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A tale of two parks: contemporary fire regimes of Litchfield and Nitmiluk National Parks, monsoonal northern Australia

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Abstract. Fires burn vast areas of the monsoonal savannas of northern Australia each year. This paper describes the contemporary fire regimes of two ecologically similar, relatively large national parks (Litchfield—1464 km^2; Nitmiluk—2924 km^2) in the Top End of the Northern Territory, over 8 and 9 years, respectively. Fire histories for both parks were derived from interpretation of LANDSAT TM imagery, supplemented with NOAA-AVHRR for cloudy periods at the end of the 7-month dry season (*c.* April–Oct). Data concerning seasonality, extent and frequency of burning were analysed with respect to digital coverages for the park as a whole, landscape units, vegetation types, infrastructure and tenure boundaries. Ground-truth data established that interpreted accuracy overall, for 2 assessment years, ranged between 82 and 91% for both parks. Over 50% of Litchfield and 40% of Nitmiluk was burnt on average over this period, with Litchfield being burnt substantially in the earlier, cooler, and moister, dry season, and Nitmiluk mostly in the parched late dry season, after August. On both parks the current frequency of burning in at least low open woodland / heath habitats is ecologically unsustainable. Both parks are prone to extensive fire incursions. The data support earlier regional assessments that the average fire return interval is around 2 years in at least some areas of northern Australia. Nevertheless, comparison of contemporary fire regimes operating in three major regional national parks shows distinct differences, particularly with respect to the extent and seasonality (hence intensity) of burning in relation to different landscape components. Management implications are considered in discussion.

Introduction

Vast tracts of savanna currently are burnt annually in northern Australia over the *c.* 7 month dry season (May–November), particularly in the 'Top End' of the Northern Territory and the Kimberley region of north-western Australia (Allan and Willson 1995; McMillan *et al.* 1997). Given the productivity of grassy fuels over this region, fires may recur at any one site on an annual–biennial basis (Stocker and Mott 1981; Walker 1981). These fires are mostly anthropogenic, lit for a variety of pastoral, indigenous (Aboriginal), and conservation management purposes (Haynes 1985; Press 1988; Lewis 1989; Head *et al.* 1992). Most burning occurs later in the season, after July, under relatively severe fire climate (Gill *et al.* 1996) conditions.

Fire regimes play a critical role in regulating eucalypt-dominated savanna pattern, structure, and faunal dynamics (e.g. Braithwaite and Estbergs 1985; Bowman *et al.* 1988; Andersen 1991; Trainor and Woinarski 1994; Williams *et al.* 1998). Significantly, contemporary fire regimes in both northern and north-western Australia are damaging fire-sensitive communities/habitats, e.g. cypress pine (*Callitris intratropica*) communities (Bowman and Panton 1993); monsoon rainforests (McKenzie and Belbin 1991; Russell-Smith and Bowman 1992); paperbark (*Melaleuca*) wetlands (Williams 1984); sandstone heaths (Russell-Smith *et al.* 1998), and certain faunal assemblages (Woinarski 1992; Lowe 1995).

Growing appreciation of the implications of such fire regimes for the conservation of biodiversity has resulted in

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rapid and significant change in the resourcing and practice of fire management on regional conservation parks and reserves, particularly in the Top End of the Northern Territory. In part, this process has been prompted by the undertaking of relatively fine-resolution fire mapping and monitoring derived from interpretation of remotely sensed LANDSAT data, as developed initially for the World Heritage Kakadu National Park (Day 1985; Press 1988; Graetz 1990; Ryan *et al.* 1995). An assessment of the seasonality, extent and patchiness of fires in Kakadu, 1980–1994, derived from interpretation of LANDSAT imagery, was reported recently (Russell-Smith *et al.* 1997*a*).

This paper extends that assessment to two other major reserves in the Top End, Litchfield and Nitmiluk National Parks (NPs), over 8 years (1990–97) and 9 years (1989–1997), respectively. These two parks, like Kakadu, include extensive vegetation and landscape features derived mostly from sandstone formations, and occur in broadly similar landscape and sparsely settled, land tenure settings, but are markedly smaller. After consideration of the potential errors associated with developing these fire histories, specifically for both parks we explore: (1) the seasonality, extent and frequency of burning; (2) the patterning of fires with respect to vegetation types, infrastructure (roads, developed sites), and boundaries; and (3) implications for conservation management at individual park and broader regional scales.

Methods

Study regions

Litchfield and Nitmiluk (formerly Katherine Gorge) NPs are both situated in the Top End of the Northern Territory, Australia (Fig. 1), in a region characterised by high fire frequency (Fig. 3). Litchfield covers 1464 km^2, and Nitmiluk 2924 km^2. The physiography of both parks is dominated by sandy plateau sediments overlaying sandstone strata, bounded by steep slopes and escarpments, and surrounded by lowland plains derived principally from transported Quaternary sediments (Mulder and Whitehead 1988; Pietsch 1989). The climate is monsoonal and, although the amount of rainfall received over the summer months (November–April) varies markedly from year to year, the annual wet season is highly reliable (Taylor and Tulloch 1985). Mean annual rainfall for Litchfield is *c.* 1600 mm, and for Nitmiluk is *c.* 1000 mm. Winds in the dry season are predominantly from the south-east (Gill *et al*. 1996).

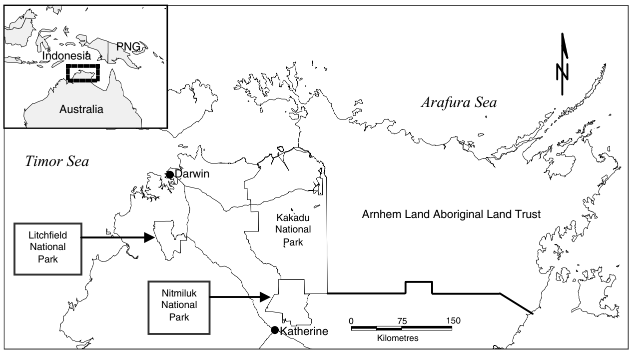

Fig 1. Location of some major ‘Top End’ National Parks in the Northern Territory, including the Litchfield and Nitmiluk study areas.

