CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/WF22173

International Journal of WILDLAND FIRE
International Association of Wildland Fire

Fire on a tropical floodplain: a fine-scale fire history of coastal floodplains in the Northern Territory, Australia

Robin Leppitt[A,B,*], Jay Evans[A,C,D], Luke Einoder[A,E], Peter M. Kyne[A], John C. Z. Woinarski[A,B] and Stephen T. Garnett[A,B]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Robin Leppitt
Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia
Email: robin.leppitt@gmail.com

Received: 4 August 2022
Accepted: 16 May 2023
Published: 20 June 2023

Cite this:
Leppitt R *et al.* (2023)
International Journal of Wildland Fire
32(8), 1200–1211. doi:10.1071/WF22173

ABSTRACT

Background. The coastal floodplains of northern Australia are fire-prone, but the impact of fire on floodplain biota is not well understood. **Aims.** In this study, we sought to characterise the fire history of six adjacent floodplains in coastal Northern Territory, Australia. **Methods.** We built a fine-scale 31-year fire history (1988–2018) to compare fire regimes on floodplains across land tenures and floodplain fire regimes with the surrounding savanna fire regime, determine the extent to which current fire regimes are meeting existing ecological fire thresholds, and investigate the relationship between rainfall totals and the extent of burning. **Key results.** Floodplains in conservation reserves burnt more frequently than those on pastoral lands, and savannas burnt more often than floodplains. Current floodplain fire regimes comfortably meet existing ecological fire thresholds. The proportion of floodplain burning is inversely proportional to the amount of rain in the previous wet season. **Conclusions.** Floodplain fire regimes vary markedly between land-use types, and floodplain fire regimes differ to those of savannas. The current management thresholds for floodplain fire regimes would benefit from further evidence of conservation outcomes. **Implications.** For more effective floodplain fire management, research is needed to generate floodplain-specific thresholds that best conserve their considerable conservation value.

Keywords: fire, fire management, floodplain, invasive grasses, Kakadu National Park, northern Australia, traditional burning, tropics.

Introduction

Changes to the fire regimes of northern Australia as a result of European settlement in the last two centuries are one of the primary drivers in the decline of many components of its vertebrate fauna and some plant species (Fraser *et al.* 2003; Franklin *et al.* 2005; Woinarski *et al.* 2011; Bowman *et al.* 2022). In an attempt to halt or reverse this decline, there has been a concerted effort to quantify the effect of various fire regimes on biodiversity to improve fire management practices. Most northern Australian fire research has focused on savanna woodlands (Andersen *et al.* 1998; Russell-Smith *et al.* 2003; Evans and Russell-Smith 2020), which are the dominant vegetation type of monsoonal northern Australia and are the most fire-prone biome on earth (Andersen *et al.* 2012). To a lesser extent, other fire-sensitive habitat types in northern Australia have also been the subject of research (e.g. monsoon forest, Bowman and Fensham 1991; *Callitris intratropica*, Bowman and Panton 1993; sandstone plateau, Russell-Smith *et al.* 1998). In contrast, very little is known about the effects of fire on northern Australia's tropical floodplains, notwithstanding their substantial extent and considerable ecological, cultural, and economic value (Lucas *et al.* 1997; Dyer *et al.* 2001; Finlayson *et al.* 2006).

The World Heritage-listed Kakadu National Park (NP) incorporates floodplains including Australia's second largest Ramsar-listed wetland as well as multiple globally recognised Key Biodiversity Areas (KBAs). Much of the conservation value placed upon floodplains stems from their unusually diverse and abundant waterbird, amphibian, and reptile populations, and extremely productive wetland systems (Bayliss and Yeomans 1990; Finlayson 2005; Finlayson *et al.* 2006; Madsen *et al.* 2006*a*, 2006*b*). The main land-uses of these floodplains are pastoralism, conservation, and Indigenous cultural practices. Outside conservation areas, the primary industry on the floodplain is beef production, with the floodplains' water-holding capacity providing greener pastures for a greater part of the year than that of the surrounding savanna.

Northern Australian floodplains are seasonally inundated in the wet season (broadly November–May) when high rainfall and temperatures trigger rapid production of grassy biomass. The floodplains subsequently dry out through the dry season (July–October), when the biomass cures and often burns. Wet season rainfall totals can affect the extent of burning in the subsequent dry season in some environments (Heinl *et al.* 2006; Archibald *et al.* 2010), but the extent to which they affect fire on northern Australian floodplains is not well understood. As with the surrounding savanna, fire can have important effects on the structure and floristics of floodplain vegetation, and hence biodiversity more generally, over short and long temporal scales (Heim *et al.* 2019).

The vegetation of the northern Australian floodplains has probably been influenced by human-induced fire regimes since their formation. These floodplains formed when rising sea levels, following thawing from the last ice age, stabilised around 6000–7000 years ago (Woodroffe *et al.* 1987). The fire regimes practised by Indigenous peoples over millennia are considered responsible for northern Australian floodplains being a largely treeless, grassy expanse – as are the floodplains' geomorphological origins (Lucas *et al.* 1997). Indigenous fire regimes seek to improve access to natural resources through patchy, seasonal burning (Roberts 1993). Indigenous burning is still practised on some floodplains of northern Australia (McGregor *et al.* 2010). Fire continues to shape floodplain vegetation (Cowie *et al.* 2000), with the timing and size of fire being one of the dominant drivers of the highly variable annual floodplain vegetation dynamic (Kleindl *et al.* 2015). Fire regimes influence perennial/annual vegetation competition and vegetation homogeneity, particularly of the grass community (Cowie *et al.* 2000; Boyden *et al.* 2003), and the cessation of fire management may lead to increased woody vegetation on floodplains (Lucas *et al.* 1997; Crowley *et al.* 2009).

