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A LANDSAT MSS-derived fire history of Kakadu National Park, monsoonal northern Australia, 1980–94: seasonal extent, frequency and patchiness

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Summary

1. A 15-year fire history (1980–94) was assembled for Kakadu National Park, a 20 000 km^2 World Heritage property in monsoonal northern Australia, based on interpretation of LANDSAT MSS imagery sampled at least three times over the 7-month dry season.
2. Detailed ground-truthing was undertaken at the end of the early dry season period (May–July) for both 1993 and 1994; ground-truth data were not available for previous years. Overall agreement was greater than 80% in both years. In sum, these data inspire a relatively high degree of confidence in the interpreted fire history of the Park for any one year, at least at the landscape and habitat scales examined here.
3. An average of 46% of the Park was found to be burnt each year over the 15 years of records, with 25% burnt in the early, and 21% burnt in the late, dry season. The data indicate a pronounced shift from a fire regime dominated by late (typically more intense and potentially extensive) dry season fires up until the mid-1980s, to one dominated by early (typically of low intensity and patchy) dry season fires subsequently.
4. Whereas an average of 55% of lowland savanna habitats has been burnt annually, 28% of habitats occupying both sandstone plateau and riverine landforms have been burnt each year. The great majority of burning in relatively fire-sensitive sandstone habitats continues to be in the late dry season. Data indicate a marked increase in the extent of burning on floodplains, and in associated fire-sensitive *Melaleuca* forests and lowland rainforests, from 1990; this increase is attributed to increased herbaceous fuel loads associated with the removal of feral Asian water buffalo.
5. Proximity analyses indicate that slightly more early dry season burning has been undertaken close to roads, and at greater distances from settlements; no proximity differences were discernible for fires late in the dry season. Burning has been concentrated close to lowland drainage lines, both in the early and late dry season.
6. Lowland savanna sites are burnt on average 3 out of 5 years. In contrast, the majority of sandstone plateau and riverine floodplain sites have burnt on average 0–4 times and 0–3 times, respectively, over the 15 years of records.
7. The median size of contiguously burnt areas (patches) has been declining steadily over the 15 years of records, from upwards of 300 ha initially to *c.* 60 ha in 1994.
8. It is concluded that although the assembled data are imperfect in that they under-represent wet season burns and very small fires, are prone to positional errors of up to *c.* 300 m, and because little confidence can be placed in the sequential fire histories for any 1-ha site, they afford an effective means by which the Park's fire management programme can be monitored, its problems identified, and its needs assessed. The demonstrable utility of this programme has led to its recent extension on other

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significant conservation properties in monsoonal northern Australia; the procedure offers potential for wider adoption in savanna regions generally.

Key-words: Arnhem Land, burning, Northern Territory, remote sensing, savanna.

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Introduction

It has been estimated that over 50% of the savannas in some regions of northern Australia are burnt during the 7-month (May–November) dry season each year (Braithwaite & Estbergs 1985; Press 1988). Given the productivity of grassy fuels over this region, fires may recur at any one site on an annual basis (e.g. Stocker & Mott 1981; Walker 1981; Lacey, Walker & Noble 1982). Such fires are lit mostly by people, for a variety of purposes associated principally with indigenous (Aboriginal) land management practices, the pastoral industry, and conservation management (e.g. Haynes 1985; Press 1988; Lewis 1989; Head *et al.* 1992). Fires ignited by lightning strike are relatively few in number and limited to a small proportion of the total area, being restricted to a period of between 1 and 2 months at the start of the wet season (Stocker & Mott 1981).

Considerable research has been undertaken in recent years to come to grips with the effects of such burning on the vegetation and fauna, especially in the 'Top End' of the Northern Territory. While the long-term consequences of frequent burning on eucalypt-dominated savanna vegetation are still a matter of debate (Hoare *et al.* 1980; Braithwaite & Estbergs 1985; Bowman, Wilson & Hooper 1988; Fensham 1990; Lonsdale & Braithwaite 1991), a number of points of consensus are now apparent: (i) fire-sensitive communities such as small patches of monsoon rainforest and Cypress pine *Callitris intratropica* (nomenclature follows Dunlop *et al.* 1995) are being severely impacted upon by contemporary fire regimes, typically from intense fires burning late in the dry season (Haynes 1985; McKenzie & Belbin 1991; Russell-Smith & Bowman 1992; Bowman & Panton 1993); (ii) at the landscape scale the ideal fire regime for the conservation of suites of faunal species with different requirements is one where there is a mosaic of patches representative of a range of fire histories (Braithwaite 1987, 1995; Andersen 1991; Woinarski 1990; Trainor & Woinarski 1994); and (iii), given the realities of living in a fire-prone environment, traditional Aboriginal fire/resource management practice offers a generally useful, conservative model (Haynes 1985, 1991; Press 1987, 1988; Russell-Smith *et al.* 1997).

As well as the above ecological studies, attention has been given to developing appropriate methodologies for the mapping of regional fire histories from interpretation of satellite imagery, and assessment of the assembled data (Day 1985; Press 1988; Graetz 1990; Ryan, Russell-Smith & DuRieu 1995; Allan & Willson 1995). The first four of these studies have focused on Kakadu National Park, a World Heritage property of *c.* 20 000 km^2 in the Top End of the Northern Territory. Interpretation of firescars has been derived principally from LANDSAT MSS hard-copy imagery. This paper reports on the development of a fire history for Kakadu National Park for the years 1980–94. In particular we examine: (i) the accuracy of mapping firescars utilizing the defined methodology; (ii) the seasonal extent of fires across the Park as a whole, by developmental stages of the Park, by major landscape units, and by vegetation habitat types; (iii) the frequency of occurrence of fires in individual 1-ha pixels; (iv) the frequency of burning with respect to drainage lines and developed sites such as roads, campgrounds and permanent residential areas; and (v) the sizes of contiguously burnt areas (patches). These data have relevance both for monitoring and assessment of regional fire regimes across monsoonal northern Australia, as well as for the seasonally cloudless tropics generally.

Methods

STUDY REGION

Kakadu National Park is located in a coastal to sub-coastal region of the Top End of the Northern Territory, Australia (Fig. 1a). Stage 1 of the Park was declared in 1979, with stages 2 and 3 proclaimed in 1984 and 1987, respectively (Fig. 1b); final declaration of the Park's current configuration was not completed until 1991. Managed jointly by its traditional Aboriginal owners and the Australian Nature Conservation Agency, the entire Park is inscribed in the World Heritage list both for its cultural and natural values. The Park encompasses the small town of Jabiru (*c.* 1400 persons), a number of mining lease excisions (including an active uranium mine), and a variety of infrastructural developments including tracks and roads, and various small settlements and campgrounds (Fig. 1c). The broader region surrounding Kakadu is also characterized by sparse human occupation and relatively low land-use pressures. The eastern boundary of Kakadu abuts Aboriginal Arnhem Land, a vast, little inhabited region with only a few major coastal population centres. The southern boundary abuts the 3000 km^2 Nitmiluk National Park. Low intensity pastoralism is undertaken on a few of the large properties adjoining Kakadu on its south-western and western boundaries. Given this diffuse land

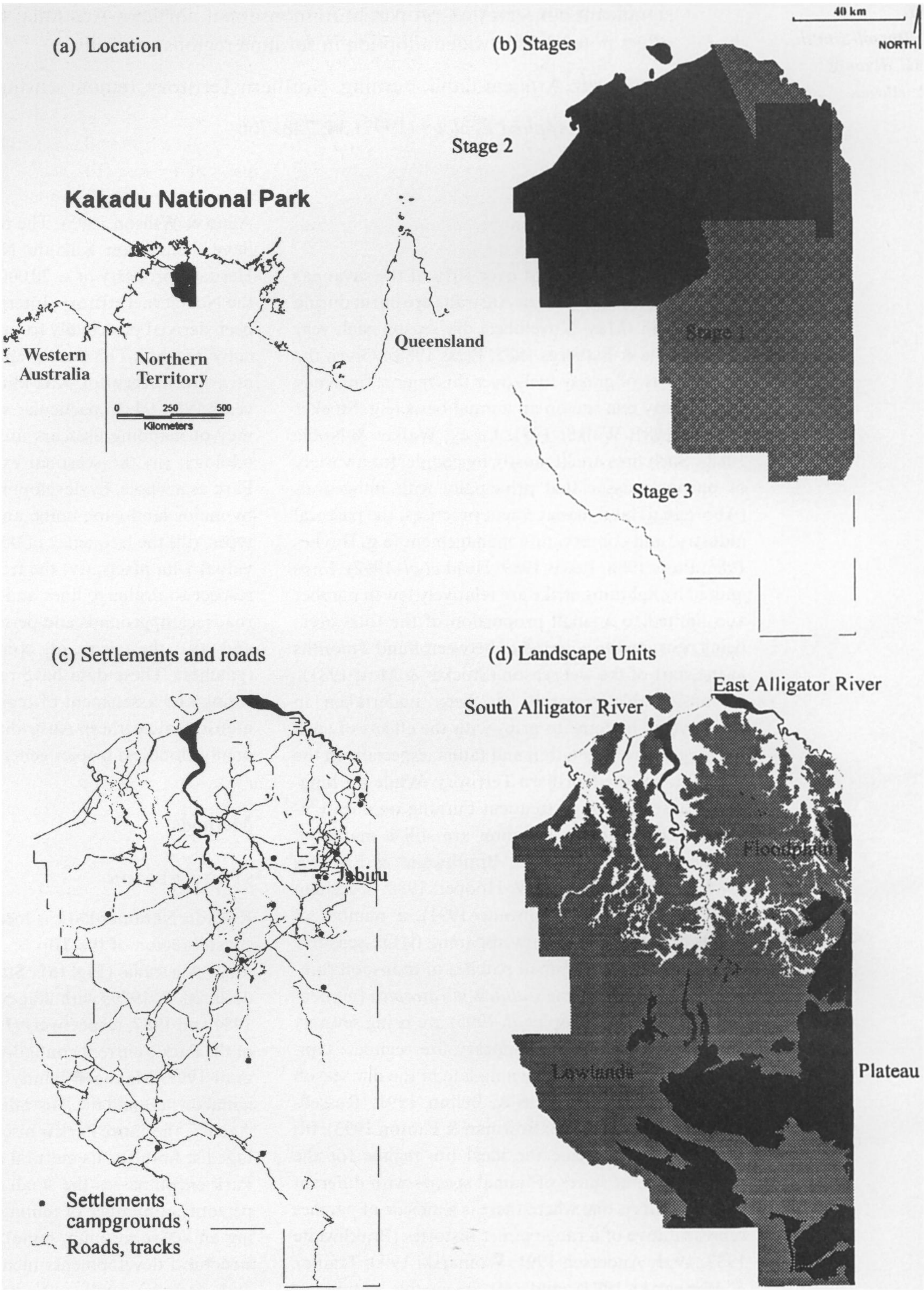

Fig. 1. Kakadu National Park: (a) location; (b) developmental stages; (c) road network, major settlements and camp-grounds; and (d) major landscape units. See text for details.

usage, in combination with the regionally continuous expanse of natural vegetation, dry season fires have the potential to burn unchecked over vast areas of the landscape.