Vegetation cover of both parks is primarily eucalypt-dominated open-forest and woodland savanna. Fire-sensitive communities in both parks include: scattered stands of cypress pine (*Callitris intratropica*; plant authorities follow Dunlop *et al.* 1995) developed particularly on sandy deposits; rainforest patches associated with springs and creeklines (in Litchfield especially) and, in Nitmiluk, a few occurrences of *Allosyncarpia*-dominated rainforest associated with protected sandstone gorges; and shrubby heath (low open woodland) typically intermixed with spinifex (*Triodia*) grasses developed on skeletal/rocky substrates.

Imagery

The fire histories for Litchfield (1990–1997) and Nitmiluk (1989–1997) National Parks were derived mostly from LANDSAT Thematic Mapper (TM; pixels 30 × 30 m) quad scenes (*c.* 90 km × 90 km), sampled three times over each dry season. Two quad scenes were required to cover Nitmiluk; one was sufficient for Litchfield. For both parks a first image was obtained ideally (depending on availability) early in the dry season (*c.* late May/early June), and a second obtained around late July/early August. As described by Russell-Smith *et al.* (1997*a*), image sampling at these times is required to cover the main prescribed burning period, and to overcome interpretation problems associated with rapid regrowth of perennial grasses under still relatively favourable soil moisture conditions. A third image was obtained as late in the dry season as possible, before the onset of cloudy conditions. For a number of years where cloudy conditions late in the dry season precluded/limited the use of LANDSAT imagery, interpretation of firescars for this sampling period was augmented using frequent NOAA-AVHRR imagery (pixels 1.1 km ×1.1 km at orbital nadir). A full schedule of the imagery used in this study is presented in Fig. 4.

Fire history

Mapping of firescars from LANDSAT TM and NOAA-AVHRR imagery was undertaken as follows:

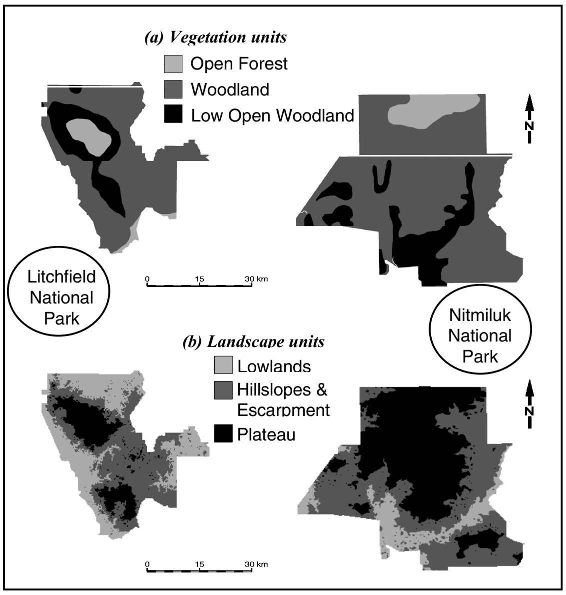

Fig 2. Major vegetation units (*a*) and Landscape Units (*b*) for Litchfield and Nitmiluk National Parks. Refer to text for details.

LANDSAT TM: Digital images were obtained for both parks according to the schedule described above. Initially, data for only one band (band 5: shortwave infrared, 1.55–1.75 µm) was purchased for the early and late images and three bands (band 3: red, 0.63–0.69 µm; band 4: 0.76–0.90 µm; and band 5) mid-year. For latter years, all three bands were acquired for each date. Digital images were first rectified, co-registered, enhanced with a histogram equalisation to highlight firescars, and then plotted as a hard-copy reference. Interpretation of firescars was undertaken by, or with the assistance of, field staff. For Litchfield this was undertaken by digitising firescars on-screen. For Nitmiluk a more manual procedure was adopted which involved: (1) overlaying the hardcopy print with plastic film; (2) manual mapping of firescars and marking of registration points, using a fine-tipped pen; (3) scanning of the mapped coverage; and (4) registration and assembly of the mapped coverage as part of the park's GIS fire history database. The above procedures were undertaken with ER Mapper image processing (Earth Resource Mapping, 1990–1998) and Arc Info GIS (Environmental Systems Research Institute, Inc. 1982–1998) softwares.

NOAA-AVHRR: Data for late dry season sampling periods, when LANDSAT TM images were not available, were extracted from the NOAA AVHRR fire history database for the Northern Territory. The database was established in 1993. Its characteristics and the digital image processing methods are described by Allan and Willson (1995) and McMillan *et al.* (1997). Although the spatial scale and the potential interpreted accuracy of the AVHRR derived fire history are markedly different from the LANDSAT TM data, they provide useful information on the presence/absence of large fires when LANDSAT data were unavailable.

Ground truth

Independent ground truth data were obtained for both parks in 1996 and 1997, in association with late dry season sampling of LANDSAT TM imagery (Fig. 4). Following the method adopted for Kakadu National Park (Russell-Smith *et al.* 1997*a*), a series of random start aerial transects was flown by helicopter across both parks. In contrast to the Kakadu assessment procedure, however, ground-truthing was undertaken here late in the fire season associated with the final annual acquisition date for LANDSAT imagery. Altitude and speed were held relatively constant at 50 m, and 40 knots, respectively. Sampling was undertaken every 30 s. At each sampling point the GPS location was recorded, and whether the vegetation directly beneath (i.e. within a diameter of *c*. 200 m) the helicopter was burnt, patchily burnt (i.e. presence of more than 20% grass cover after burning, or the immediate proximity of a distinct burnt/unburnt boundary), or unburnt. These data were used subsequently to assess the firescar interpretation.