Floodplain fire regimes in northern Australia have undergone significant changes since European settlement. Pastoral and tourism ventures have displaced, and continue to displace, Indigenous peoples from their ancestral lands, preventing or supplanting traditional burning (McGregor *et al.* 2010). The introduction and subsequent spread of the Asian water buffalo (*Bubalus bubalis* Linnaeus, 1758) has led to widespread degradation of the floodplains, particularly during their population peak in the second half of the 20th century (Skeat *et al.* 1996; Werner 2014). The reduction in grassy biomass associated with high density Asian water buffalo populations led to a reduction in the frequency and extent of floodplain fire (Roberts 1993). Similarly, overgrazing by domestic cattle can lead to a reduction in fuel loads (Sharp and Whittaker 2003). Although widespread culling of Asian water buffalo in the late 1980s saw fire return to the floodplains (Russell-Smith *et al.* 1997), Asian water buffalo numbers have increased again in some areas in recent decades (Robinson and Whitehead 2003; Petty *et al.* 2007; Campbell *et al.* 2021). Exotic pasture grasses introduced on pastoral stations now occur in some floodplain areas as extensive monocultures contributing to more intense and larger fires compared with native grasses (Cowie *et al.* 2000; Douglas and O'Connor 2004). Fire can also be used to break up monocultures of some invasive plant species, with varying success (Lonsdale and Miller 1993; Grice *et al.* 2010; McGregor *et al.* 2010). Despite these changes, the extent to which land tenure, vegetation composition, and invasive weeds and animals have influenced floodplain fire regimes is not well understood.

There have been few studies that have addressed fire management objectives for northern Australian floodplains. One study of the habitat preferences of the Alligator Rivers Yellow Chat (*Epthianura crocea tunneyi* Matthews, 1912), an endangered bird endemic to the floodplains of the Van Diemen Gulf coast of the Northern Territory, found that the chats prefer floodplain habitat that has not burnt for five or more years (Leppitt *et al.* 2022). This represents the only fire metric recommendation for the conservation of northern Australian floodplain biodiversity of which we are aware, and it pertains to only one floodplain species. In northern Australia, several studies of the fire history of Kakadu NP have included floodplains (Russell-Smith *et al.* 1997; Gill *et al.* 2000; Edwards *et al.* 2003). Other than the recommendations on fire management for the Yellow Chat, and in the absence of any detailed floodplain-specific interpretations of the fire metrics presented or knowledge of the relationships of floodplain conservation values with fire, the only published assessment of floodplain fire performance thresholds pertained to fire-driven habitat heterogeneity: (1) at least 25% of floodplains remain unburnt for 3 + years; and (2) at least 5% of floodplains remain unburnt for 10 + years. These thresholds were taken from a recommendation originally developed for savanna habitats (Woinarski and Legge 2013; Woinarski and Winderlich 2014; Russell-Smith *et al.* 2017). The extent to which savanna fire studies can be applied to floodplain fire management is unknown, but these environments have obvious differences in vegetation structure (floodplains being largely treeless) and hence fuel loads, and hydrology (floodplains undergo significant inundation in the wet season, which delays the curing of vegetation, and therefore become flammable later in the dry season than savannas). They also differ markedly in species composition and in conservation values.

In this study, we use fine-scale fire-mapping techniques to build a 31-year fire history (1988–2018) across six adjacent floodplains of varying land tenure in coastal Northern Territory, Australia. Using this approach, we provide a broad-scale assessment of floodplain fire regimes in the region to address the following aims: (1) compare fire regimes on floodplains managed for conservation with those floodplains managed for pastoralism; (2) compare fire regimes in floodplains and the contiguous savannas; (3) determine the extent to which current fire regimes are meeting existing thresholds for the floodplain vegetation community (Russell-Smith *et al.* (2017) and key species (e.g. Yellow Chat; Leppitt *et al.* (2022)); and (4) investigate the relationship between wet season rainfall totals and the subsequent extent of fire on the floodplains. The results of this study will be valuable for managing fire on these globally significant floodplains.

Methods

Study area

Floodplains of six adjacent northern Australian rivers were selected for fine-scale fire mapping. These floodplains were chosen because they encompass a relatively even proportion of conservation and pastoral tenures and contain high-value conservation areas (Ramsar-listed Wetlands of International Importance and Key Biodiversity Areas). These floodplains are also fire prone due to the high volumes of grassy fuel loads, a product of the extremely high rainfall they receive (approximately 1600 mm annually; Bureau of Meteorology rainfall data, http://www.bom.gov.au/climate/data/). The study area encompassed 4150 km^2 of the floodplains of the Adelaide River, Mary River, Wildman River, West Alligator River, South Alligator River, and the western side of the East Alligator River – all of which lie between Darwin (12.46°S, 130.85°E) and Gunbalanya (12.21°S, 133.02°E), Northern Territory, Australia (Fig. 1). The boundaries of these floodplains were mapped manually from satellite imagery because published floodplain boundaries often represent historical maximum flood extent, therefore incorporating adjacent woodland (Ward *et al.* 2014).

Land tenure of these floodplains comprises areas allocated to pastoral (47%) and conservation (53%) use, with the floodplain managed for conservation incorporating parts of Kakadu NP (managed by Parks Australia) and several smaller national parks and reserves (managed by the Parks and Wildlife Commission of the Northern Territory [PWCNT]). Other uses of the study area include recreational fishing, hunting, and wildlife tours, which have associated