As for northern Australia generally, the regional climate is characterized by marked rainfall seasonality, with over 90% occurring in the summer wet season months, from November to March. Despite few weather-recording stations in the region, mean annual rainfall apparently declines from over 1500 mm in the north-west to *c.* 1200 mm in the far south-east. Although the amount of rainfall received in any one area is highly variable from year to year, the wet season is a highly reliable event (Taylor & Tulloch 1985). Mean monthly relative humidity at 15:00 h ranges from over 70% during the wet season, to less than 30% during September. Daily maximum temperatures average above 30 °C over the year; frosts have not been reported. Winds over the dry season burning period are dominated generally by strong easterlies and south-easterlies; only from about October do winds start to become more northerly and north-westerly, increasingly under the influence of the north-west monsoon (McAlpine 1976; Russell-Smith, Needham & Brock, 1995).

Throughout this paper reference is made to three major landform units (Fig. 1d). The dominant regional landform is the rugged Arnhem Land plateau, mostly at less than 400 m elevation. The plateau comprises resistant, flat-bedded Middle Proterozoic quartzose sandstones, criss-crossed by tensional joints which have been deeply weathered and eroded to form a maze of narrow valleys and gorges (Galloway 1976). Soils, where present, are typically skeletal and infertile sands (Aldrick 1976). Especially on its north-western and western perimeters, the plateau is bounded by sheer and spectacular escarpments. The two major lowland landform units are an undulating Cainozoic plain that stretches away from plateau margins comprising deeply weathered (laterized), predominantly coarse-grained sediments; and extensive coastal/sub-coastal Holocene floodplains associated with the lower reaches of major river systems, comprising mostly fine-grained fresh-water and estuarine sediments (Williams 1991; Russell-Smith *et al.* 1995).

Vegetation cover of the region is predominantly of an open forest/woodland type dominated by *Eucalyptus* over a typically grassy understorey (Schodde *et al.* 1987; Wilson *et al.* 1990; Russell-Smith 1995a). In the lowlands, other vegetation types include samphire and mangroves, small rainforest patches, and freshwater floodplain communities ranging from open sedgelands/grasslands to tall open forests dominated by *Melaleuca*. Bare rock pavements and skeletal soils in sandstone terrain support a diffuse, but floristically diverse, shrubby heath vegetation (often with *Eucalyptus*), intermixed with flammable spinifex grasses (e.g. *Triodia*, *Plectrachne*). Sandstone rainforest, dominated by the the myrtaceous sclerophyll *Allosyncarpia ternata*, occurs in a variety of situations, but typically in rugged, broken terrain affording some level of fire protection.

SELECTION OF IMAGERY

The fire history of Kakadu National Park presented here is derived from interpretation of LANDSAT Multispectral Scanner (MSS) satellite imagery extending from 1980 to 1994. The spatial resolution of this imagery, at 79 m × 57 m, is half that of the grid size used (100 m × 100 m) in the Park's Geographical Information System (GIS), the Earth Resources Mapping System (E-RMS; New South Wales National Parks and Wildlife Service 1989); hence, it provides an appropriate scale for the preparation of fire history coverages of the Park. As detailed in an earlier assessment of imagery for mapping firescars in Kakadu National Park (Wise 1987), the use of relatively coarse-resolution data, for example NOAA-AVHRR (resolution 1·1 km × 1·1 km at nadir), while relatively inexpensive, yields a major loss of mapping detail, especially when applied to small, critical habitats such as rainforest patches. Finer resolution data, for example LANDSAT TM (resolution 30 m × 30 m) or SPOT (resolution 20 m × 20 m), although they provide increased detail and assist with the interpretation of very small firescars, are relatively uneconomic given that such enhanced accuracy is effectively redundant when converted to a 1-ha grid-cell database. Nevertheless, with the impending decommissioning of the LANDSAT 5 satellite which carries the MSS, future mapping of firescars in Kakadu will require reassessment.

Four LANDSAT MSS scenes are required to provide full coverage of Kakadu National Park, involving two separate overpasses 7 or 9 days apart (paths 104 and 105). Photographic products were purchased in preference to digital data, given the substantially lower cost of the former. Also, the Park has no readily accessible image processing system for manipulating digital data. Acquired images were produced as false-colour composite photographic prints of MSS bands 4, 5 and 7 at scales of either 1:250 000 or 1:500 000. Only standard photographic products were utilized for all interpretations. We did not experiment with band/stretch combinations for the photographic products since, as in most cases, the existence of master negatives substantially reduced costs associated with acquiring additional hardcopy imagery (see below). Following earlier studies of fire history conducted in Kakadu National Park employing manual interpretation of MSS imagery (Day 1985; Press 1988; Graetz 1990), Oliver (*in litt.* 1992) advised that additional imagery was required early in the dry season to address the evident problem of rapid regrowth after burning whilst soils still retained available moisture. In total, the interpretation of fire history presented here is derived from an assembled library of over 260 LANDSAT MSS scenes.

FIRE HISTORY

Fire history data for the years 1980–90 were mapped manually, and for the years 1991–94 using interactive digital techniques, from LANDSAT MSS imagery, as set out below. For both time periods firescars were mapped for the Early Dry Season (EDS; May–July) based on at least two imagery sampling periods, and Late Dry Season (LDS; August onwards) based on at least one sampling of imagery as late in the dry season as possible, i.e. before the onset of cloudy conditions associated with the commencement of the new wet season.

1980–90

Previous LANDSAT MSS-based studies of the fire history of Kakadu National Park conducted for this period (Day 1985; Press 1988; Graetz 1990) provided an incomplete coverage of the whole Park. Each of these studies considered only certain stages associated with the Park's development (Fig. 1b), and was restricted to specific years. To complete these data, all outstanding imagery was purchased and the fire history manually reinterpreted in full. One of us (PR) performed all interpretations to minimize operator bias. The adopted manual interpretation methodology, after Ryan *et al.* (1995), is outlined below.

Prior to firescar interpretation, important locational features (e.g. coastlines, rivers, roads, floodplain and escarpment boundaries) were exported from the Park's GIS system with an accurate projection aligned to the Australian Map Grid (AMG Zone 53), and printed on clear acetate film at the scale of the imagery to be interpreted. For early years, where acquired imagery had been processed using different projections, modified scaling was used in the preparation of acetate film reference overlays. For any one year the film was overlaid on the first available EDS image using a 'best fit method' with reference to major locational features, secured firmly, and the firescars interpreted and traced with a fine-tipped pen. The process was repeated using the same film for subsequent dry season images. This process facilitated verification of preceding interpretations, and assisted with identification of areas that had been burnt more than once in each year. The film was then manually digitized as separate EDS (pre-August) and LDS vector coverages onto the Park's GIS, and subsequently converted to a 100-m raster format. This process was repeated for all years.

1991–94

Following a brief cessation of the fire mapping programme in 1991 associated with a reassessment, the programme was resumed in 1992 with one of the authors (RD) appointed as the new image processor and interpreter. For that year, digital LANDSAT MSS data were acquired four times through the dry season in order to assess the minimum sampling requirements for imagery. Processing of these data and interpretation of firescars was undertaken using the interactive feature-mapping procedure of TNTMips (Skrdla 1992). The feature mapping routine is essentially as follows (after DuRieu 1993a). The operator first trains the system on the spectral response of definite firescars. The computer then maps all areas with similar spectral responses. The operator has the option of accepting, rejecting or modifying firescars through the addition or subtraction of areas using interactive, on-screen digitizing. As for the manual interpretation of firescars for the years 1980–90, interactive interpretation was undertaken cumulatively over the dry season using successive acquired imagery, followed by the generation of EDS and LDS vector and raster coverages.

On the basis of this study, DuRieu (1993b) recommended that, for future work: (i) imagery be acquired a minimum of three times through the year, with the sampling of EDS firescars to be undertaken at least twice; and (ii) a more economical, if slightly less accurate, solution for interpreting LANDSAT MSS imagery would be to purchase rectified hardcopy prints, scan these with a high resolution digital scanner, and then process the data as was undertaken for 1992. This recommended procedure for the interpretation of firescars was adopted for 1993 and 1994 and, retrospectively, for 1991.

GROUND-TRUTHING

No ground-truth data are available for the years 1980–92. Following an abortive attempt at ground-truthing in 1992 by flying a helicopter around fire boundaries and recording positions with Global Positioning System (GPS), successful ground-truthing was undertaken in 1993 and 1994 by adopting the following procedure. On days immediately prior to the two satellite overpasses associated with the sampling of the second EDS imagery (i.e. at the end of July/early August), a series of stratified random-start transects was flown (by helicopter) across the Park, ensuring that the northern, central and southern sectors were relatively uniformly sampled. Altitude and speed were held relatively constant at 100 m and 60 knots, respectively. Every 30 s, one observer recorded the GPS location, and another observer recorded: (i) whether the vegetation directly beneath the helicopter (i.e. within a diameter of *c.* 200 m) was burnt, patchily burnt or unburnt, where patchy burning refers to the presence of more than 20% grass cover after burning, or to locations within 100 m of a fire boundary; and (ii) the broadly defined vegetation type concerned (e.g. lowland woodland, open floodplain, etc.). These data were subsequently used to verify the EDS firescar interpretation.

ANALYSIS

Ground-truth data were processed using TNTMips. All other GIS analyses were performed with E-RMS and IDRISI (Eastman 1993), typically in combination. Full methodological details are given in Ryan (1995); here we summarize only the salient points.

GIS coverages

A range of GIS coverages was utilized for the analyses presented here. As well as the fire history data described above, other coverages comprised the Park boundary; development stages of the Park; major landscape units (i.e. plateau, lowlands, floodplains); generalized vegetation habitats mapped at 1:100 000 scale (modified after Schodde *et al.* 1987); more refined map data for rainforests (J. Russell-Smith & D. E. Lucas, unpublished data) and *Melaleuca* communities (P.S. Brocklehurst *et al.*, unpublished data); drainage lines, settlements, roads and tracks.

Climatic data

These were derived from three regional weather-recording stations, namely Jabiru Airport, Jabiru Town and Oenpelli, for the years 1980–94 in order to provide a climatic context for the study. Mean values were derived from these station records for: (i) mean maximum temperature for the three EDS months, May–July, and three LDS months, August–October; (ii) mean 15:00 h relative humidity for the same three EDS and LDS months; (iii) number of consecutive wet season months where rainfall was > 50 mm and > 100 mm, respectively; and (iv) total wet season rainfall (i.e. rainfall calculated for the period 1 August–31 July).

Seasonal extent of burning

A first set of analyses explored the seasonal extent of burning over the 15 years of fire history for the Park as a whole; by developmental stages of the Park (to provide comparisons for before/since the implementation of Park management programmes); by major landscape units; and by vegetation habitats, including relatively fire-sensitive communities. Where appropriate, two-tailed *t*-tests were used to compare sample means, and Spearman rank correlations (r_s) were used to explore relationships between the seasonal extent of burning and independent climatic variables.

Proximity analyses

Statistical comparisons (two-tailed *t*-tests) of the extent of annual burning were undertaken for three situations: (i) within 0·5 km, and 0·5–2 km away from, drainage lines; (ii) within 1 km, and 1–5 km away from, major settlements and camp-grounds; and (iii) within 1 km, and 1–5 km away from, tracks and roads.

Frequency of burning

A third set of analyses explored the frequency with which individual 1-ha pixels had been burnt for the Park as a whole, and by major landscape units.

Firescar patch-size distribution

A final analysis described the maximum and median patch sizes of contiguously EDS and LDS burnt pixels over the 15 years of records.