Analysis

A number of GIS coverages were utilised. Fire history data for the first two sample periods (i.e. up until early August) were combined and are referred to throughout as Early Dry Season (EDS) coverages. Fire history coverages for the end of the dry season likewise are referred to as Late Dry Season (LDS) coverages. Other coverages comprised: park boundaries; major landscape units (i.e. lowlands, hillslopes and escarpments, plateaux; Fig. 2*b*) derived from digital 1:250 000 topographic mapping (map accuracy error ± 125 m); major vegetation units (open forest, woodland, low open woodland; Fig. 3*a*) mapped at 1:1 000 000 (modified after Wilson *et al.* 1990); more refined map data for rain forests at 1:100 000 (Russell-Smith and Lucas unpublished); and camping areas, roads and tracks. Definition of major landscape and vegetation units for both parks is given in Table 1.

Analyses based on these coverages were as follows. Assessment of mapping accuracy based on ground-truth data was undertaken on circular polygons of 100 m radius, centred on respective GPS positions (error ± 100 m, associated with selective availability of the satellite signal). Sampling points recorded as patchily burnt in field assessment, were treated as burnt in analyses. The seasonal extent of burning (EDS vs. LDS) was assessed for each park over respective study periods: for the park as a whole; by major landscape units; and by broad vegetation units and relatively fire-sensitive rainforest communities. Where appropriate, two-tailed *t*-tests were used to compare mean areas burnt using the 8 years data available for Litchfield, and 9 years for Nitmiluk, respectively. Where given in results, ± SEM refers to ± 1 standard error of the mean.

Frequency of burning of individual 900 m^2 pixels was assessed for each park as a whole, and by major vegetation units. As a means for assessing whether management-prescribed burning was concentrated in the vicinity of fixed assets and infrastructure, proximity analyses (two-tailed *t*-tests) were undertaken between the seasonal extent of burning within 0–0.5 km of, and 0.5–2.0 km away from, camping areas, roads and tracks. Choice of these distances was predicated on the relatively concentrated track network, particularly in Litchfield NP. Finally, assessment of the locations and extent of fire incursions over respective sample periods was undertaken for both parks. Analyses of the patch size distribution of individual fires was not undertaken more generally,

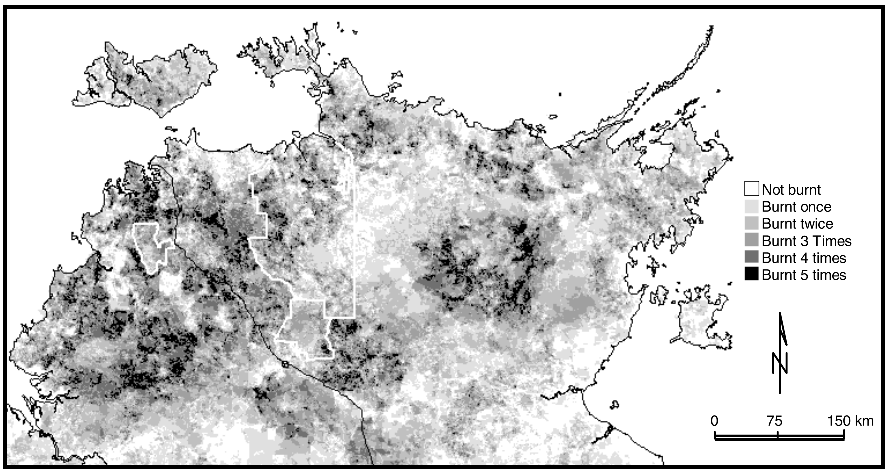

Fig 3. Frequency of burning in the 'Top End' of the Northern Territory, 1993–1997, derived from NOAA-AVHRR imagery (data: G.E. Allan, unpublished).

Table 1. Definitions of major (*a*) landscape and (*b*) vegetation units for Litchfield and Nitmiluk National Parks

	Litchfield National Park	Nitmiluk National Park
(a) Landscape units		
Lowlands	Slopes ≤ 2°, elevation < 90 m	Slopes ≤ 2°, elevation < 180 m
Hillslopes and escarpments	Slopes > 2°, elevation 90–160 m	Slopes > 2°, elevation 180–270 m
Plateau	Slopes ≤ 2°, elevation > 160 m	Slopes ≤ 2°, elevation > 270 m
(b) Vegetation units		
Open forest	Trees 10 – 30 m; foliage projective cover 30–70%	
Woodland	Trees 10–30 m; foliage projective cover 10–30%	
Low open woodland	Trees 5–10 m; foliage projective cover 1–10 %	

however, given that large 'contiguously burnt areas' can be the product of a multitude of small independent fires, particularly in the EDS (Russell-Smith *et al.* 1997*a*). Data assembled for the undertaking of this study are available from the *IJWF* website at http://www.publish.csiro.au/journals/ijwf/AccessMat.cfm.

Accuracy assessments based on independent ground-truth data, and boundary analyses of the extent of fire incursions, were processed using the vector analytic capabilities of MapInfo Professional, Version 4.5.2 (MapInfo Corporation, 1985–1998). All other GIS analyses were raster-based and performed with the GRID module of Arc Info (Environmental Systems Research Institute, Inc. 1982–1998). Statistical analyses were undertaken with Microsoft Excel 97 (Microsoft Corporation 1985–1997).

Results

Coverage and ground truth

Acquisition dates for LDS LANDSAT TM imagery sampled in this study indicate generally close correspondence with onset of rainy conditions at the end of the year (Fig. 4). Where suitable LANDSAT images for mapping LDS fires were unavailable (e.g. Nitmiluk 1995–1997), from 1993 these were augmented with archived, coarser-resolution NOAA-AVHRR imagery (Fig. 4).