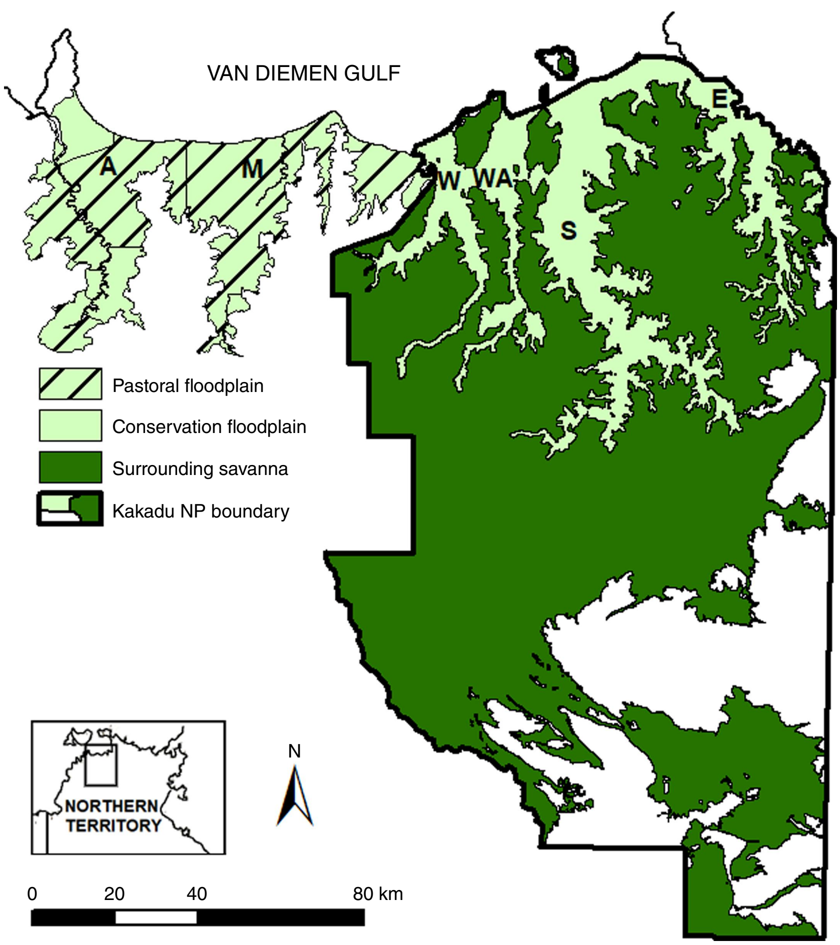

Fig. 1. Map of the study area showing the floodplains (light green area) of the Adelaide River (A), Mary River (M), Wildman River (W), West Alligator River (WA), South Alligator River (S), and East Alligator River (E), by land tenure (pastoral or conservation). The dark green represents the lowland savanna of Kakadu National Park (NP).

Table 1. Existing ecological fire thresholds for northern Australian floodplains.

Threshold	Assessed	Reference
At least 25% of floodplain should remain unburnt for 3 years	Achieved consistently >40% for 2006–2015 (Kakadu National Park only)	Russell-Smith *et al.* (2017)
At least 5% of floodplain should remain unburnt for 10 years	Achieved consistently >15% for 2006–2015 (Kakadu National Park only)	Russell-Smith *et al.* (2017)
Floodplain unburnt for 5+ years, no spatial threshold provided	Not assessed	Leppitt *et al.* (2022)

Assessments shown are assessments completed in the reference provided.

accommodation and infrastructure. Much of the conservation reserve network is also owned or co-managed by Indigenous peoples.

To enable comparison with the fire history of the floodplain study area, we compiled a fire history of the lowland savanna of Kakadu NP (land tenure entirely conservation) (Fig. 1). We chose this area of savanna because fire scar mapping was available for all landscapes within Kakadu NP, and because it is immediately adjacent to a large portion of the surveyed floodplains.

Fire mapping

Fire maps of both the floodplains and savannas of Kakadu NP were provided by the Darwin Centre for Bushfire Research (DCBR). To characterise the fire history over the rest of the study area, we obtained all available Landsat (30 m by 30 m resolution) satellite imagery from 1988 until 2018, sourced from the United States Geological Survey (USGS) database. Because suitable Landsat imagery was not available for the entire floodplain for 10 of the 31 years, fire maps outside of Kakadu NP were partially supplemented with data from the Northern Australia Fire Information (NAFI) service (MODIS satellites, 250 m by 250 m resolution; https://firenorth.org.au/nafi3/).

We viewed annual sets of true colour images in the Geographical Information System (GIS) program ArcMap (ESRI 2015) to select those that were largely cloud free. We applied a two-step process to map fire. The first step involved manually thresholding difference indices calculated from consecutive image dates, then editing commission errors on-screen from the vectorised outputs. Indices utilised were the normalised burn ratio and mid-infrared burn index. These indices incorporate the near infrared and short-wave infrared spectral regions and are sensitive to variations in soil moisture and leaf water content (Xu 2006; Wang and Qu 2007, 2009) so are effective in highlighting burned areas (López García and Caselles 1991; Pereira *et al.* 1999; Pleniou and Koutsias 2013). These indices are often confounded by factors that include changes in the presence of surface water (e.g. inundation or drying of the floodplains, tidal movement), vegetation changes as the floodplains dry out, and clouds and their shadows. We therefore applied a second step to cross-check mapped burn scars against corresponding true-colour images and then manually discarded areas that were not burn scars. Differenced image pairs were a maximum of 48 days apart, because longer time periods made burn scars too difficult to discern visually. Burn scars were then converted to polygons, attributed with month of burn (median of image date pairs) and combined with all the other polygons for that year, resulting in 31 fire maps representing where and when fires had burnt in the study area across each of 31 years.

Floodplain fire ecological thresholds

Two recommended thresholds specific to conservation reserves or for conservation outcomes in northern Australian floodplains (Table 1) have been proposed in an assessment of the fire management of Kakadu NP (Russell-Smith *et al.* 2017), and one in a study of the habitat use of the Alligator Rivers Yellow Chat, a bird endemic to the floodplains of this study area (Leppitt *et al.* 2022). These three thresholds take the form of a percentage of floodplain unburnt over a given time horizon (3, 5, and 10 years). As far as we are aware, these are the only floodplain-specific thresholds for northern Australia. The fire history we generated for the floodplains was used to determine how often these thresholds were met during the study period.

