenhouse gas reductions, not biodiversity, pastoral and cultural targets. While the fire regime changes incentivised by emissions abatement programs may produce collateral benefits for biodiversity (Russell-Smith *et al.* 2015), there is debate about the alignment of these benefits (Corey *et al.* 2020). If the opportunity arises to register an emissions abatement project in the future, the Group could potentially monetise their activities through emissions abatement as a co-benefit to the primary focus of biodiversity, pastoral and cultural outcomes, a complex mix of objectives seen also in other regions (Ansell and Evans 2020). To help the Group find this balance, implementing their Dampier Peninsula Fire Project Monitoring Plan will be critical. Ideally, a novel incentive program that integrates outcomes across multiple axes, including emissions, biodiversity, cultural, economic and social outcomes, could provide a flexible framework to support collaborative fire management involving partners with diverse objectives.

## Data availability statement

All data are available from: https://firenorth.org.au/nafi3/.

## Conflicts of interest

The authors declare no conflicts of interest.

## Declaration of funding

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