Ground-truth results for the years 1996 and 1997 are presented for both parks in Table 2. Data indicate that overall agreement with mapped interpretation of LDS firescars was greater than 80% in both years, for both parks. Mapping accuracy was generally poorer in patchily burnt pixels, and also burnt pixels in Nitmiluk NP (Table 2). These ground-truth data provide for a relatively high degree of confidence in the interpreted fire histories of both parks for any one year, at least at the landscape scales considered here.

Seasonal extent of burning

The interpreted fire histories of Litchfield (1990–1997) and Nitmiluk (1989–1997) NPs are given in Fig. 5*a*,*b*. Over these periods an average of 56% of Litchfield and 40% of Nitmiluk has been burnt each year. On two occasions, 1996 in Litchfield and 1993 in Nitmiluk, over three-quarters of each park was burnt; in the case of Nitmiluk this occurred mostly in the LDS. Burning in Litchfield has been undertaken predominantly in the EDS. In Nitmiluk, while more burning has occurred in the LDS, the mean extent of EDS and LDS burning is not statistically significant (Table 3). The above observations for both parks hold generally also for the distribution of fires across major landscape units (Table 3).

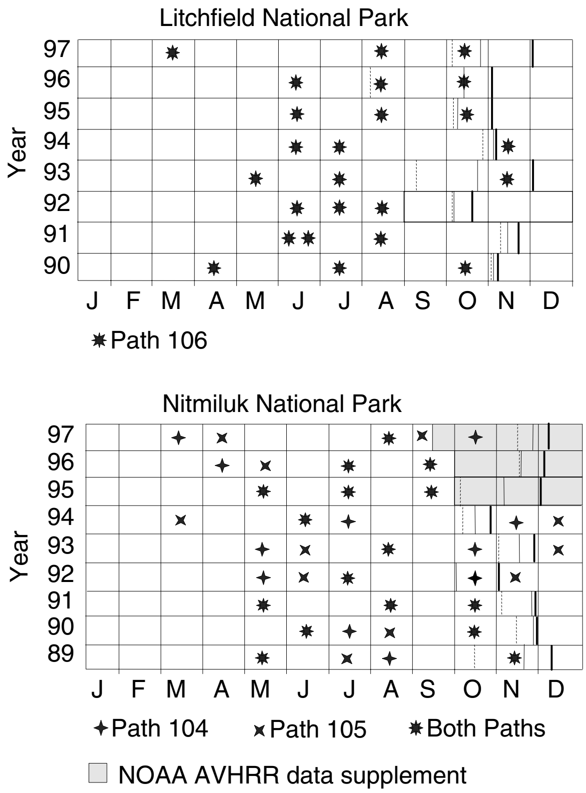

Fig. 4. Acquisition dates for LANDSAT imagery (and NOAA-AVHRR supplementation) relative to onset of rainy (cloudy) conditions at commencement of wet season, where: ⋮ = 25 mm, | = 50 mm, **I** = 100 mm , cumulative rainfall. Mean rainfall calculated from stations as follows: Litchfield National Park–Batchelor Aerodrome and 'Labelle Downs' station; Nitmiluk National Park–'Eva Valley' Station and Katherine Aero Museum. (Source: Bureau of Meteorology.)

Table 2. Agreement between interpretation of firescars from LANDSAT TM imagery, and ground-truth data for (*a*) Litchfield National Park and (*b*) Nitmiluk National Park, late dry season, 1996 and 1997
n = number of GPS survey points

Landscape Unit	Unburnt % agreement	Patchy burnt % agreement	Burnt % agreement	Total % agreement
(a) Litchfield National Park				
(i) 1996				
Plateau	93 (n = 28)	Nil	92 (n = 36)	92 (n = 64)
Hillslopes/Escarpment	84 (n = 57)	71 (n = 7)	92 (n = 38)	86 (n = 102)
Lowlands	73 (n = 33)	100 (n = 2)	92 (n = 59)	96 (n = 94)
Total	83 (n = 118)	78 (n = 9)	92 (n = 133)	88 (n = 260)
(ii) 1997				
Plateau	89 (n = 19)	67 (n = 3)	100 (n = 14)	92 (n = 36)
Hillslopes/Escarpment	86 (n = 7)	0 (n = 2)	99 (n = 73)	95 (n = 82)
Lowlands	100 (n = 13)	100 (n = 2)	60 (n = 15)	80 (n = 30)
Total	92 (n = 39)	57 (n = 7)	93 (n = 102)	91 (n = 148)
(b) Nitmiluk National Park				
(i) 1996				
Plateau	97 (n = 179)	17 (n = 6)	89 (n = 37)	90 (n = 105)
Hillslopes/Escarpment	95 (n = 122)	46 (n = 24)	78 (n = 64)	84 (n = 210)
Lowlands	91 (n = 23)	0 (n = 11)	40 (n = 15)	55 (n = 49)
Total	95 (n = 207)	29 (n = 41)	77 (n = 116)	82 (n = 364)
(ii) 1997				
Plateau	98 (n = 179)	Nil	41 (n = 34)	89 (n = 213)
Hillslopes/Escarpment	96 (n = 158)	Nil	56 (n = 41)	88 (n = 199)
Lowlands	82 (n = 44)	Nil	59 (n = 17)	75 (n = 61)
Total	95 (n = 381)	Nil	51 (n = 92)	87 (n = 473)

The seasonal extent of burning in both parks by three major vegetation units, and rainforests, is given in Fig. 6. The seasonal contrast in the timing of fires at the park-wide scale between Litchfield (mostly EDS; Fig. 5*a*) and Nitmiluk (mostly LDS; Fig. 5*b*), is reflected consistently across all major vegetation units, and also for rainforest vegetation. Of note in assembled rainforest raw data is the relatively large proportion (e.g. >30%) of rainforest burnt on four or more occasions in each park, including twice in the LDS in Litchfield and five times (including 3 consecutive years) in Nitmiluk.