Data analysis

The fire mapping performed for this study, as well as the fire-mapping provided by the DCBR, was ground-truthed by visiting a total of 183 sites (78 in the area mapped by this study, 105 in the area mapped by the DCBR) within the study area during the late dry seasons of 2017 and 2018. At each of these survey points we recorded whether or not the site had burned and then compared the result with the fire maps for that year.

We generated four fire metrics from fire mapping: (1) total area of floodplain burnt each year; (2) patch size of each fire scar; (3) fire frequency; and (4) seasonality of each fire scar using ArcMap (ESRI 2015). The differences in average patch size between pastoral and conservation floodplain, floodplain and savanna, and early and late dry season fires were assessed by applying the Kruskal–Wallis test, a nonparametric analysis of variance (Kruskal and Wallis 1952). Interpretations of the estimates of patch size were carefully examined to ensure adjacent fires were not mistaken for single large contiguous burnt areas, which was possible when lower resolution imagery was used or there were longer intervals between mapped image pairs, because this increased the chances that more than one fire had occurred within the time period of interest. Seasonality of all fire scars was determined by classifying fires as early dry season (EDS) if they occurred before 1 August, or late dry season (LDS) if they occurred after 31 July (following Russell-Smith and Edwards 2006). Fire frequency was calculated as the number of years an individual 30 m^2 pixel from the fire scar raster file was mapped as burnt by the fire scar mapping over the entire survey period. We also analysed the frequency of fire when areas of floodplain that did not burn for the entire survey period were excluded, because these areas may be entirely non-flammable (e.g. permanently inundated areas, saltpans), to determine how much of the floodplain that can burn remains unburnt for the 3-, 5-, and 10-year time horizons used by Russell-Smith et al. (2017) and Leppitt et al. (2022).

We applied least-squares regression using the package 'Stats' in the statistical environment R (R Core Team 2017), with calendar year as the independent variable to examine the trends of the percentage of area burned each year over time for the whole floodplain, pastoral floodplain, conservation floodplain, and Kakadu NP savanna (R Core Team 2017):

$$\hat{y} = \beta_0 + \beta_1 x$$

where $\hat{y}$ is the regression estimate of the percentage burnt, x is the calendar year, β_0 is the regression intercept, and β_1 is the regression slope. The statistical significance of the regression trends over time was assessed using the standard error of the slope and its associated P-value.

We plotted the percentage of area burned on the whole floodplain against the total rainfall for the preceding wet season. Because there were no weather stations on the floodplains, monthly rainfall data were obtained from the Bureau of Meteorology for Darwin Airport, Jabiru Airport, and the South Alligator Ranger Station weather stations (situated approximately on the western, eastern, and southern edges of the study area, respectively). Annual rainfall totals were calculated by adding monthly rainfall totals from July of one year to June of the next, to capture the entire wet season preceding the fire season. Where rainfall data from a particular weather station were not available for a given month, that weather station was omitted from the rainfall calculations.

Results

Fire-mapping accuracy

The fire scar mapping performed in this study was 96.2% accurate when ground-truthed at the 78 sites visited on the ground, and mapping provided by the DCBR was 81.0% accurate for the 105 sites visited, for an overall estimated accuracy of 87.4%.

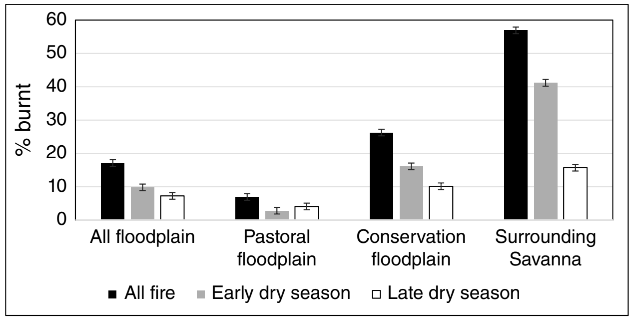

Fig. 2. Mean (±standard deviation) percentage of the study area burned annually during 1988–2018 by season, as well as by land tenure (pastoral or conservation), and the surrounding savanna of Kakadu National Park.

Area burned

On average, 17.1 ± 1.0% (standard deviation) of the floodplains burnt annually, with 7.3 ± 0.6% in the LDS (Fig. 2). A greater proportion of conservation floodplain (26.3 ± 1.6%) was burnt annually than was pastoral floodplain (7.0 ± 0.7%). Seasonality of fire varied between tenures, with a greater proportion of fires on conservation floodplain occurring in the EDS (61.2%) than in the LDS (38.8%). In contrast, on pastoral floodplain, fires more commonly occurred in the LDS (58.6%). Within Kakadu NP, fire was more extensive in the adjacent savanna, with more than twice the area burned on average each year (56.9 ± 1.8%) compared with the floodplain (26.5 ± 1.4%). There was a significant positive trend in the percentage of Kakadu NP savanna burnt annually over the 31-year study period ($P = 0.002$), but no significant trend across time in fire extent on pastoral or conservation floodplain, or floodplain collectively (Fig. 3).

Fire frequency

In total, 2970 km^2 (71.3%) of the surveyed floodplains burnt at least once from 1988 to 2018 (Fig. 4), meaning that 1180 km^2 (28.7%) remained unburned throughout the entire survey period. After removing unburnt areas of floodplain, fire frequency varied markedly between land tenures: 89.6% of conservation floodplain burnt at least once compared with 62.4% of pastoral floodplain, and 88.4% of pastoral floodplain burned five times or less, compared with 47.3% of conservation floodplain. For areas that burnt at least once, average fire frequency over the entire survey period varied. For the entire floodplain it was 5.0 times over the 31-year fire history, for pastoral floodplain 1.9 times, and for conservation floodplain 7.7 times, and the average interval between fires was 6.0 years for the entire floodplain, 15.5 years for pastoral floodplain, and 3.9 years for conservation floodplain. Within pastoral floodplain, >99% of floodplain that burned