Results

GROUND-TRUTHING

Ground-truth data for the years 1993 and 1994 are presented in Table 1. These data indicate that the overall agreement with mapped interpretation of EDS firescars was greater than 80% in both years. Mapping accuracy was generally markedly greater in unburnt compared with burnt vegetation, although similar high levels of agreement were obtained for unburnt and burnt floodplains. Whereas firescar interpretation of unburnt lowland woodland and open forest communities exceeded 80% in both years studied, three-quarters of burnt lowland woodland survey sites were interpreted accurately. In sum, the ground-truth data for both years inspired a relatively high degree of confidence in the interpreted fire history of the Park for any one year, at least at the landscape and habitat scales applied here.

SEASONAL EXTENT OF BURNING AT THE LANDSCAPE SCALE

Salient climatic data for the years 1980–94 are summarized in Fig. 2. While we do not present any detailed analysis here, it is apparent that climatic conditions in the region under study have been relatively stable over this period. Nevertheless, there is a generalized drying trend evident over the 15 years of records (Fig. 2d).

The interpreted fire history of Kakadu National Park for the years 1980–94 is given in Fig. 3. Over this period, an average of 46% of the entire Park was burnt each year, with 25% burnt in the EDS. While the mean extent of burning in the EDS is not significantly different from that in the LDS over the full period (Table 2), there is an evident trend for most burning to be conducted in the EDS from about the mid-1980s (Fig. 3). This shift is also reflected in data for stages 2 and 3 of the Park, declared in 1984 and 1987, respectively (Table 2).

The interpreted fire histories of the three major landscape units occurring in the Park, the sandstone plateau, floodplain and lowland units, are given in Fig. 4 (a–c, respectively). On average, 28% of the floodplain and plateau units, and 55% of the lowland unit, were burnt between 1980 and 1994. Over this period, burning of the plateau unit has been concentrated in the LDS, and burning of the lowland unit in the EDS; no significant seasonal difference is evident for burning of floodplains (Table 2). Of note in the 1992 floodplain fire history data is the omission

Table 1. Agreement between interpretation of firescars from LANDSAT MSS imagery, and EDS (pre-August) ground-truthed data, where n = number of GPS survey locations

Landscape unit	Unburnt % agreement	Patchy burnt % agreement	Burnt % agreement	Total % agreement
(a) 1993				
Escarpment/plateau	100 ($n = 59$)	($n = 0$)	0 ($n = 1$)	98·3 ($n = 60$)
Lowland woodland	91·6 ($n = 216$)	56·0 ($n = 25$)	74·7 ($n = 107$)	83·9 ($n = 348$)
Floodplain	92·6 ($n = 54$)	67·0 ($n = 15$)	93·3 ($n = 15$)	88·1 ($n = 84$)
Total	93·6 ($n = 329$)	60·0 ($n = 40$)	76·0 ($n = 123$)	86·4 ($n = 492$)
(b) 1994				
Escarpment/plateau	97·3 ($n = 73$)	100 ($n = 2$)	81·3 ($n = 16$)	94·5 ($n = 91$)
Lowland woodland	83·7 ($n = 382$)	69·4 ($n = 62$)	75·6 ($n = 329$)	79·1 ($n = 773$)
Floodplain	91·3 ($n = 103$)	87·5 ($n = 8$)	90·3 ($n = 31$)	92·8 ($n = 139$)
Total	87·6 ($n = 558$)	72·2 ($n = 72$)	77·6 ($n = 376$)	82·8 ($n = 1006$)

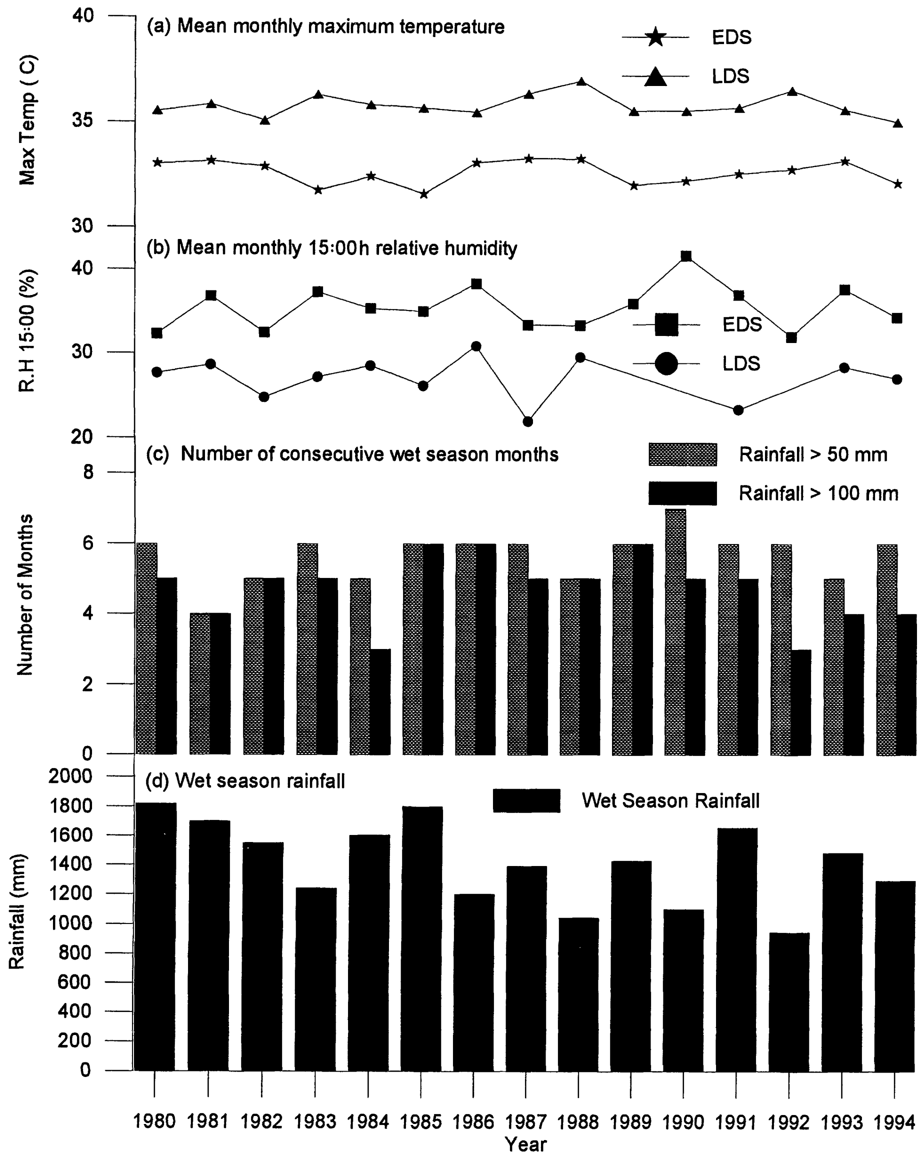

Fig. 2. Climatic trends for Kakadu National Park, 1980–94. (a) Mean maximum temperature for the three EDS months, May–July, and three LDS months, August–October; (b) mean 15:00 hours relative humidity for the three EDS months, May–July, and three LDS months, August–October; (c) number of consecutive wet season months where rainfall > 50 mm and > 100 mm; (d) wet season rainfall (i.e. rainfall calculated for period 1 August–31 July). Data presented are means calculated for three weather stations, namely Jabiru Town, Jabiru Airport, Oenpelli. Note missing data for 15:00 LDS relative humidity 1989, 1990. Source: Bureau of Meteorology, Darwin.

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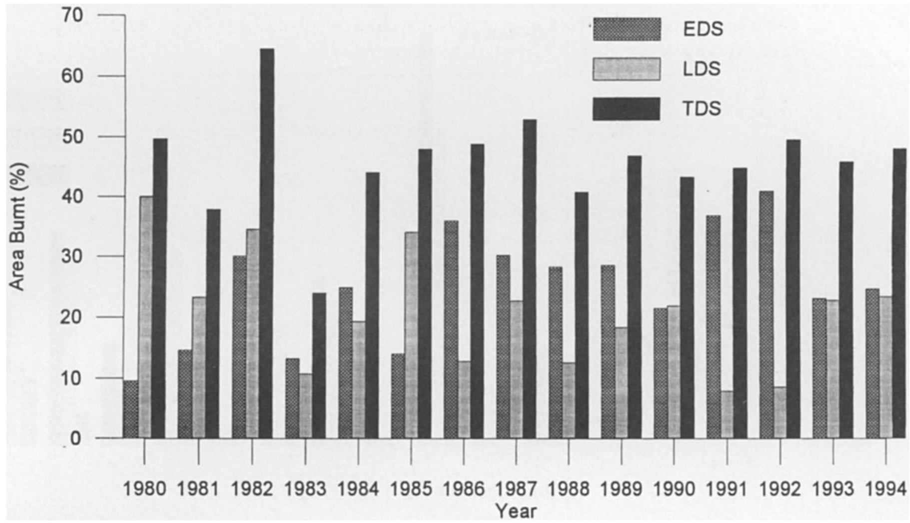

Fig. 3. Interpreted early (EDS), late (LDS) and total (TDS) dry season fire history of Kakadu National Park, 1980–94.

of one extensive fire that occurred at the start of the wet season, in December; the extent of this fire could not be mapped from LANDSAT imagery given the prevailing cloudy conditions.

Considering only proclaimed Park areas, the extent of EDS burning increased significantly, and the extent of LDS burning remained generally the same, both for the Park as a whole and for all three major landscape units over the 15-year study period (Table 3a). While there was also a marginally significant decline in rainfall over the same period ($r_s = -0{\cdot}507$, $P = 0{\cdot}054$), relatively weaker, non-significant correlations between the extent of EDS burning and rainfall both for the Park and respective landscape units (Table 3a) are suggestive that the increase in EDS burning was more largely associated with greater management efforts than with declining rainfall *per se*. The effectiveness of undertaking extensive EDS burning as a means for limiting LDS fires is also suggested by the strength of the inverse relationship between EDS and LDS burning of the lowland landscape unit (Table 3b). Conversely, for floodplain and plateau landscape units, where comparatively little EDS burning has been undertaken (Table 2), the relationship between the extent of EDS and LDS burning is non-significant, and even significantly positive, respectively (Table 3b).

SEASONAL EXTENT OF BURNING AT THE HABITAT SCALE

The mean extent of burning in 12 main habitat types (derived after Schodde *et al.* 1987) is given in Fig. 5. These data illustrate that, over the 15-year study period, most burning has occurred in open forest and woodland communities, particularly in the lowlands. Whereas burning of lowland habitats has been dominated mostly by EDS fires, fire regimes in sandstone plateau habitats have been dominated by LDS fires.

The seasonal extent of fire in three relatively fire-sensitive habitat types, plateau rainforest, lowland rainforest and paperbark (*Melaleuca* spp.) forest, is explored in more detail in Fig. 6 (a–c, respectively). Data for lowland paperbark forests indicate that there has been a substantial increase in the extent of burning from 1990 to 1994. A similar pattern is also seen for lowland rainforest, but is not so apparent for plateau rainforest. While these data are considered further in the Discussion, we note here that paperbark forests and lowland rainforests both occupy equivalent, or adjacent, landforms. Thus, both paperbark forest and lowland rainforest occur as riparian vegetation, and as adjacent communities on riverine floodplains (paperbark forest) or their upland margins (small rainforest patches).