Fire frequency

The frequency with which individual 900 m^2 pixels have been burnt over respective study periods for both parks is given for major vegetation units, and rainforest vegetation, in Fig. 7 *a*, *b*. Fires recur typically within 1–2 years at any one site in Litchfield, and the extensive woodland communities in Nitmiluk. Recurring fires are less frequent in open forest and low open woodland communities especially in Nitmiluk, and in rainforest patches in both parks.

Proximity to camping areas, roads, tracks

Statistical comparisons of the seasonal proximity of burns close to, and farther away from, infrastructure are given for both parks in Table 4. Proximity analyses for Litchfield demonstrate that, whereas there has been significantly more burning undertaken in the EDS relative to the LDS both close to and farther away from infrastructure developments, no proximity differences are apparent within respective seasons over the 8 years of observations. For Nitmiluk, there are no evident patterns in the seasonal distribution of fires with respect to infrastructure, nor within seasons.

Boundary incursions

The frequency and ultimate extent of fires burning into both parks is given in Table 5. The data illustrate that both parks are vulnerable to frequent incursions by potentially extensive wildfires.

Discussion

Reliability of fire mapping

Based on ground-truthing exercises undertaken at the end of the dry season in conjunction with LANDSAT overpasses, data presented in Table 2 indicate that mapping accuracy, overall, ranged between 82 and 91%, for both parks, over 2 assessment years. Potentially ambiguous ground points (i.e. ‘patchy burnt’ in Table 2) ranged from 0 to 11.3% of samples in Nitmiluk, and 3.5% to 4.7% in Litchfield, over both years. A similar level of accuracy was attained for fire

Table 3. Comparisons (two-tailed *t*-tests) between the extent of burning in the early and late dry seasons for (*a*) Litchfield National Park ($n = 8$) and (*b*) Nitmiluk National Park ($n = 9$) for (i) the park as a whole, and (ii) major landscape units

For each comparison, means 1 and 2 (± SEM) refer to respective proportions of areas burnt as defined in the expression, mean 1 *v* mean 2

Area	Mean 1	Mean 2	*P*
(a) Litchfield National Park			
(i) Whole Park	41.2 ± 4.7	14.7 ± 4.1	0.013
(ii) Major Landscape Units			
Lowlands	38.1 ± 5.4	13.1 ± 3.9	0.009
Hillslopes/Escarpment	40.5 ± 5.0	15.8 ± 5.9	0.039
Plateau	12.3 ± 2.7	15.8 ± 4.3	0.34
(b) Nitmiluk National Park			
(i) Whole Park	15.4 ± 2.2	25.3 ± 6.2	0.14
(ii) Major Landscape Units			
Lowlands	18.6 ± 3.0	12.8 ± 4.5	0.22
Hillslopes/Escarpment	13.2 ± 1.6	22.6 ± 5.0	0.11
Plateau	16.7 ± 3.9	30.9 ± 8.6	0.12

Table 4. Comparisons (two-tailed *t*-tests) between the extent of burning close to, and further away from, roads and camping areas in the early and late dry seasons, for (*a*) Litchfield National Park (1990–1997, $n = 8$) and (*b*) Nitmiluk National Park (1990–1997, $n = 9$)

For each comparison, means 1 and 2 (± SEM) refer to respective proportions of areas burnt as defined in the expression, mean 1 *v* mean 2

Fire season	Proximity to roads/ campgrounds	Mean 1	Mean 2	*P*
(a) Litchfield National Park				
Early *v* Late	0.0–0.5 km	41.9 ± 6.1	13.9 ± 3.7	0.011
Early *v* Late	0.5–2.0 km	41.6 ± 5.5	10.5 ± 2.8	0.002
Early	0.0–0.5 *v* 0.5–2.0 km	41.6 ± 5.5	41.9 ± 6.1	0.896
Late	0.0–0.5 *v* 0.5–2.0 km	10.5 ± 2.8	13.9 ± 3.7	0.260
(b) Nitmiluk National Park				
Early *v* Late	0.0–0.5 km	11.6 ± 3.3	13.6 ± 6.1	0.772
Early *v* Late	0.5–2.0 km	11.1 ± 3.3	13.6 ± 6.3	0.727
Early	0.0–0.5 *v* 0.5–2.0 km	11.1 ± 3.3	11.7 ± 3.3	0.496
Late	0.0–0.5 *v* 0.5–2.0 km	13.6 ± 6.3	13.6 ± 6.1	0.915

mapping in Kakadu, based on two annual assessments undertaken in conjunction with EDS LANDSAT overpasses (Russell-Smith *et al.* 1997*a*). While the mapping accuracy overall affords confidence in the generality of analyses presented here at the broad landscape scale, the relatively poor discrimination of burnt pixels in the Nitmiluk lowland unit in 1996, and again more generally in Nitmiluk in 1997 (Table 2), suggests that the mapped extent of burning in that park at least is probably underestimated.

An additional source of error concerns cloudiness, particularly at the LDS–wet season interface (Russell-Smith *et al.* 1997*a*). In this study we have attempted to account for this by using supplementary coarse-resolution NOAA-AVHRR imagery to map firescars over the LDS cloudy period up until significant rain (Fig. 3). This proved useful for broadly mapping large lightning-lit fires in Nitmiluk NP in late 1996 (298 km^2) and 1997 (920 km^2), which otherwise were obscured on available LANDSAT imagery. Cloud cover through most of the wet season prohibits the use of LANDSAT for mapping generally small fires lit for the purposes of reducing fuel loads of dominant annual *Sorghum* grasses (e.g. Russell-Smith 1995).

