Australian Savanna Fire Regimes: Context, Scales, Patchiness

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ABSTRACT

The development of continental-scale fire mapping using AVHRR since the early 1990s and, more recently, MODIS imagery, is transforming our understanding of Australian fire regimes—particularly the national significance of savanna burning. The savannas of northern Australia are the most fire-prone part of a fire-prone continent. The savanna region comprises 1,898,562 km^2 (24.7% of the Australian landmass), of which 21% has been burnt on average each year, over the period 1997-2005. Savanna fires currently contribute about 68% of national fire extent annually—the remainder comprising mostly fire in central Australia (associated in recent years with decadally high rainfall, hence high fuel loads), with just 2% in relatively densely populated southern Australia. At finer scales of resolution employing LANDSAT imagery, northern Australian studies since the early 1980s are providing novel landscape-scale assessments including monitoring of fire regime heterogeneity and biomass burning emissions. While seasonality has been shown in a number of studies to be correlated with fire intensity, remote sensing studies of fire severity are just commencing. The paper particularly addresses recent north Australian studies that explore the importance of spatial and temporal patchiness in fire extent and severity.

Keywords: fire frequency, fire history, fire regime heterogeneity, greenhouse gas emissions, obligate seeder, satellite imagery

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INTRODUCTION

Australia is recognised as one of the most fire-prone of continents (Dwyer *et al*. 2000, Duncan *et al*. 2003, Carmona-Moreno *et al*. 2005), with most contemporary fire extent occurring in tropical savanna biomes of monsoonal northern Australia (Craig *et al*. 2000; Meyer 2004; Russell-Smith *et al*. 2003c, 2007). Continental-scale understanding of fire occurrence in Australia has developed rapidly over the past decade with the application of daily observations of the relatively coarse resolution Advanced Very High Resolution Radiometer (AVHRR) instrument (pixel size ~1.1 km x 1.1 km at orbital nadir) on the United States' National Oceanic and Atmospheric Administration (NOAA) series of satellites. Assembled data are available from 1997 for the whole of the continent, and from 1990 for Western Australia and the Northern Territory.

As well, for northern Australia a variety of AVHRR- and especially LANDSAT-scale fire mapping studies have been undertaken to characterise regional fire regimes, and address attendant ecological, greenhouse gas emissions, and land management issues (e.g., Press 1988; Beringer *et al*. 1995; Russell-Smith *et al*. 1997, 2003a, 2003c; Gill *et al*. 2000, 2003; Edwards *et al*. 2001; Williams *et al*. 2002; Bowman *et al*. 2003, 2004; Fisher *et al*. 2003; Yates and Russell-Smith 2003; Vigilante *et al*. 2004; Spessa *et al*. 2005; Felderhof and Gillieson 2006). To date, while hot spot and fire mapping products derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery are used in website fire information applications (e.g., http://www.firewatch.dli.wa.gov.au, http://www.firenorth.org.au), and automated fire mapping products are currently under development through the Western Australia Department of Land Information, few regional assessments have been undertaken using this data source. One exception concerns recent assessment of albedo change associated with north Australian savanna burning using the MODIS instrument (Jin and Roy 2005).

An associated recent development has been growing appreciation of the need to better understand and measure spatial patchiness of fire extent and severity components in north Australian savannas for various ecological, greenhouse, and landscape management applications. Ecological issues include patchiness requirements for conservation of fire-sensitive vegetation (e.g., long-lived obligate seeder taxa: Russell-Smith *et al*. 2001, Russell-Smith 2006), recruitment dynamics of woody savanna taxa, including *Eucalyptus* and *Corymbia* dominants (e.g., Fensham and Bowman 1988, Setterfield 2002), and interactions with the home ranges of relatively immobile fauna (Fraser *et al*. 2003, Woinarski *et al*. 2005). Fire regime and greenhouse issues include the need to incorporate patchiness with respect to the extent and amount of consumption of different fuel components (Meyer 2004, Russell-Smith *et al*. 2004, AGO 2006). Landscape management considerations include assessment of spatio-temporal patchiness configurations (i.e., mosaics) required for maintaining ecosystem functioning (e.g., Andersen *et al*. 2003, Price *et al*. 2005, Woinarski *et al*. 2005), and associated implications for delivering effective fire management (Price *et al*. 2007).

By way of introducing the regional context of fire patterning in northern Australian savannas, this paper first provides a general description of contemporary fire patterns in northern Australia as derived from AVHRR imagery, illustrating the main drivers of landscape scale fire patterns with reference to the tropical savannas region included in the Northern Territory. We then consider recent north Australian studies that address aspects of spatio-temporal patchiness, particularly at finer spatial scales than observed with AVHRR. Finally, we look at how this current understanding of patchiness is being applied to a novel biodiversity and greenhouse gas emissions abatement fire management program in the remote western Arnhem Land region of the Northern Territory.