PROXIMITY TO DRAINAGE LINES, SETTLEMENTS AND ROADS

Statistical comparisons of the seasonal proximity of burns close to, and farther away from, drainage lines, settlements (towns, camp-grounds, etc.) and major tracks and roads, are given in Table 4. Proximity analyses for drainage lines are considered here for plateau and lowland landscape units separately; by definition the floodplain unit comprises one drainage feature. These data indicate that, in common with the pattern of burning for the plateau generally, burning both close to, and farther away from, drainage lines for the years 1980–94 has occurred mostly in the LDS. No statistical differences are evident in these data for the amount of burning either in the EDS or LDS, both close to or farther away from plateau drainage lines (Table 4).

As for the lowlands generally, burning both close to, and up to 2 km away from, lowland drainage features has been concentrated in the EDS over the 15 years of records. Burning, both in the EDS and LDS, has been concentrated in the near vicinity of drainage lines (Table 4).

With respect to settlements and roads (occurring

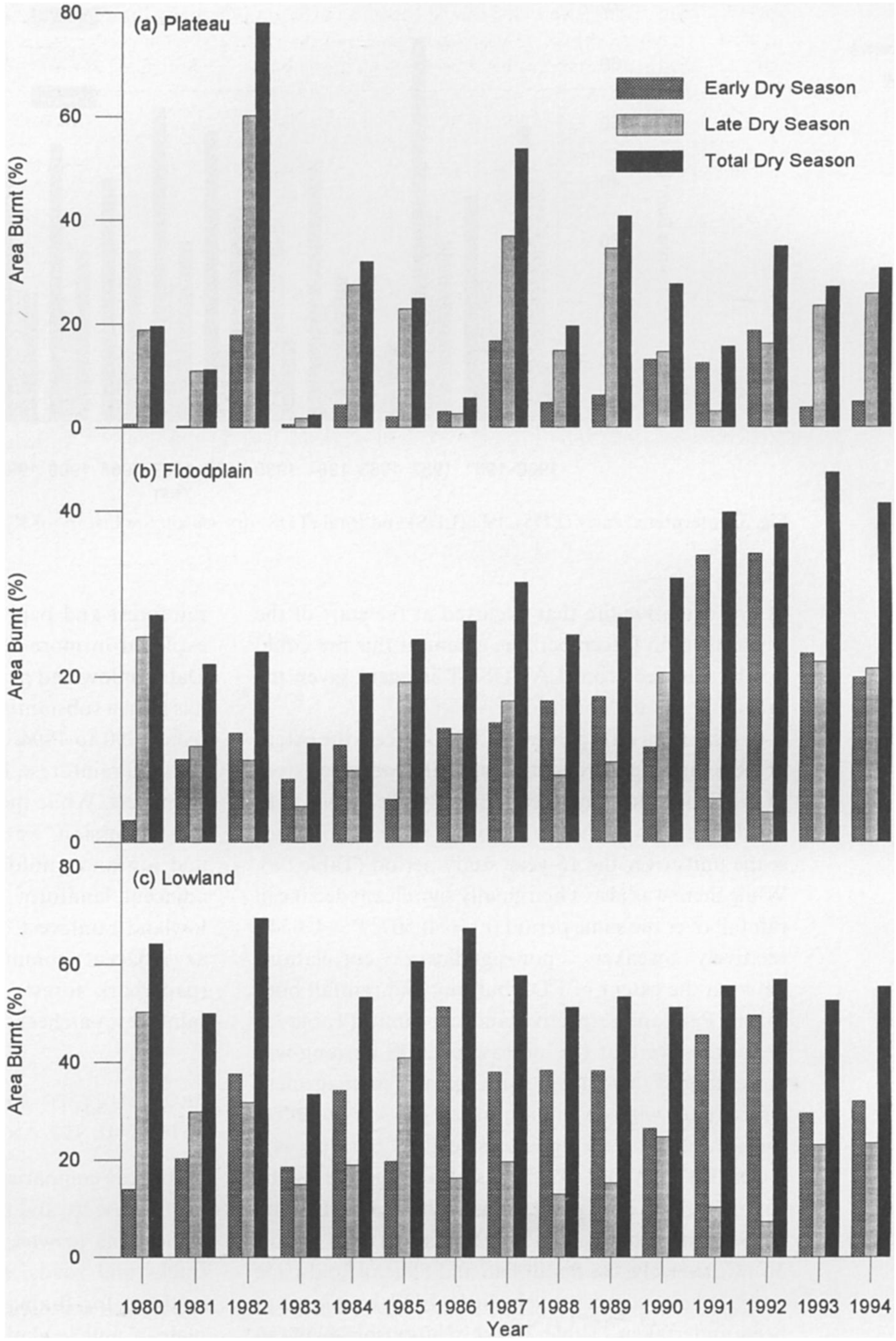

Fig. 4. Interpreted early (EDS), late (LDS) and total (TDS) dry season fire histories, 1980–94, for major landscape units occurring in Kakadu National Park: (a) plateau; (b) floodplain; (c) lowland.

essentially only within the lowland landscape unit), significantly more burning has been undertaken in the EDS, both in close proximity to (within 1 km), and farther away from (1–5 km), these constructed features. Slightly more EDS burning has occurred further away from settlements; a similar but reversed trend is evident for more EDS burning closer to roads. In the LDS, similar proportions have been burnt close to, and farther away from, both settlements and roads.

FIRE FREQUENCY

The frequency with which individual 100 m × 100 m (1-ha) pixels have been burnt in the Park as a whole over the 15 years of fire history is presented in Fig. 7. Unburnt areas over this period constitute 3·1% of the total area (Fig. 7a); conversely, those burnt annually constitute *c.* 1%. Unburnt and infrequently burnt areas (1–4 times; Fig. 7b) comprise mostly floodplain

Table 2. Comparisons (two-tailed *t*-tests) between the extent of burning in the early (EDS) and late (LDS) dry seasons for (a) the Park as a whole, (b) the developmental stages of the Park, and (c) 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 vs. mean 2

	Fire treatment	Years	Mean 1	Mean 2	*P*
(a) Entire Park	EDS vs. LDS	1980–94	25·0 ± 2·4	20·8 ± 2·5	0·23
(b) Park Stages					
Stage 1	EDS vs. LDS	1980–94	21·1 ± 2·4	20·5 ± 3·3	0·88
Stage 2	EDS vs. LDS	1980–94	24·0 ± 2·6	20·4 ± 2·8	0·34
	EDS vs. LDS	1980–83	15·6 ± 4·1	25·5 ± 4·7	0·15
	EDS vs. LDS	1984–94	27·1 ± 2·7	18·5 ± 3·3	0·06
	EDS	1980–83 vs. 1984–94	15·6 ± 4·1	27·1 ± 2·7	0·06
	LDS	1980–83 vs. 1984–94	25·5 ± 4·7	18·5 ± 3·3	0·26
Stage 3	EDS vs. LDS	1980–94	29·7 ± 2·8	21·6 ± 2·8	0·05
	EDS vs. LDS	1980–86	24·9 ± 4·9	23·8 ± 5·9	0·89
	EDS vs. LDS	1987–94	33·9 ± 2·6	19·6 ± 1·5	0·0005
	EDS	1980–86 vs. 1987–94	24·9 ± 4·9	33·9 ± 2·6	0·14
	LDS	1980–86 vs. 1987–94	23·8 ± 5·9	19·6 ± 1·5	0·50
(c) Landscape units					
Plateau/escarpment	EDS vs. LDS	1980–94	7·5 ± 1·7	20·9 ± 3·9	0·005
Floodplains	EDS vs. LDS	1980–94	15·8 ± 2·4	13·2 ± 1·8	0·41
Lowlands	EDS vs. LDS	1980–94	32·9 ± 3·0	22·6 ± 3·0	0·0

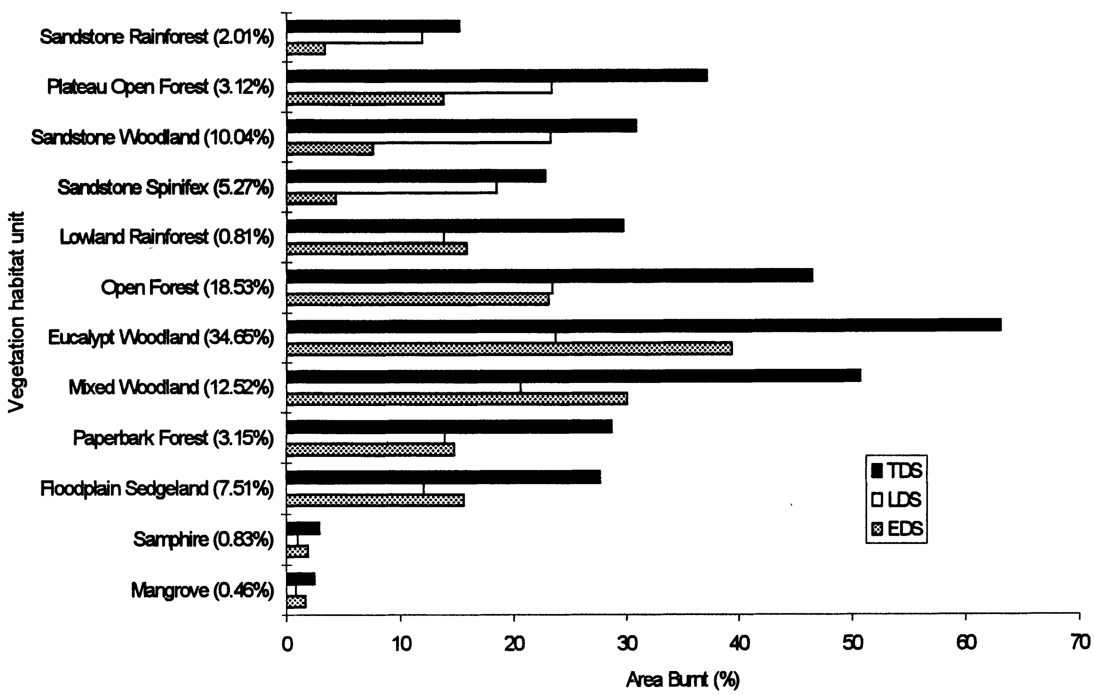

Fig. 5. Interpreted early (EDS), late (LDS) and total (TDS) dry season fire histories, 1980–94, for 12 major vegetation units (after Schodde *et al.* 1987) in Kakadu National Park. Numbers in parentheses represent the percentage of the Park occupied by respective vegetation units.

Table 3. Correlations (r_s) between (a) early (EDS), late (LDS) and total (TDS) dry season burning for the Park as a whole and major landscape units vs. four independent variables, where YEAR is the annual sequence 1980–94, RAIN is the amount of rainfall calculated for the preceding period 1 August–31 July, and M50 + and M100 + are the number of preceding consecutive wet season months where rainfall was > 50 mm and > 100 mm, respectively; and (b) the amount of burning undertaken over the years 1980–94 for EDS and LDS periods for the Park as a whole and major landscape units. All data for RAIN, M50 + and M100 + derived as for Fig. 2. Note that, for each year, only areas proclaimed as Kakadu National Park are included in the analysis (i.e. 1980–83 includes stage 1 only; 1984–86 includes stages 1 and 2 only; 1987–94 includes all stages). NS = not significant; $\alpha = 0{\cdot}05$

		YEAR		RAIN		M50 +		M100 +	
		r_s	P	r_s	P	r_s	P	r_s	P
(a) Park	EDS	0·579	0·024	–0·475	NS	0·149	NS	0·019	NS
	LDS	–0·025	NS	0·139	NS	–0·102	NS	–0·161	NS
	TDS	–0·393	NS	–0·179	NS	0·037	NS	–0·209	NS
Plateau/escarpment	EDS	0·514	0·05	–0·432	NS	0·259	NS	–0·258	NS
	LDS	0·196	NS	0·086	NS	–0·132	NS	–0·047	NS
	TDS	0·361	NS	–0·146	NS	0·118	NS	–0·047	NS
Lowland	EDS	0·632	0·012	–0·511	NS	0·096	NS	–0·028	NS
	LDS	–0·461	NS	0·568	0·027	–0·059	NS	0·180	NS
	TDS	0·089	NS	0·075	NS	0·324	NS	0·408	NS
Floodplain	EDS	0·768	0·0008	–0·421	NS	–0·010	NS	–0·370	NS
	LDS	–0·039	NS	0·404	NS	0·134	NS	0·133	NS
	TDS	0·654	0·0082	–0·029	NS	0·316	NS	–0·104	NS

		r_s	P
(b) Park	EDS vs. LDS	–0·314	NS
Plateau/escarpment	EDS vs. LDS	0·521	0·0462
Lowland	EDS vs. LDS	–0·725	0·0022
Floodplain	EDS vs. LDS	–0·275	NS

and sandstone habitats; conversely, frequently burnt areas (5 or more times; Fig. 7c, d) comprise mostly lowland woodland and open forests. These observations are reinforced by the frequency distributions of burnt individual 1-ha pixels for sandstone plateau, floodplain and lowland habitats, as given in Fig. 8 (a–c, respectively).