Further, it is probable that small, patchy EDS fires are not readily interpreted from LANDSAT imagery (Russell-Smith *et al.* 1997*a*). Using LANDSAT MSS imagery, Crapper and Hynson (1983) and Minnich (1983) both concluded that a minimum area of change detection was of the order of 5 ha, despite pixel sizes of *c.* 0.5 ha. Positional errors of as much as ± 270 m may be associated with rectification and mosaicing digital LANDSAT imagery, and printing of fire maps at 1:250 000 (DuRieu 1993). Errors associated with mapping fire boundaries (and patchiness) using NOAA-AVHRR imagery are substantial, varying with the orbital position of the satellite relative to any site on the ground (hence distortion of pixels, e.g. 6.8 km × 4.3 km at the edge of the swath), over the 9 day orbital cycle. The use of satellite-derived fire histories as a record of past burning, and for various landscape-scale applications, requires appropriate qualification.

Fire history

Vast areas of northern Australia are burnt each year (Fig. 3; McMillan *et al.* 1997). A study of the recent fire history for the 20 000 km^2 Kakadu NP, derived from interpretation of LANDSAT MSS, found that an average of 46% of the park had been burnt over the 15-year record, with 25% burnt in the early, and 21% burnt in the late, dry seasons (Russell-Smith *et al.* 1997*a*). That study found also that there was substantial variation between the extent and seasonality of burning by different landscape units (floodplains, lowlands, plateau), and that there had been a major shift in fire regime over the study period from one dominated by LDS fires in the first years of the park's existence, to one dominated by management-imposed EDS burning over the last decade. Fires occurring in the latter part of the dry season tend to be more intense with a consequent impact on stem mortality (Lonsdale and Braithwaite 1991; Williams *et al.* 1998), and have the potential to burn unchecked over vast areas.

While broadly similar proportions of Litchfield (56%) and Nitmiluk (41%) also have been burnt annually over 8 and

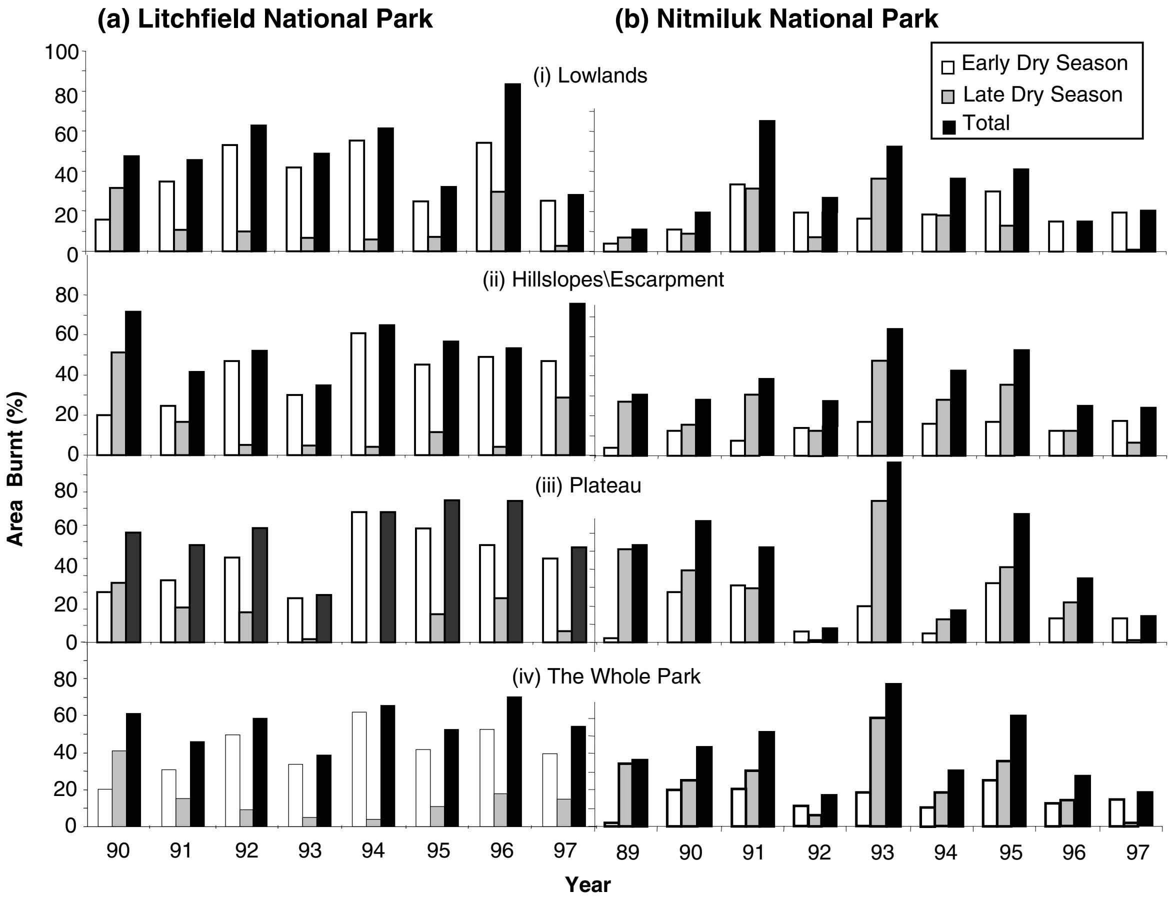

Fig. 5. Percentage area burnt for each of the major Landscape Units within (*a*) Litchfield National Park, 1990–1997, where (i) Lowlands (543 km^2), (ii) Hillslopes/Escarpment (646 km^2), (iii) Plateau (271 km^2), and (iv) the Whole Park (1464 km^2), and within (*b*) Nitmiluk National Park, 1989–1997, where (i) Lowlands (340 km^2), (ii) Hillslopes/Escarpment (1254 km^2), (iii) Plateau (1330 km^2), and (iv) the Whole Park (2924 km^2).

9 years of records, respectively (Table 3), there have been distinct differences in the seasonality of fires. With the exception of one year, burning in Litchfield consistently has been undertaken in the EDS (Table 3; Figs 5*a*, 6*a*), including burning with respect to infrastructure (Table 4). By contrast, in Nitmiluk, burning in most years has occurred in the LDS (Table 3; Figs 5*b* ,6*b*). Fire frequencies in both parks are mostly annual–biennial across major vegetation types (Fig. 7*a*, *b*). Both parks are shown to be vulnerable to fire incursions on all flanks (Table 5).