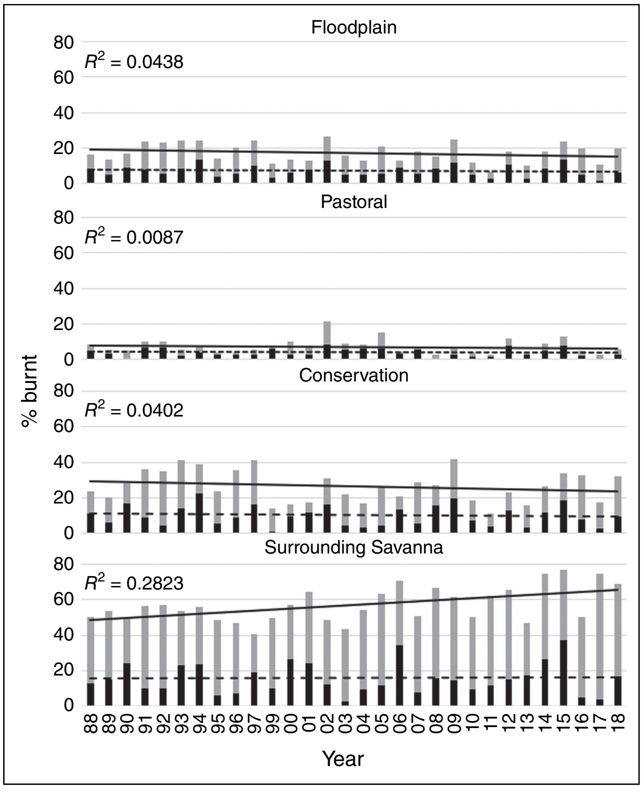

Fig. 3. The percentage of the study area burned each year for the entire surveyed floodplain, each land tenure, and surrounding savanna (Kakadu National Park). The black bars represent the extent of late dry season fires, and the black and grey bars combined represent the total area burned. The solid lines are the trend of total fire, and the dashed line is the trend line of late dry season fire. The R^2 value is calculated for the total trend of fire (solid black bar).

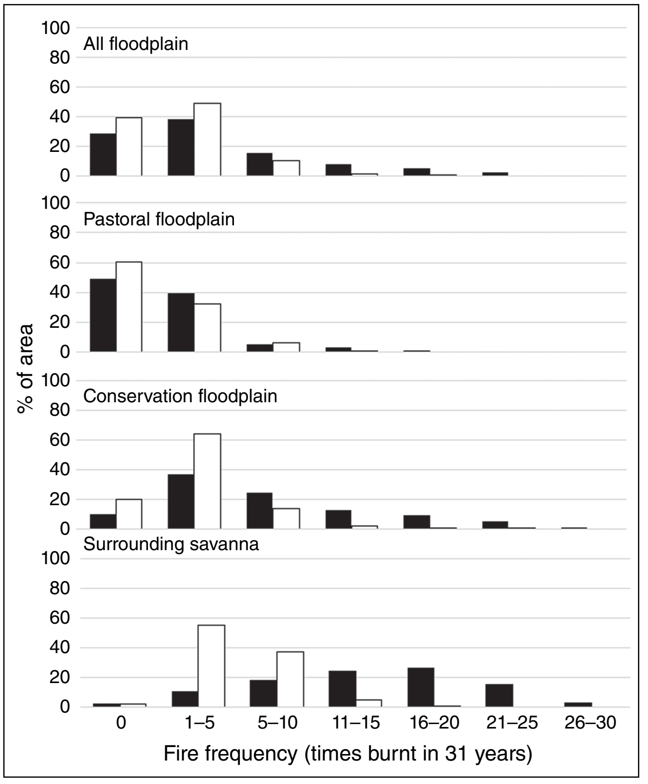

Fig. 4. The percentage of the study area burned at a range of different fire frequencies for the entire surveyed floodplain, each land tenure, and surrounding savanna (Kakadu National Park), over the 31-year period. Black bars represent all fires, and white bars represent late dry season fires only. All fire frequencies except for no fires (zero) have been binned into 5-year intervals.

more than three times was on the Adelaide River, whereas within conservation floodplain, the frequency of fire was more evenly spread, but was highest on the Adelaide River and South Alligator River floodplains (Fig. 5).

The average patch size of all fires that burnt on the floodplain during the study period was 45.9 ha (Table 2). Floodplain fire patches were significantly larger on pastoral floodplain compared with conservation floodplain but were significantly smaller than fires in adjacent savanna (Tables 2 and 3).

Floodplain fire thresholds

The percentage of unburnt floodplain over the three time horizons was relatively consistent over the course of the survey period, with the most variability in the 3-year time horizon (Fig. 6). A minimum of 59.8% and a maximum of 77.1% of floodplain was unburnt over the previous 3 years, a minimum of 53.3% and a maximum of 63.8% over the previous 5 years, and a minimum of 43.2% and a maximum of 50.1% over the previous 10 years. After excluding unburnt areas (possibly non-flammable), an average of 38.5% of floodplain was unburnt over the preceding 3 years, 29.6% over the preceding 5 years, and 17.6% over the preceding 10 years. The thresholds outlined by Russell-Smith *et al.* (2017) were therefore met (i.e. the observed extent of longer-unburnt floodplains was greater than the threshold value), whether or not unburnt floodplain was included.

Relationship with rainfall

There was a significant negative relationship between proportion of floodplain burnt and the preceding wet season's rainfall, meaning less rain often resulted in more floodplain fire. In contrast, on savanna, less rain resulted in a reduced overall area burnt, although this was a weak relationship (Fig. 7).