PATCH SIZE DISTRIBUTION

The EDS and LDS maximum and median sizes of aggregated pixels classified as having been burned are given in Fig. 9a,b, respectively, for the years 1980–94. From Fig. 9b it is apparent that median burnt patch sizes have been declining more-or-less steadily over the 15 years of records. In contrast, no such trend is apparent in data for the maximum sizes of contiguously burnt areas; in fact, one such area in the 1991 EDS extended over a quarter of the entire Park (Fig. 9a). Such observations need careful qualification, however. Thus, if we consider the actual configuration of the 1991 EDS contiguously burnt area, it comprised a highly patchy mosaic of burnt and internally unburnt country. Orientated along the major thoroughfare axis of the Park, this configuration doubtless represents the product of a multitude of small, separate EDS management fires. In contrast, the configuration of one large contiguously burnt area of over 400 000 ha in the 1982 LDS (Fig. 9a) is more-or-less homogeneous, with relatively few internal unburnt patches. Such configurations are typical of uncontrolled LDS fires, particularly in the vast unpopulated expanses of the Arnhem Land plateau.

Discussion

ACCURACY AND RELIABILITY

Remote sensing techniques are increasingly used to monitor the distribution of active fires (e.g. Matson, Stephens & Robinson 1987; Malingreau 1990; Langaas 1992), for estimating gaseous and particulate emissions from biomass burning (e.g. Kaufman *et al.* 1990; Brustet *et al.* 1991), for mapping of fuel loads (e.g. Paltridge & Barber 1988), and for mapping the regional extent and seasonality of wildfires (e.g. Minnich 1983; Allan 1993a). Much of this work has been undertaken using the relatively coarse-resolution AVHRR sensor carried on the NOAA series of satellites. While NOAA-AVHRR data have been applied successfully to mapping the distribution of firescars at large regional scales (e.g. Hick *et al.* 1986; Allan 1993a,b), the use of relatively fine-resolution imagery provides obvious advantages where more detailed, accurate mapping of firescars is required.

Ground-truthing data presented in Table 1 indicate that, for the peak EDS burning period, firescar map-

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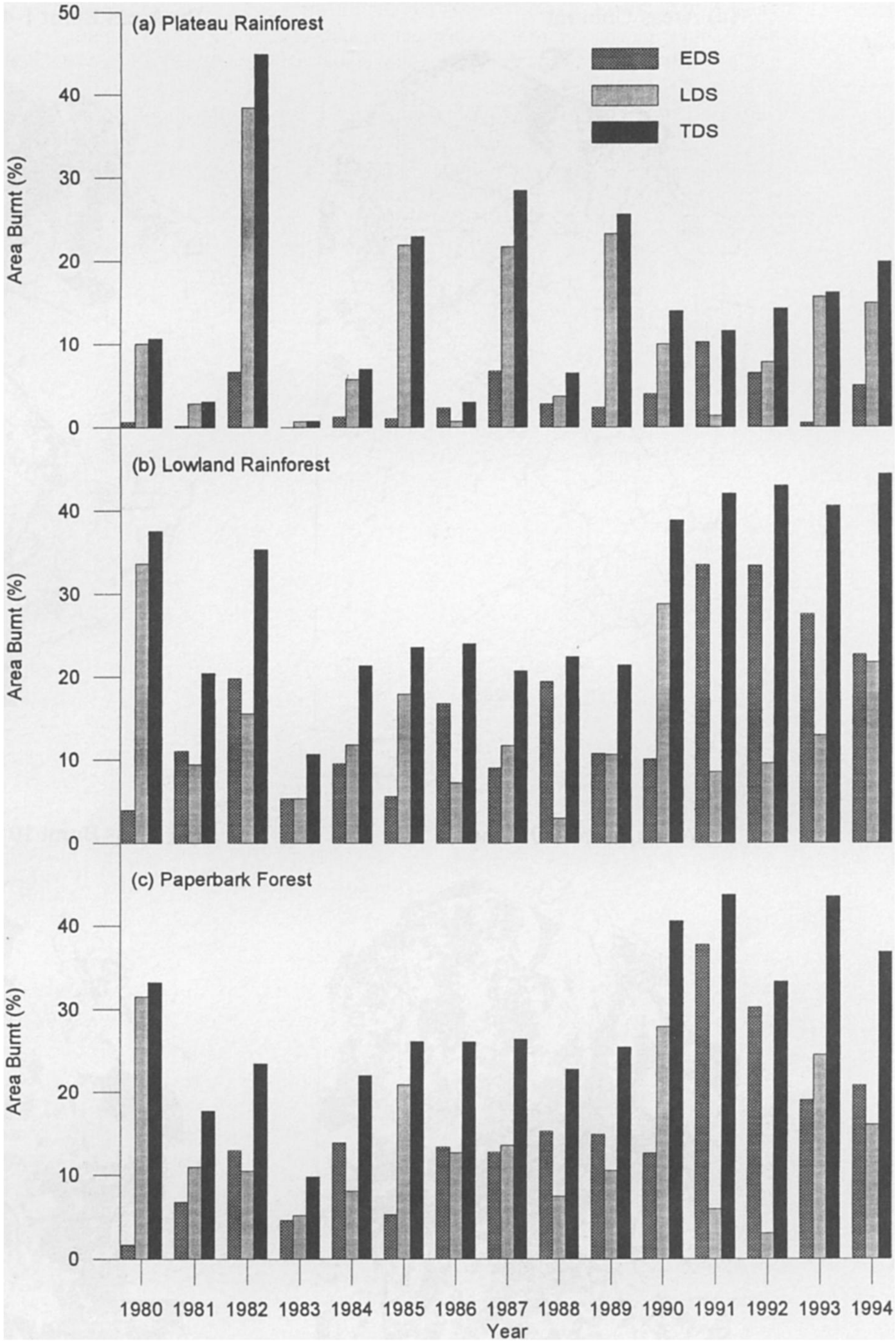

Fig. 6. Interpreted early (EDS), late (LDS) and total (TDS) dry season fire histories, 1980–94, for three relatively fire sensitive vegetation types: (a) plateau (*Allosyncarpia*) rainforest; (b) lowland rainforest; (c) lowland paperbark (*Melaleuca*) forest.

ping accuracy derived from semi-automatic interpretation of LANDSAT MSS imagery was, overall, somewhat greater than 80% both in 1993 and 1994. Greater accuracy may be anticipated in the LDS given less potential for ground cover regrowth following fire. Thus, while these data inspire a relatively high level of confidence in the generality of analyses presented here at landscape and habitat scales, the reliability of assembled sequential fire histories for individual 100 m × 100 m pixels over the 15 years of records may be calculated as being only 3·5%, assuming an annual mapping accuracy of 80%. We suggest, however, that the accuracy associated with determining the sequential fire history of individual small sites may be greatly improved by detailed inspection of the original imagery. Major sources of error inherent in the compilation of these data are set out below.

Ground-truthing

We consider that the ground-truthing methodology applied here provides a generally accurate estimate of the error associated with the mapping of EDS firescars. Thus, while we recognize that the use of non-

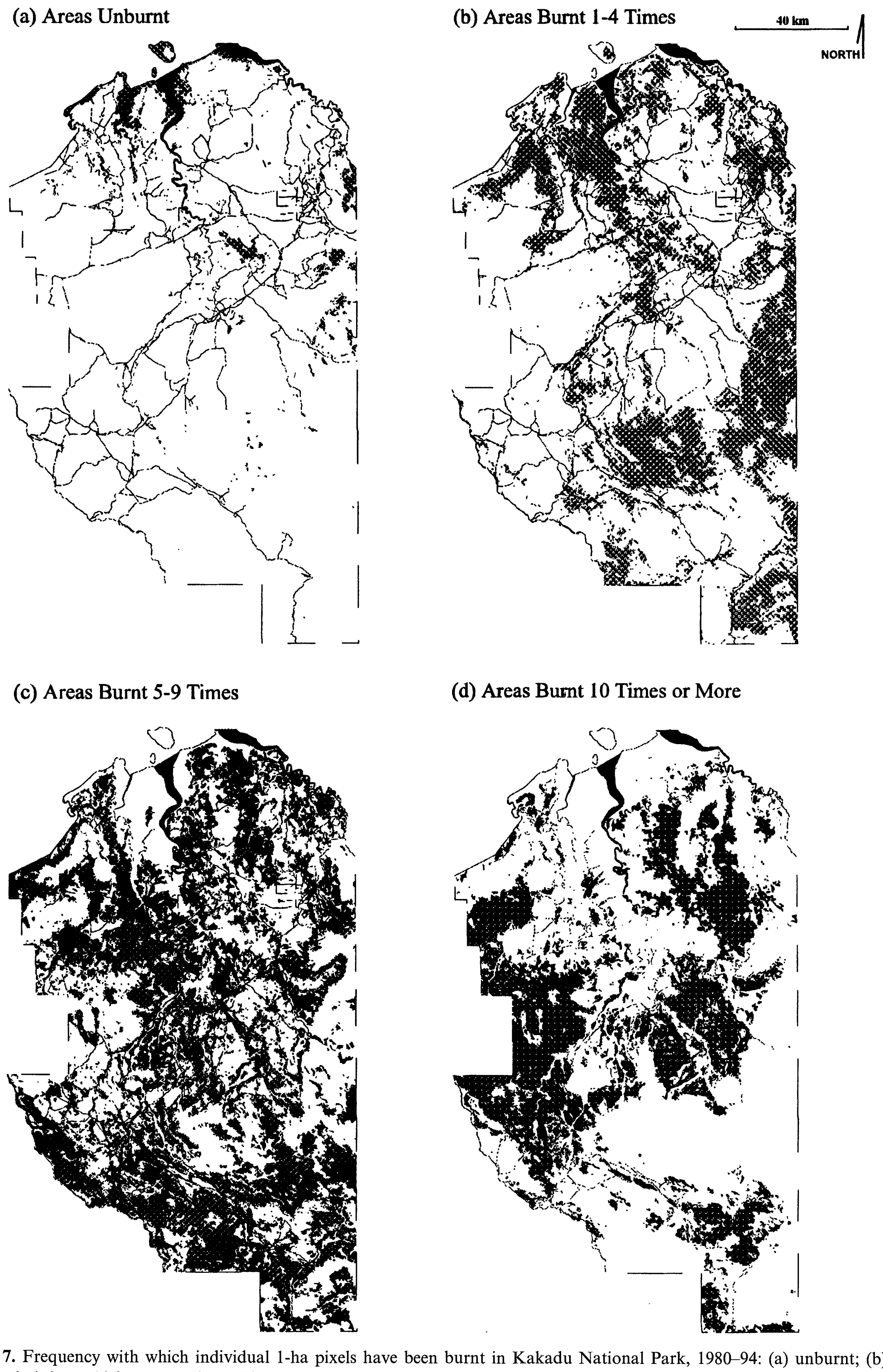

Fig. 7. Frequency with which individual 1-ha pixels have been burnt in Kakadu National Park, 1980–94: (a) unburnt; (b) burnt 1–4 times; (c) burnt 5–9 times; (d) burnt 10 or more times.