Ecological consequences of interpreted burning patterns are more difficult to gauge from these data given a current lack of independent field-based data (but see below), as well as the generally coarse scale of available relevant vegetation/habitat coverages, with the notable exception of mapped rainforest distribution (see Methods). Our data suggest that around 40% of rainforest has been burnt on average over the study period in each park (Fig. 6). Of this, most has been burnt in the EDS in Litchfield (suggesting management-imposed fires of relatively low intensity), and most in the LDS in Nitmiluk (suggesting greater impact by relatively intense wildfires). Given that fires typically are extinguished on monsoon rainforest margins where fuels are compact and moist (Bowman and Wilson 1988), it is likely that the extent of burning in these communities is over-estimated, at least under EDS conditions. Further, these data potentially are confounded also by the typically small sizes of rainforest patches relative to the significant positional fire mapping errors involved.

Extensive low open woodland communities (heaths), occurring typically in both parks on rocky or skeletal substrates derived from sandstone, are likewise fire-sensitive, being comprised of many obligate seeder shrub species (Russell-Smith *et al.* 1998). Regeneration in such species is sensitive to high fire frequencies (e.g. Gill and Groves 1979; Kruger and Bigalke 1984). Whereas in Litchfield fire frequencies in these communities are particularly high (Fig. 7*a*), even in Nitmiluk over 40% of heath habitats are shown to have been burnt on at least three occasions over 9 years (Fig. 7*b*). Such fire frequencies are

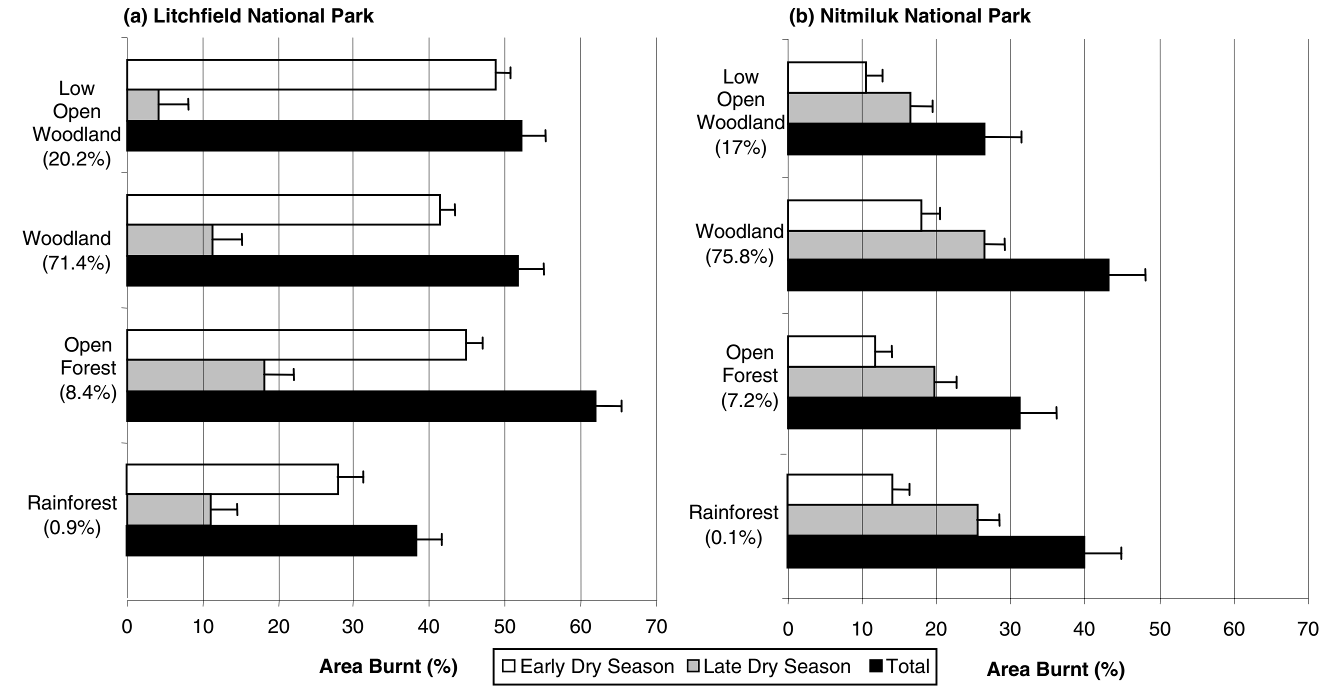

Fig. 6. Interpreted early, late and total dry season fire histories, (*a*) Litchfield National Park, 1990–1997, and (*b*) Nitmiluk National Park, 1989–1997, for three major vegetation units and rainforest. Numbers in parentheses represent the percentage of the Park occupied by the respective vegetation unit. (Error bars = SEM)

unsustainable for populations of obligate seeding shrub species, many of which take 5 or more years before becoming effectively reproductive (Russell-Smith *et al.* 1998).

Available, albeit limited, direct evidence concerning the effects of contemporary fire regimes in both parks points to: (1) substantial expansion of rainforest communities in one section of Litchfield NP based on a recent aerial photo assessment of woody change from 1944 to 1997 (Bowman and Milne, unpublished), presumably reflecting a regime of low intensity, frequent fires; and (2) extensive collapse since the 1950s of populations of the fire-sensitive, obligate seeder conifer, *Callitris intratropica*, in open forest and woodland communities in Nitmiluk NP (R.E. Petherick personal communication, our observations), presumably as a result of relatively intense wildfires under LDS conditions.