Discussion

This study represents the first floodplain-specific assessment of fire regimes in northern Australia and the first assessment of the fire regimes of northern Australian floodplains outside of Kakadu NP. The results of this study demonstrate the

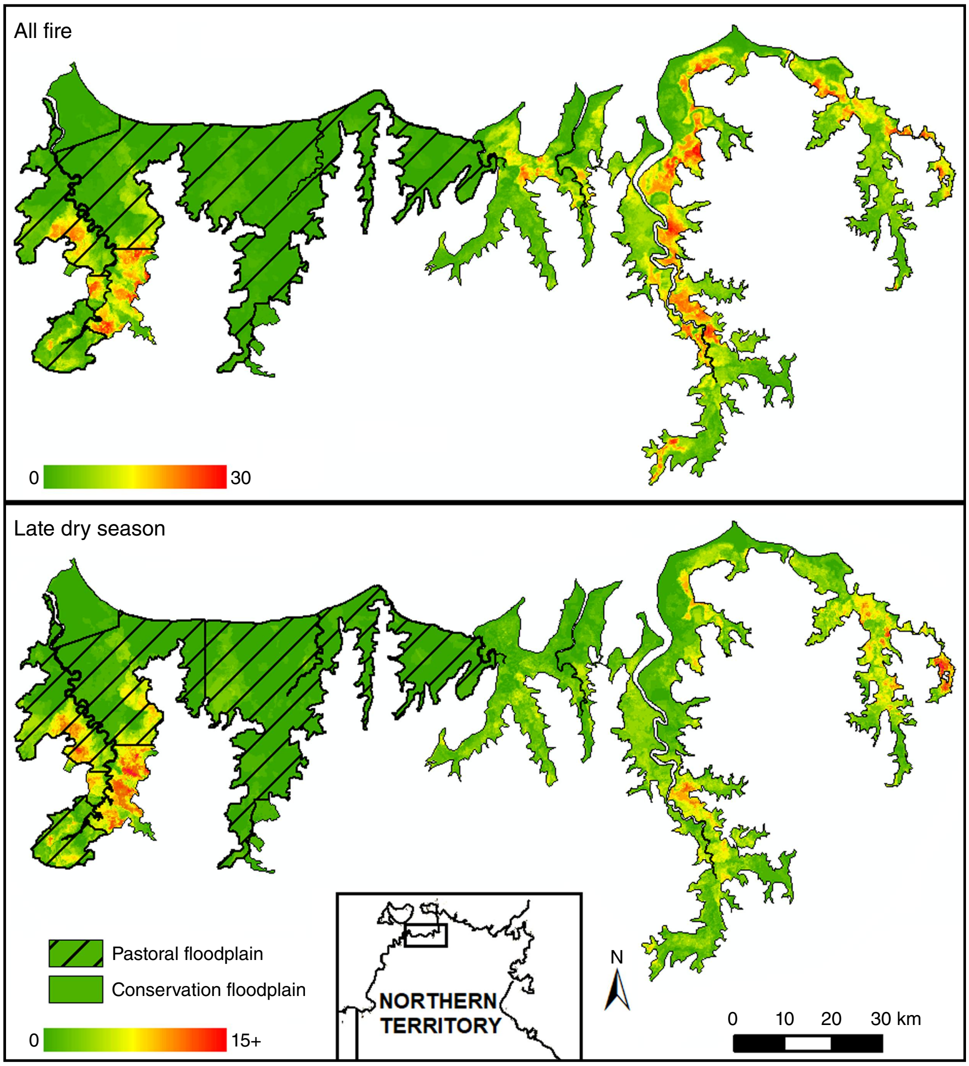

Fig. 5. Map of the surveyed floodplains showing the frequency of all fires and fires in the late dry season only during 1988–2018, across each land tenure (pastoral and conservation). The colour gradient reflects the number of times that each 30 m^2 pixel has been burned for the specified fire type. Note that colour scale is adjusted for late dry season fire to better illustrate areas that burned frequently at that time.

Table 2. The average patch size in hectares of all fires, early dry season fires, and late dry season fires for all floodplain, land tenures (pastoral and conservation), and surrounding savanna from 1988 to 2018.

	All fires	Early dry season	Late dry season
All floodplain	45.9	44.1	48.6
Pastoral floodplain	56.6	55.9	57.1
Conservation floodplain	43.8	42.4	46.2
Surrounding savanna	127.8	125.7	133.5

Table 3. Results of Kruskal–Wallis nonparametric analysis of variance tests to determine if the difference in the patch size of fires was significant.

Difference in average patch size	P
All floodplain < Surrounding savanna	<0.001
Conservation floodplain < Pastoral floodplain	<0.001
All floodplain EDS < All floodplain LDS	<0.001
Pastoral floodplain EDS < Pastoral floodplain LDS	<0.001
Conservation floodplain EDS < Conservation floodplain LDS	<0.001

EDS, early dry season; LDS, late dry season; land tenures, conservation and pastoral.

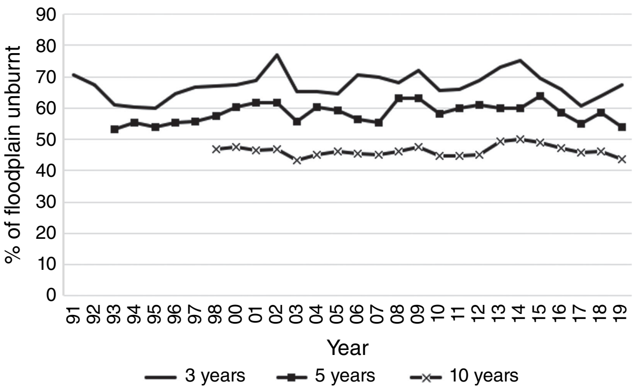

Fig. 6. The percentage of floodplain that had remained unburnt over the preceding indicated time horizon (3, 5, and 10 years). The 3- and 10-year time horizons are from the ecological performance thresholds for floodplain burning suggested in Russell-Smith *et al.* (2017), whereas the 5-year time horizon is the floodplain fire history associated with the floodplain endemic bird, the Alligator Rivers Yellow Chat (*Epthianura crocea tunneyi*; Leppitt *et al.* 2022) (Table 1).