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differential navigational GPS currently incurs errors of $\pm$ 100 m due to selective availability of the satellite signal, our methodology explicitly required the recognition of unambiguous ground-truth points (i.e. clearly burnt or unburnt) or, where this was not attained (e.g. locations within 100 m of a fire bound-

Table 4. Comparisons (two-tailed *t*-tests) between the extent of burning close to, and farther away from, drainage lines, settlements and roads in the early (EDS) and late (LDS) dry seasons, for the years 1980–94. For each comparison, means 1 and 2 ($\pm$ SEM) refer to respective proportions of areas burnt (%) as defined in the expression, mean 1 vs. mean 2

	Fire season	Proximity to feature (km)	Mean 1	Mean 2	*P*
(a) Drainage lines					
Plateau	EDS vs. LDS	0–0·5	3·8 ± 0·9	11·5 ± 2·3	0·007
	EDS vs. LDS	0·5–2	1·8 ± 0·4	6·0 ± 1·2	0·005
	EDS	0–0·5 vs. 0·5–2	3·8 ± 0·9	1·8 ± 0·4	0·44
	LDS	0–0·5 vs. 0·5–2	11·5 ± 2·3	6·0 ± 1·2	0·27
Lowlands	EDS vs. LDS	0–0·5	18·5 ± 1·8	12·8 ± 1·8	0·03
	EDS vs. LDS	0–0·5	13·1 ± 1·1	9·0 ± 1·2	0·015
	EDS	0–0·5 vs. 0·5–2	18·5 ± 1·8	13·1 ± 1·1	0·016
	LDS	0–0·5 vs. 0·5–2	12·8 ± 1·8	9·0 ± 1·2	0·08
(b) Settlements	EDS vs. LDS	0–1	21·1 ± 3·1	13·1 ± 2·9	0·07
	EDS vs. LDS	1–5	28·6 ± 3·0	16·3 ± 2·9	0·006
	EDS	0–1 vs. 1–5	21·1 ± 3·1	28·6 ± 3·0	0·09
	LDS	0–1 vs. 1–5	13·1 ± 2·9	16·3 ± 2·9	0·44
(c) Roads	EDS vs. LDS	0–1	34·6 ± 2·9	17·3 ± 2·5	0·0001
	EDS vs. LDS	1–5	27·3 ± 2·6	20·8 ± 2·7	0·09
	EDS	0–1 vs. 1–5	34·6 ± 2·9	27·3 ± 2·6	0·07
	LDS	0–1 vs. 1–5	17·3 ± 2·5	20·8 ± 2·7	0·35

ary; see the Methods), such locations were recorded as potentially ambiguous. Data presented in Table 1 indicate that 8% of all ground-truth sample locations were potentially ambiguous (i.e. 'patchy burnt') in 1993, and 7% in 1994. Nevertheless, the use of differential GPS systems or, where feasible, averaging a number of non-differential GPS readings, will improve the reliability of error estimation.

Wet season cloud cover

In most years cloudiness at the LDS–wet season interface provides a small but significant source of error since fires occurring at this time cannot be mapped using currently available satellite imagery. While we obtained imagery as late in the dry season as possible, we are aware that in some years significant fires occurred after the date of our imagery, especially on floodplains, associated both with lightning strikes and traditional hunting/management practices. Further, reliability of assembled fire history coverages will decrease in future years given that strategic burning will also be undertaken in the wet season as a means for reducing annual *Sorghum* spp., the major grass fuels of the lateritic lowlands (e.g. Russell-Smith 1995b). Such observations reinforce the need to develop new approaches to mapping firescars at this time of year, for example through the use of radar satellite technology.

Small fires/early dry season regrowth

Regrowth of perennial grasses often occurs rapidly following burning in the EDS. This potential source of error can be addressed by obtaining imagery at short intervals but, for an area the size of Kakadu, imposes a cost constraint. Additionally, fires at this time tend to be small in extent, patchy, and may incur minimal damage to the canopy. Thus, although we have sampled twice in the EDS, and most burning currently occurs in a narrow window between June and late July (DuRieu 1993b), it is probable that many small firescars remain undetected. Crapper & Hynson (1983) and Minnich (1983) both concluded that areas of change (e.g. firescar detection) using LANDSAT MSS imagery were minimally of the order of 5 ha, despite the theoretical pixel resolution of *c.* 0·5 ha.

Positional errors

These are introduced into the production of fire history coverages due to the mechanics of the processes involved. For the period 1980–90, manually mapped firescars were constrained by pen thickness; using 1:500 000 imagery, boundary positional errors from this source are *c.* ± 150 m. Given also positional errors associated with the rectification of interpreted firescar coverages to the Australian Mapping Grid projection, additional errors of up to ± 100 m may be anticipated. For the period 1991–94, positional errors of up to ± 270 m on firescar maps produced at 1:250 000 and ± 200 m at 1: 100 000 scales are associated with rectification and mosaicing of digital imagery (DuRieu 1993b). As such, positional errors may be of the order of 2–3 pixels when applied to a raster of 100 m × 100 m.

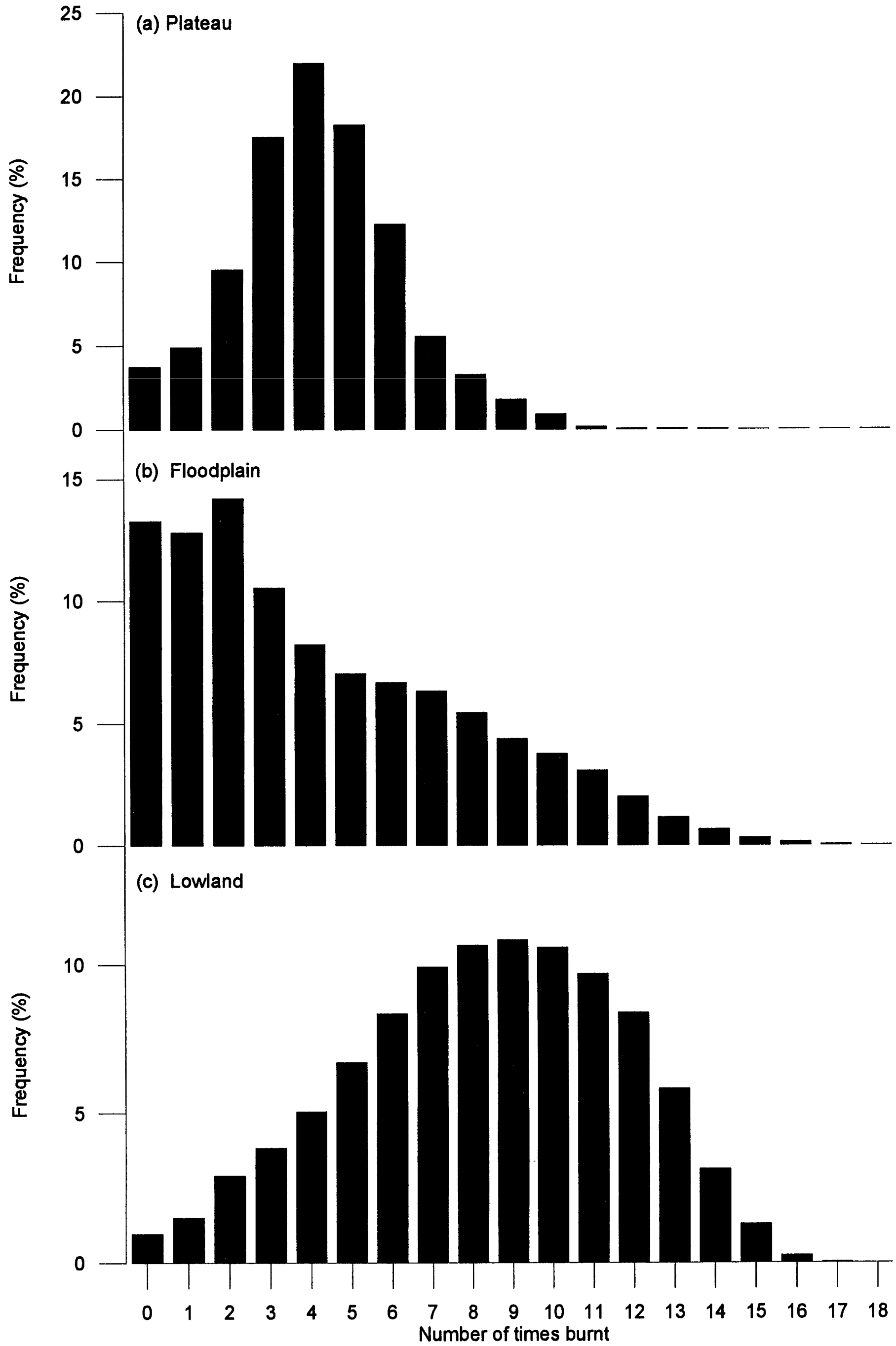

Fig. 8. Frequency with which individual 1-ha pixels have been classified as burnt in Kakadu National Park, 1980–94, for major landscape units: (a) plateau; (b) floodplain; (c) lowland.

SEASONAL EXTENT, FREQUENCY AND PATCHINESS

It is widely acknowledged that extensive areas of the savannas of northern Australia are burnt each year. While regional-scale estimates of the extent and seasonality of burning over a large number of years are yet to be undertaken, a number of earlier studies centred on Kakadu National Park concluded that over 50% of that regional landscape was burnt annually (Braithwaite & Estbergs 1985; Press 1988), typically by fires occurring mostly in the LDS (Day 1985; Press 1988; Graetz 1990). Preliminary interpretation of firescars from NOAA-AVHRR imagery for the *c.* 500 000 km^2 Top End region of the Northern Territory suggests that 16% and 30% of that region was burnt in 1993 and 1994, respectively (Allan & Willson 1995). The ecological significance of fires occurring in the latter part of the dry season is that they tend to be more intense (Williams, Gill & Moore 1997) with a consequent impact on stem mortality (Lonsdale & Braithwaite 1991), and have the potential to burn over vast areas.