Table 5. The number, total, mean and maximum area burnt by incursion of fires from surrounding properties in (*a*) Litchfield National Park (1990–1997) and (*b*) Nitmiluk National Park (1989–1997)

Incursion	No.of incursions over *n* years (km^2)	Total incursion area burnt (km^2)	Mean incursion area burnt (km^2)	Maximum incursion area burnt (year)
(a) Litchfield National Park				
Northern Boundary	3/8	80	27	38 (1991)
Eastern Boundary	4/8	618	154	479 (1996)
Southern Boundary	5/8	888	178	558 (1990)
Western Boundary	6/8	181	30	53 (1995)
(b) Nitmiluk National Park				
Northern Boundary	3/9	523	174	412 (1994)
Eastern Boundary	5/9	983		576 (1994)
Southern Boundary	7/9	1,195	171	500 (1991)
Western Boundary	3/9	1,512	504	821 (1989)

Management implications

Above data highlight the challenge faced generally by land managers across the fire-prone savannas of northern Australia, where each dry season a first practical (and legally liable) requirement is to effectively manage fires from entering or exiting across property boundaries. Such practice typically involves grading bare-earth breaks (control lines) and, for greater security, the annual burning of firebreaks. For smaller conservation reserves where there may appear no option other than to protectively burn park perimeters annually (particularly in identified problem areas), such practice has significant implications for biodiversity conservation. One solution for reducing grassy fuel-loads, especially in areas dominated by annual *Sorghum* grasses, is to burn in the early wet season before seed-set (Stocker and Sturtz 1966). This practice has been shown to have little deleterious impact on floristic composition other than on annual *Sorghum* itself (e.g. Lane and Williams 1997), and increasingly is being employed strategically to good effect in Kakadu, Litchfield and Nitmiluk National Parks.

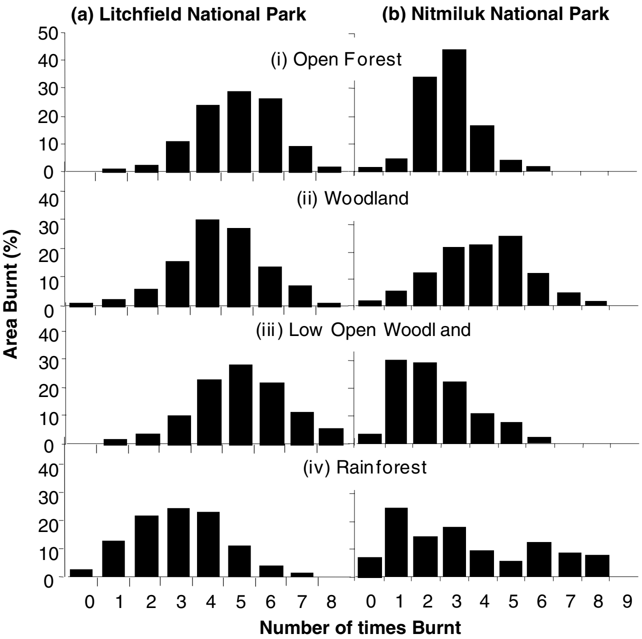

Fig 7. Frequency of pixels (0.09 ha) classified as burnt for (*a*) Litchfield National Park, 1990–1997 and (*b*) Nitmiluk National Park, 1989–1997, for three major vegetation classes (i) Open Forest, (ii) Woodland, (iii) Low Open Woodland, and (iv) Rainforest.

It is increasingly recognised that a diversity of fire regimes is required in northern Australian savannas to adequately conserve groups such as ants (Andersen 1991), lizards (Braithwaite 1987; Trainor and Woinarski 1994), birds (Woinarski 1990) and, arguably, biodiversity generally (Braithwaite 1995). As practised traditionally by Aboriginal people in at least coastal to sub-coastal regions of northern Australia (e.g. Crawford 1982; Haynes 1985; Russell-Smith *et al.* 1997*b*), this can be achieved by: (1) burning from early in the dry season to create a mosaic of small to larger, low to high intensity burnt patches within a matrix of unburnt vegetation/habitat; and (2) burning strategically onto natural firebreaks (e.g. watercourses, previously burnt areas) to provide a system of natural buffers. Assembled fire history data suggest that, on at least the first criterion, conservation management objectives currently are better addressed on Kakadu and Litchfield NPs, whereas Nitmiluk continues to be faced with a predominantly LDS fire regime.

Achieving such a conservative, mosaic approach to fire management requires information, effective resourcing and long-term dedication. Such practice only recently has commenced for Litchfield and Nitmiluk NPs, but includes this evaluation and the establishment of a complementary system of ground-based monitoring plots to inform managers of the impacts/responses of management-imposed fire regimes. Nevertheless, it is instructive to consider the pace of change. For example, as recently as 1993 the Nitmiluk NP management plan called simply for the annual burning of one-third of the park on a rotational basis (Conservation Commission of the Northern Territory [CCNT] 1993). The current 5-year fire management plan, introduced in 1996, specifies contemporary best ecological management practice (Parks and Wildlife Commission of the Northern Territory [formerly CCNT] 1996).

Conclusion

Relatively fine-resolution fire history data presented in this paper, whilst only decadal in extent, provide an invaluable basis for developing informed fire management programs for Litchfield and Nitmiluk National Parks. The data support other regional assessments that as much as 50% of savanna landscapes over parts of northern Australia are burnt on an annual basis. Nevertheless, comparison of contemporary fire regimes operating in each of three major regional national parks shows distinct differences, particularly with respect to the extent and seasonality (hence intensity) of burning in relation to different landscape components. The data highlight also the need for high resolution (e.g. 1: 50 000) vegetation/habitat maps, and complementary field observations (e.g. permanent sampling plots) when assessing the ecological implications of defined fire regimes. Nevertheless, fire frequencies in at least low open woodland/heath habitats in both parks currently are ecologically unsustainable. Despite limitations, the procedure provides useful insights for fire management in fire-prone seasonal savannas, for developing a knowledge base for park staff and other regional land managers, and as a basis for exploring the ecological implications of different fire regimes.

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