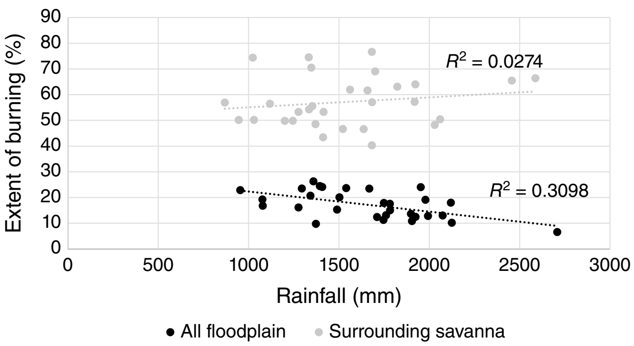

Fig. 7. The relationship between the percentage of land burnt for the surveyed floodplains and Kakadu National Park savanna and the annual rainfall in the preceding wet season from 1988 to 2018. R^2-values for each trendline are shown.

significant differences in fire history between conservation and pastoral floodplain land tenures, and between the surveyed floodplains and adjacent Kakadu NP savanna. This study found that the fire regimes of the surveyed floodplains have comfortably met the thresholds set out by Russell-Smith *et al.* (2017) and Leppitt *et al.* (2022) every year for at least the last three decades. This study also found that rainfall in the previous wet season explains more of the variation in the extent of burning on the surveyed floodplains than in Kakadu NP savanna, and that the relationship between the previous wet season's rainfall total and the extent of floodplain burning is negative. These results confirm that northern Australian floodplains require floodplain-specific fire management, and that significantly more research needs to be undertaken on the effects of various fire regimes on floodplain biota to better inform and establish ecological fire thresholds.

Floodplain tenure and fire

We found a major difference between land tenures in floodplain fire regimes, with dramatically less fire on pastoral floodplain than on conservation floodplain. This result is unsurprising – northern Australian pastoral fire management generally seeks to exclude wildfire from the floodplains to maintain grassy pastures throughout the year (Dyer *et al.* 2001). Fire can have an immediate impact on the availability of grass for cattle, particularly if soil moisture is low, making the pastures unusable until the following wet season. Fire management for conservation of savannas in northern Australia generally encourages fire that attempts to reproduce pre-colonial fire regimes, which is assumed to have consisted of frequent patchy burning in the early dry season that reduced the incidence of large, high-intensity late dry season fires (Fraser *et al.* 2003; Woinarski *et al.* 2005; Yates *et al.* 2008). Fire managers of conservation floodplains appear to have been at least partially successful in achieving this fire regime for the survey period, with the majority of conservation floodplain fire being in the early dry season.

Pastoral floodplains may also burn less frequently or extensively than conservation floodplains because of the high grazing pressure exerted by cattle (*Bos indicus* Linnaeus, 1758), which reduce grassy fuel loads, and hence fire probability. Feral herbivores are present on floodplains inside Kakadu NP (such as horse (*Equus caballus* Linnaeus, 1758), donkey (*Equus asinus* Linnaeus, 1758), pig (*Sus scrofa* Linnaeus, 1758), Asian water buffalo, and cattle), but management of feral animals over several decades has probably kept densities and therefore grazing pressure lower within the park than on the pastoral floodplains (Australian Government 2016). The majority of burning of floodplains under pastoral use occurred on the Adelaide River floodplain, which is the only floodplain with both pastoral and conservation floodplain directly adjacent (i.e. not separated by a river). This may be because fires moved from the more frequently burnt conservation floodplain to pastoral floodplain. It is also the only floodplain that is in close proximity to some urban areas, which may also make it more prone to fires started accidentally or deliberately by people.

Comparison between floodplain and savanna burning

We also found a major contrast in fire regimes between habitat types, with the surveyed floodplains burning much less frequently and extensively than Kakadu NP savanna. This is probably because pastoralists aim to exclude fire (Dyer *et al.* 2001), whereas fire is integral to management across both savanna and floodplains within Kakadu NP (Australian Government 2016). Even when pastoral floodplains were excluded from analysis, all observed fire metrics showed considerably more burning in savanna than floodplains. The surveyed floodplains likely burnt less than Kakadu NP savanna due to their higher water holding capacity: northern Australian floodplains are often inundated for extensive periods of the year (see Ward *et al.* 2014), reducing the amount of time they are dry enough to burn. However, a study of the Okavango Delta in Botswana found the opposite: floodplains burnt more frequently than adjacent drylands due to increased vegetation growth from streamflow on the floodplains (Heinl *et al.* 2006, 2007). In global comparisons, the relationship between floodplain and surrounding landscape burning may therefore be influenced by human use, climate, and fuel loads.

The average patch size of fires in Kakadu NP savanna is considerably higher than those on the floodplain (Table 2). In northern Australia, floodplains dry gradually, with water receding to channels and depressions and then backwater swamps as the dry season progresses (Ward *et al.* 2014). Fires that burn during this drying process often extinguish when they encounter wet areas (McGregor *et al.* 2010), thereby limiting their size. Additionally, the smaller size of the floodplains when compared with the Kakadu NP savanna and their often-elongated narrow shape means that fires spread less comprehensively than across large contiguous patches of savanna.