Data presented here indicate that, in the early years

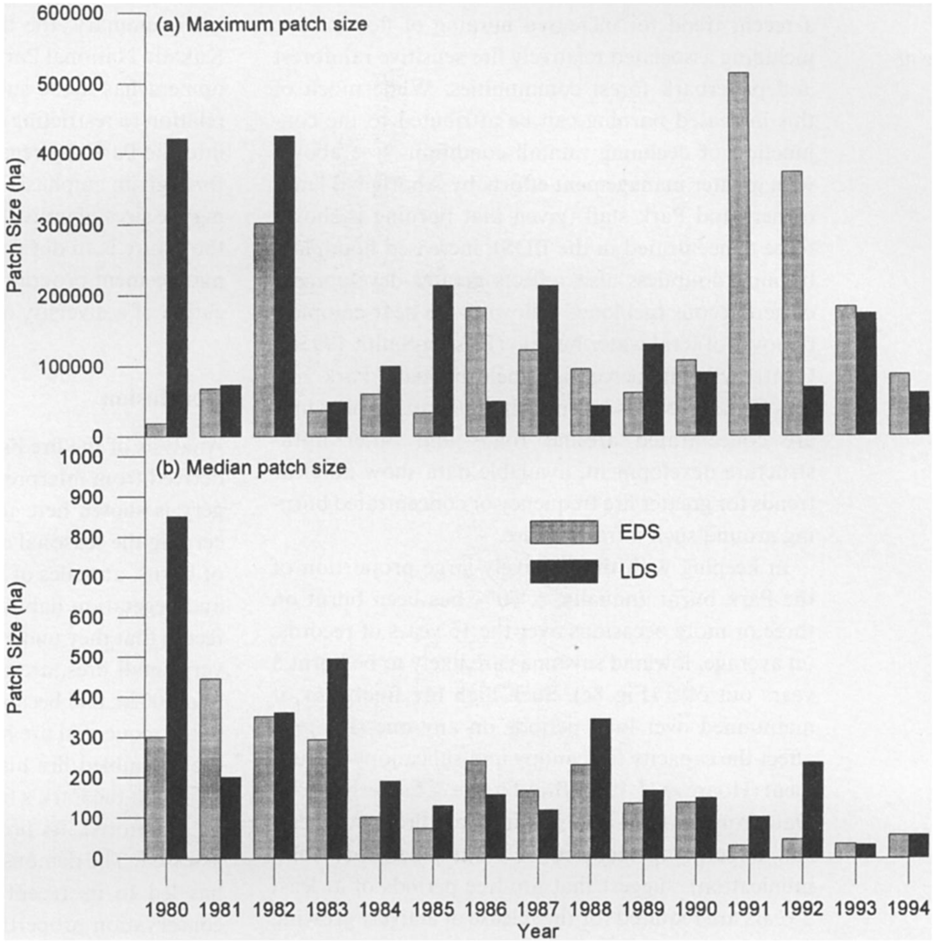

Fig. 9. Early (EDS) and late (LDS) dry season aggregations of 1-ha pixels classified as burnt, 1980–94: (a) maximum size; (b) median size.

of the Park (including areas incorporated in its developmental stages), the fire regime was dominated by LDS fires. However, from the mid-1980s, there has been a significant trend towards EDS burning. Despite an accompanying general decline in rainfall over this same period, for much of the Park area this shift in fire regime can be attributed to greater emphasis on management-prescribed EDS burning. A point to make here is that, under highly predictable monsoonal climatic conditions, variability in rainfall quantity *per se* has limited effect on the length of the growing season as determined by surface soil moisture availability under freely draining conditions (e.g. McDonald & McAlpine 1991). For example, modelling of soil water balance in clay soils using 60 years of rainfall data from the regional Oenpelli station indicates that there was only a 5-week difference (from mid-April to late May) between the first and ninth deciles for the predicted end of the growing season (McDonald & McAlpine 1991, fig. 16). Also, the curing of annual *Sorghum* spp., the major grassy fuel of regional eucalypt-dominated woodland savanna communities, rapidly follows the highly predictable timing of seed set, typically by late April (Andrew & Mott 1983). And, following the extended and very high rainfall in the 1994–95 wet season (1995 mm and 1792 mm recorded at Oenpelli & Jabiru stations, respectively), over 32% of the Park was burnt in the EDS and 5% in the LDS. Declining wet season rainfall is likely to have been a contributory factor for increased EDS burning of floodplains and other drainage run-on situations, however, given their greater propensity to dry-out earlier in the year.

Burning has been concentrated in lowland habitats, particularly eucalypt-dominated savanna communities, with over 50% burnt on average each year. In contrast, a quarter of both sandstone plateau and floodplain landform units have been burnt on average over this period. Of particular concern is the predominance of uncontrolled LDS fires on the plateau, including the continuing unacceptably large extent of fires in plateau rainforest communities; a number of studies have pointed to severe fire impact on this vegetation type (e.g. Russell-Smith *et al.* 1993; Bowman 1994). Such fires typically emanate from sources hundreds of kilometres east or south-east of the Park boundary, fanned by dry south-easterly winds. In recent years such fires have been controlled largely by a rim of EDS strategic burning undertaken beyond the Park boundary. The assembled data also indicate a recent trend for increased burning of floodplains, including associated relatively fire-sensitive rainforest and paperbark forest communities. While much of this increased burning can be attributed to the conjunction of declining rainfall conditions (see above) with greater management efforts by Aboriginal landowners and Park staff (given that burning is shown to be concentrated in the EDS), increased floodplain burning doubtless also reflects greater development of herbaceous fuel loads following the near-complete removal of feral water buffalo (Russell-Smith 1995b). Contrary to the perceptions held by many Park visitors (and assertions by critics!) that management fires are concentrated around roads and other infrastructure development, available data show no clear trends for greater fire frequency or concentrated burning around such infrastructure.

In keeping with the relatively large proportion of the Park burnt annually, *c.* 70% has been burnt on three or more occasions over the 15 years of records; on average, lowland savannas are likely to be burnt 3 years out of 5 (Fig. 8c). Such high fire frequency, if maintained over long periods on any one site, may affect the capacity for canopy and subcanopy recruitment (Hoare *et al.* 1980; Braithwaite & Estbergs 1985). Data from the long-term Munmarlary fire experiment, still undergoing analysis (J. Hoare, personal communication), suggest that fire-free periods of at least 2 years are required for the release of actively growing saplings into the subcanopy (i.e. above typical EDS flame heights) on relatively productive tall, open eucalypt forest sites. While comparable data for floodplain and plateau communities are not yet available, we may anticipate that: (i) in keeping with Aboriginal traditional management practice (e.g. Russell-Smith *et al.* 1997, herbaceous fuel loads surrounding floodplain paperbark forests and rainforest communities need to be burnt on a regular, frequent basis if the current decline of both these forest types (Williams 1984; Russell-Smith & Bowman 1992) is to be halted; and (ii) plateau communities are likely to be particularly vulnerable to frequent burning given infertile, typically seasonally xeric substrates.

A number of recent studies has determined that a range of fire regimes is required to conserve faunal groups adequately in the northern savannas (Braithwaite 1987, 1995; Woinarski 1990; Andersen 1991; Trainor & Woinarski 1994). The management imperative therefore is the development of a fine-scale mosaic of patches encompassing a range of fire histories, maintained by the annual imposition of a mosaic of EDS and LDS fires, and unburnt patches. Partial achievement of this objective is indicated by the steady reduction of the median sizes of burns over this period. On the other hand, the high frequency of fires, especially in lowland savanna habitats, has resulted in there being relatively few areas that have remained unburnt, or burnt on a few occasions only (Fig. 8), over this period.

In summary, the fire management programme in Kakadu National Park over the first 15 years of development has made substantial progress, especially in relation to restricting occurrences of wildfires burning into the Park, by regaining control of the fire regime through an emphasis on EDS burning, and by reducing the sizes of individual fires. The hard challenge for the future is to develop an effective fine-scale habitat management programme through the localized application of a diversity of fire regimes.

Conclusion

Analysis of the fire history of Kakadu National Park derived from interpretation of LANDSAT MSS imagery is shown here to afford powerful insights concerning the seasonal extent, frequency and patchiness of burns, at scales of the Park, major landscape units and vegetation habitats. While these data are imperfect in that they under-represent wet season burns and very small fires, are prone to positional errors of up to *c.* 300 m, and because little confidence can be placed in the sequential fire histories of small individual sites, the assembled fire history affords an effective means by which the Park's fire management programme can be monitored, its problems identified, and its needs assessed. The demonstrable utility of this programme has led to its recent extension on other significant conservation properties in monsoonal northern Australia; the procedure offers potential for wider adoption in savanna regions generally.

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The present paper builds on significant work undertaken over the past decade by many staff of the Australian Nature Conservation Agency (formerly Australian National Parks and Wildlife Service) to develop a functional fire history and GIS programme in Kakadu National Park, particularly Malcolm Forbes, Jon Day, Tony Press, Richard Thackway, Jeff Tranter, Tony Rosling and Wendy Davy. The paper benefited substantially from constructive comments provided by Greg Hill, Peter Whitehead, Andrew Watkinson and anonymous referees. Financial support for the undertaking of this programme was provided by Forests Unit, Department of Environment, Sports and Territories, Commonwealth of Australia; and the Australian Nature Conservation Agency. The paper is dedicated to the field staff and traditional owners of Kakadu National Park.

References

Aldrick, J.M. (1976) Soils of the Alligator Rivers area. *Land Systems of the Alligator Rivers Area, Northern Territory* (ed. R. Story), pp. 71–88. Land Research Series no. 38, CSIRO, Melbourne,.

Allan, G.E. (1993a) *The Fire History of Central Australia.*

Bushfires Research Project, Vol. 4. Commonwealth Scientific and Industrial Research Organisation and Conservation Commission of the Northern Territory, Alice Springs.

Allan, G.E. (1993b) *Patch Size Discrimination within the Fire Mosaic of Central Australia: NOAA-AVHRR vs. LANDSAT MSS*. Bushfires Research Project, Vol. 5. Commonwealth Scientific and Industrial Research Organisation and Conservation Commission of the Northern Territory, Alice Springs.

Allan, G.E. & Willson, A. (1995) Learning more about fire in the Top End: processing and interpreting spatial and temporal fire history data derived from NOAA AVHRR satellite images. *NARGIS*, 95, *2nd North Australian Remote Sensing and Geographic Information Systems Forum*, pp. 21–26. Supervising Scientist, Commonwealth of Australia, Canberra.

Andersen, A.N. (1991) Responses of ground-foraging ant communities to three experimental fire regimes in a savanna forest of tropical Australia. *Biotropica*, **23**, 575–585.

Andrew, M.H. & Mott, J.J. (1983) Annuals with transient seed banks: the population biology of indigenous sorghum species of tropical north-west Australia. *Australian Journal of Ecology*, **8**, 265–276.

Bowman, D.M.J.S. (1994) Preliminary observations on the mortality of *Allosyncarpia ternata* stems on the Arnhem Land plateau, northern Australia. *Australian Forestry*, **57**, 62–64.

Bowman, D.M.J.S. & Panton, W.J. (1993) Decline of *Callitris intratropica* in the Northern Territory: implications for pre- and post-colonisation fire regimes. *Journal of Biogeography*, **20**, 373–381.

Bowman, D.M.J.S., Wilson, B.A. & Hooper, R.J. (1988) Response of *Eucalyptus* forest and woodland to four fire regimes at Munmarlary, Northern Territory, Australia. *Journal of Ecology*, **76**, 215–232.

Braithwaite, R.W. (1987) Effects of fire regimes on lizards in the wet–dry tropics of Australia. *Journal of Tropical Ecology*, **3**, 265–275.

Braithwaite, R.W. (1995) Biodiversity and fire in the savanna landscape. *Biodiversity and Savanna Ecosystem Processes* (eds O. T. Solbrig, E. Medina & J. Silva), pp. 121–140. Springer-Verlag, Berlin.

Braithwaite, R.W. & Estbergs, J.A. (1985) Fire patterns and woody vegetation trends in the Alligator Rivers Region of northern Australia. *Ecology and Management of the World's Savannas* (eds J. C. Tothill & J. J. Mott), pp. 359–364. Australian Academy of Science, Canberra.

Brustet, J.M., Vickos, J.B., Fontan, J., Manissadjan, K., Podaire, A. & Lavenu, F. (1991) *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications* (ed. J. S. Levine), pp. 47–52. MIT Press, Cambridge, Massachusetts.

Crapper, P.F. & Hynson, K.C. (1983) Change detection using Landsat photographic imagery. *Remote Sensing of Environment*, **13**, 291–300.

Day, J.C. (1985) Applications of satellite imagery for fire management in Kakadu National Park. *Towards an Expert System for Fire Management at Kakadu National Park* (eds J. Walker, J. R. Davis & A. M. Gill), pp. 122–137. Technical Memorandum 85/2, CSIRO Division of Water and Land Resources, Canberra.

Dunlop, C.R., Leach, G.J., Latz, P.K., Barritt, M.J., Cowie, I.D & Albrecht, D.E. (1995) *Checklist of the Vascular Plants of the Northern Territory, Australia*. Conservation Commission of the Northern Territory, Darwin.

DuRieu, R. (1993a) Fire management in Kakadu. *Australian GIS User*, **4**, 36–38.

DuRieu, R. (1993b) *Kakadu Firescar Monitoring, 1992*. Unpublished report to Australian National Parks and Wildlife Service, Canberra.

Eastman, J.R. (1993) *IDRISI Version 4·1 Update Manual*. Clarke University, Massachusetts.

Fensham, R.J. (1990) Interactive effects of fire frequency and site factors in tropical *Eucalyptus* forests. *Australian Journal of Ecology*, **15**, 255–266.

Galloway, R.W. (1976) Geology of the Alligator Rivers area. *Land Systems of the Alligator Rivers Area, Northern Territory* (ed. R. Story), pp. 50–70. Land Research Series no. 38, CSIRO, Melbourne.

Graetz, D. (1990) *Analysis of land degradation in Kakadu National Park (Stage III): landscape dynamics, 1972-Present*. Unpublished report to Australian National Parks and Wildlife Service, Canberra.

Haynes, C.D. (1985) The pattern and ecology of *munwag*: traditional Aboriginal fire regimes in north-central Arnhem Land. *Proceedings of the Ecological Society of Australia*, **13**, 203–214.

Haynes, C.D. (1991) Use and impact of fire. *Monsoonal Australia: Landscape, Ecology and Man in the Northern Lowlands* (eds C. D. Haynes, M. G. Ridpath & M. A. J. Williams), pp. 61–71. Balkema, the Netherlands.

Head, L., O'Neill, A., Marthick, J. & Fullager, R. (1992) A comparison of Aboriginal and pastoral fires in the north-west Northern Territory. *Conservation and Development Issues in Northern Australia* (eds I. Moffatt & A. Webb), pp. 130–144. North Australia Research Unit, Australian National University, Darwin.

Hick, P.T., Prata, A.J., Spencer, G. & Campbell, N. (1986) NOAA-AVHRR satellite data evaluation for areal extent of bushfire damage in Western Australia. *Proceedings of the first Australian AVHRR Conference, October 1986*. Perth, Western Australia.

Hoare, J.R.L., Hooper, R.J., Cheney, N.P. & Jacobsen, K.L.S. (1980) *A Report on the Effects of Fire in Tall Open Forests and Woodland with Particular Reference to Fire Management in Kakadu National Park in the Northern Territory*. Report to the Australian National Parks and Wildlife Service, Canberra.

Kaufman, Y.J., Setzer, A., Justice, C., Tucker, C.J., Pereira, M.C. & Fung, I. (1990) Remote sensing of biomass burning in the tropics. *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges* (ed. J. G. Goldammer), pp. 371–399. Springer-Verlag, Berlin.

Lacey, C.J., Walker, J. & Noble, I.R. (1982) Fire in Australian tropical savannas. *Ecology of Tropical Savannas* (eds B. J. Huntley & B. H. Walker), pp. 246–272. Springer-Verlag, Berlin.

Langaas, S. (1992) Temporal and spatial distribution of savanna fires in Senegal and The Gambia, West Africa, 1989–90, derived from multi-temporal AVHRR night images. *International Journal of Wildland Fire*, **2**, 21–36.

Lewis, H.T. (1989) Ecological and technical knowledge of fire: aborigines vs. park rangers in northern Australia. *American Anthropologist*, **91**, 940–961.

Lonsdale, W.M. & Braithwaite, R.W. (1991) Assessing the effects of fire on vegetation in tropical savannas. *Australian Journal of Ecology*, **16**, 363–374.

McAlpine, J.R. (1976) Climate and water balance. *Land Systems of the Alligator Rivers Area, Northern Territory* (ed. R. Story), pp. 35–49. Land Research Series no. 38, CSIRO, Melbourne.

McDonald, N.S. & McAlpine, J. (1991) Floods and droughts: the northern climate. *Monsoonal Australia: Landscape, Ecology and Man in the Northern Lowlands* (eds C. D. Haynes, M. G. Ridpath & M. A. J. Williams), pp. 19–29, Balkema, the Netherlands.

McKenzie, N.L. & Belbin, L. (1991) Kimberley rainforest communities: reserve recommendations and mangement considerations. *Kimberley Rainforests Australia* (eds N. L. McKenzie, R. B. Johnston & P. G. Kendrick), pp. 453–468. Surrey Beatty & Sons, Sydney.

Malingreau, J.-P. (1990) The contribution of remote sensing to the global monitoring of fires in tropical and subtropical ecosysytems. *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges* (ed. J. G. Goldammer), pp. 337–370. Springer-Verlag, Berlin.

Matson, M., Stephens, G. & Robinson, J. (1987) Fire detection using data from the NOAA-N satellites. *International Journal of Remote Sensing*, **8**, 961–970.

Minnich, R.A. (1983) Fire mosaics in southern California and Northern Baja California. *Science*, **219**, 1288–1294.

New South Wales National Parks and Wildlife Service (1989) *Environmental Resource Mapping System (E-RMS) User's Manual*. New South Wales National Parks and Wildlife Service, Armidale, and the Australian National Parks and Wildlife Service, Canberra.

Paltridge, G.W. & Barber, J. (1988) Monitoring grassland dryness and fire potential in Australia with NOAA/AVHRR data. *Remote Sensing of Environment*, **25**, 381–394.

Press, A.J. (1987) Fire management in Kakadu National Park: the ecological basis for the active use of fire. *Search*, **18**, 244–248.

Press, A.J. (1988) Comparisons of the extent of fire in different land management systems in the Top End of the Northern Territory. *Proceedings of the Ecological Society of Australia*, **15**, 167–175.

Russell-Smith, J. (1995a) Flora. *Kakadu: Natural* and *Cultural Heritage and Management* (eds A. J. Press, D. M. Lea, A. Webb & A. J. Graham), pp. 127–166. Australian Nature Conservation Agency and North Australia Research Unit, Australian National University, Darwin.

Russell-Smith, J. (1995b) Fire management. *Kakadu: Natural and Cultural Heritage and Management* (eds A. J. Press, D. M. Lea, A. Webb & A. J. Graham), pp. 217–237. Australian Nature Conservation Agency and North Australia Research Unit, Australian National University, Darwin.

Russell-Smith, J. & Bowman, D.M.J.S. (1992) Conservation of monsoon rainforest isolates in the Northern Territory, Australia. *Biological Conservation*, **59**, 51–63.

Russell-Smith, J., Lucas, D.E., Brock, J. & Bowman, D.M.J.S. (1993) *Allosyncarpia*-dominated rain forest in monsoonal northern Australia. *Journal of Vegetation Science*, **4**, 67–82.

Russell-Smith, J., Lucas, D., Gapindi, M., Gunbunuka, B., Kapirigi, N., Namingam, G., Lucas, K., Giuliani, P. & Chaloupka, G. (1997) Aboriginal resource utilisation and fire mangement practice in western Arnhem Land, monsoonal northern Australia: notes for prehistory, lessons for the future. *Human Ecology* (in press).

Russell-Smith, J., Needham, S. & Brock, J. (1995) The physical environment. *Kakadu: Natural and Cultural Heritage and Management* (eds A. J. Press, D. M. Lea, A. Webb & A. J. Graham), pp. 94–126. Australian Nature Conservation Agency and North Australia Research Unit, Australian National University, Darwin.

Ryan, P.G. (1995) *Kakadu National Park fire history analysis, 1980–1994*. Unpublished report to Australian Nature Conservation Agency, Canberra.

Ryan, P.G., Russell-Smith, J. & DuRieu, R. (1995) Long-term monitoring of fire regimes in Kakadu National Park, Northern Territory, Australia. *NARGIS*, 95, *2nd North Australian Remote Sensing and Geographic Information Systems Forum*, pp. 13–20. Supervising Scientist, Commonwealth of Australia, Canberra.

Schodde, R., Hedley, A.B., Mason, I.J. & Martensz, P.N. (1987) *Vegetation habitats, Kakadu National Park, Alligator Rivers Region, Northern Territory, Australia.* Unpublished report to Australian National Parks and Wildlife Service, Canberra.

Skrdla, M.P. (1992) *A Guide to Map and Image Processing*. MicroImages Press, Lincoln, Nebraska.

Stocker, G.C. & Mott, J.J. (1981) Fire in the tropical forests and woodlands of northern Australia. *Fire and the Australian Biota* (eds A. M. Gill, R. M. Groves & I. R. Noble), pp. 425–439. Australian Academy of Science, Canberra.

Taylor, J. & Tulloch, D. (1985) Rainfall in the wet–dry tropics: extreme events at Darwin and similarities between years during the period 1870–1973. *Australian Journal of Ecology*, **10**, 281–295.

Trainor, C.R. & Woinarski, J.C.Z. (1994) Responses of lizards to three experimental fire regimes in the the savanna forests of Kakadu National Park. *Wildlife Research*, **21**, 131–148.

Walker, J. (1981) Fuel dynamics in Australian vegetation. *Fire and the Australian Biota* (eds A. M. Gill, R. M. Groves & I. R. Noble), pp. 101–127. Australian Academy of Science, Canberra.

Williams, A.R. (1984) Changes in *Melaleuca* forest density on the Magela floodplain, Northern Territory, between 1950 and 1975. *Australian Journal of Ecology*, **9**, 199–202.

Williams, M.A.J. (1991) Evolution of the landscape. *Monsoonal Australia: Landscape, Ecology and Man in the Northern Lowlands* (eds C. D. Haynes, M. G. Ridpath & M. A. J. Williams), pp. 5–17. Balkema, The Netherlands.

Williams, R.J., Gill, A.M. & Moore, P.H.R. (1997) Seasonal change in fire behaviour in a tropical savanna in northern Australia. *International Journal of Wildland Fire*, in press.

Wilson, B.A., Brocklehurst, P.S., Clark, M.J. & Dickinson, K.J.M. (1990) *Vegetation Survey of the Northern Territory*. Technical Report No. 49, Conservation Commission of the Northern Territory, Darwin.

Wise, P. (1987) *Remote Sensing Options for Bushfire Mapping in Kakadu National Park*. Report to the Australian National Parks and Wildlife Service, Canberra.

Woinarski, J.C.Z. (1990) Effects of fire on the bird communities of tropical woodlands and open forests in northern Australia. *Australian Journal of Ecology*, **15**, 1–22.

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