Burning for conservation – ecological thresholds

Notwithstanding some well documented traditional ecological knowledge (Russell-Smith *et al.* 1997; McGregor *et al.* 2010), there is a paucity of published research investigating the responses of floodplain taxa to fire. Thresholds represent monitoring criteria that are often used to evaluate fire regimes, and are most successful when they are based upon the fire requirements of the biodiversity they seek to protect (van Wilgen *et al.* 2014). The thresholds for floodplain burning set out in Russell-Smith *et al.* (2017) were largely based upon studies of savanna burning. However, the species composition and conservation values of floodplains and savannas are markedly dissimilar (Woinarski *et al.* 1988), and the extent to which savanna burning techniques are applicable to floodplains is unknown. For example, the maintenance of long-unburnt habitat is a metric of fire management in northern Australia savanna because key components of northern Australian biota appear to favour long-unburnt habitat (that is, habitat that had not burnt for 5 years or longer) (Andersen *et al.* 2005), but it may not directly translate to a floodplain setting. The 28.7% of the floodplains that remained unburnt for the entire 31-year survey period is likely non-flammable, either because it is permanently inundated, or because it is a non-flammable environment (e.g. saltpan, samphire). Therefore, the inclusion of non-flammable areas of floodplain into calculations of unburnt floodplain, as was done in Russell-Smith *et al.* (2017), does not give an accurate measure of floodplain that is long unburnt, because it is also measuring floodplain that is seemingly un-burnable. The number of years unburnt threshold may therefore be more useful if it is only applied to floodplain that is flammable. When only considering areas of floodplain that burnt at least once during the survey period, all three published thresholds (Russell-Smith *et al.* 2017; Leppitt *et al.* 2022) were still met, but that does not mean there is empirical evidence that they meet management objectives of maintaining the biological diversity of Kakadu NP (Australian Government 2016), or that of other floodplains in the region. Determining more appropriate thresholds for floodplain burning will require further research to establish how different fire regimes affect floodplain habitat structure and diversity.

Fire management for the conservation of biodiversity should be informed by the responses to fire of key floodplain plant and animal species, and the potential for use of fire to manage floodplain pest and weed species, but the influence that floodplain fire regimes have on those species is mostly unknown. In addition to the floodplain-endemic Yellow Chat, the floodplains are used by the nationally listed Plains Death Adder (*Acanthophis hawkei*) and globally significant numbers of waterbirds (Finlayson *et al.* 2006). More research is needed on the responses to fire of floodplain species of conservation or management concern. However, in the current absence of robust evidence of biodiversity responses to fire, floodplain burning thresholds for the purpose of conservation should ideally encourage a return to floodplain burning regimes preceding European settlement, because floodplain biota likely adapted to these fire regimes over the millennia they were practised (Yates *et al.* 2008). These fire regimes were likely practised on the floodplains since their formation (Lucas *et al.* 1997). Indigenous floodplain burning was gradual and patchy, and used the matrix of wet and dry areas of floodplain present in the early dry season to keep fire patch sizes small and iteratively build up protective firebreaks (including burning the same area several times) that would restrict the spread of intense LDS fire used to promote habitat heterogeneity (Haynes 1985; McGregor *et al.* 2010). Therefore, more apt thresholds may incorporate more nuanced patch size and frequency requirements, rather than seasonality or a broad proportional area of floodplain unburnt over a given time horizon as is used in Russell-Smith *et al.* (2017).

Although this study found that the majority of the floodplain meets the preferred fire regime of the Alligator Rivers Yellow Chat, the proportion of the floodplain that needs to meet this criterion is unclear. Alligator Rivers Yellow Chats appear to inhabit quite a narrow floodplain niche (Leppitt *et al.* 2022), so fire management for this threatened taxon may need to target specific chat 'hot-spots', or areas of floodplain that meet other chat habitat criteria (as per Leppitt *et al.* 2022).

Wet season rainfall and fire

This study found that high-rainfall wet seasons generally result in less floodplain being burnt during the subsequent dry season. This is probably due to greater levels of rainfall and floodplain inundation reducing the amount of time floodplains are dry enough to burn. In contrast, this study found that the relationship between wet season rainfall total and the extent of burning in Kakadu NP savanna in the preceding dry season was much less pronounced. Previous studies have found that savannas generally have a positive relationship between rainfall and subsequent extent of burning; generally, rainfall promotes the growth of readily burnable grassy biomass, which fuels more extensive fires when the landscape dries (Archibald *et al.* 2010). However, this relationship becomes less pronounced at very high levels of annual rainfall (Archibald *et al.* 2010) because extended wet seasons can reduce the amount of time that landscapes are dry enough to burn, as well as the growing season of the grasses that emerge after the water recedes.

Conclusions

This study has quantified the fire regimes prevalent under two of the dominant land tenures on the northern Australian floodplains – pastoralism and conservation. It has demonstrated that in the Van Diemen Gulf coastal floodplains of the Northern Territory, pastoralists have been largely successful at excluding fire from their floodplain pastures. In conservation reserves, where management objectives are more complex, burning has been much more frequent, with most fires occurring in the early dry season. Further research is required to fully understand the influence of fire regimes on floodplain vegetation, conservation values, and potential uses for the control of pest and weed species, because this can inform thresholds which land managers can strive to achieve. These thresholds should enable the continued use of the floodplains as an important food source for Indigenous peoples, as well as allowing floodplain biota to thrive, with an emphasis on floodplain-dependent species. Better-informed floodplain fire management will increase the resilience of floodplain biodiversity to the threats posed by weeds, feral animals, and sea-level rise.

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Data availability. Data available at https://doi.org/10.6084/m9.figshare.19185107.v1.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. This research received support from Charles Darwin University and the Australian Government's National Environmental Science Program through the Threatened Species Recovery Hub. PMK was supported through the Marine Biodiversity Hub, a collaborative partnership supported through funding from the Australian Government's National Environmental Science Program.

Acknowledgements. The authors acknowledge the Traditional Owners of the lands on which the research was conducted, most notably Victor Cooper, Sean Nadji, and the Larrakia people, on which Charles Darwin University's Casuarina campus stands. We also acknowledge Roy Tipiloura and Harold Swan, who contributed to the collection of data.

Author contributions. All authors were involved in conceiving the ideas and designing the methodology: RL collected the data; RL and JE analysed the data; and RL led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Author affiliations

[A]Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia.

[B]Threatened Species Recovery Hub, National Environmental Science Program, Australia.

[C]Darwin Centre for Bushfire Research, Research Institute for Environment and Livelihoods, Charles Darwin University, Darwin, NT 0909, Australia.

[D]Bushfire and Natural Hazards Cooperative Research Centre, East Melbourne, Vic. 3002, Australia.

[E]Kakadu National Park, Jabiru, NT 0886, Australia.