REGIONAL CONTEXT

Australia's 1.9 X 10^6 km^2 tropical savannas region (comprising a quarter of the Australian land mass) is defined after the Interim Biogeographic Regionalisation of Australia (IBRA: Thackway and Cresswell 1995). Salient details describing rainfall distribution and seasonality, vegetation, and landuse extent for the sparsely populated north Australian savannas region are given in full in Russell-Smith *et al*. (2003c), and are summarised below:

Rainfall—Rain occurs over the savanna region mostly between October-March under the influence of the Asian monsoon, and declines rapidly inland, from over 2,000 mm yr^{-1} in a few coastal areas, to <400 mm yr^{-1}. While the amount of rainfall received in any one local area is annually highly variable, the wet season in higher rainfall coastal and sub-coastal regions is a highly reliable event (Taylor and Tulloch 1985). Climatic conditions are conducive for the production of grassy fuels sufficient for carrying ground fires on an annual basis in higher rainfall areas, to once every few years under lower rainfall conditions (Walker 1981, Williams *et al*. 2002). Crown fires are typically absent. In some higher rainfall, mesic savannas (ie., regions receiving >1000 mm yr^{-1}), equilibrium fuel loads may attain 10 t ha^{-1} in 2-3 years without fire (Cook *et al*. 1995); however, over much of the region equilibrium fuel loads are significantly less than this. The vast majority of fires are started by humans, although fires ignited by lightning associated with the onset of monsoonal conditions (typically Nov-Dec) may be a significant source in some inland locations (Russell-Smith *et al*. 2007); prior to human involvement, fires would have occurred mostly at this time. The fire (dry) season of monsoonal northern Australia, mostly driven by dry south-easterlies, is counter-seasonal to that of southern Australia (spring through summer). Throughout the paper, the seasonality of fires in any one dry season is conveniently, if arbitrarily, defined as occurring in the early dry season (EDS), or late dry season (LDS), if fires occur before the end of July, or from August onwards, respectively. For much of the savanna region, this seasonal distinction correlates generally with fires of low severity and low intensity in the EDS period, by contrast with fires of much higher severity and intensity as the dry season progresses (Williams *et al*. 2002, Russell-Smith and Edwards 2006).

Vegetation—In northern areas, vegetation cover is mostly eucalypt-dominated woodland developed on a range of typically nutrient-poor soils, becoming increasingly open-canopied and lower in stature with declining rainfall. In the south, woodland savannas give way to the vast hummock grasslands of the central Australian dunefields. Other regionally significant vegetation types include: 1) pastorally productive tussock (or 'Mitchell') grassland communities predominantly in western Queensland (QLD), with restricted areas in the Northern Territory (NT) and Western Australia (WA); and 2) scattered hummock grassland communities developed on rocky infertile substrates (eg., sandstone), with significant components of spinifex (*Triodia* spp.) and a range of typically fire-sensitive shrubby species. Rainforest communities are confined mostly to the humid tropics of north-eastern Queensland, elsewhere occurring as small patches scattered within the savanna mosaic.

Landuse—The great majority of land is used for pastoral production, especially the grazing of cattle (*Bos taurus* and *Bos indicus*), and also sheep in parts of western QLD. Most of this land is leasehold (ie., leased from respective State and Territory governments). Lands allocated to freehold Aboriginal tenure in recognition of traditional cultural usages constitute the next most common landuse type, especially in the NT, followed by unallocated government lands, especially in WA. Also, in the NT, lands set aside for conservation purposes include significant areas under Aboriginal freehold tenure (eg., Kakadu and Nitmiluk National Parks). Despite the small area used for mining purposes, such landuse constitutes by far the greatest economic return to the regional economy (Gray 1996).

LANDSCAPE-SCALE CONTEMPORARY FIRE PATTERNS

At the Australia-wide scale, an annual average of 497,240 km^2 was recorded as being fire affected over the 9-year period 1997-2005, based on semi-automated mapping of large fires (~>4 km^2: Craig *et al*. 2002) from AVHRR imagery. Of this, an annual average of 336,980 km^2 (67.8%) occurred in the tropical savannas region, with the great majority of the remainder occurring in semi-arid central Australia (Figure 1). Significantly, most (76%) of the annual fire extent in the tropical savannas (as well as in central and southern Australia—79%) occurred in the latter part of the dry season, under increasingly severe fire-weather conditions (Figure 2).

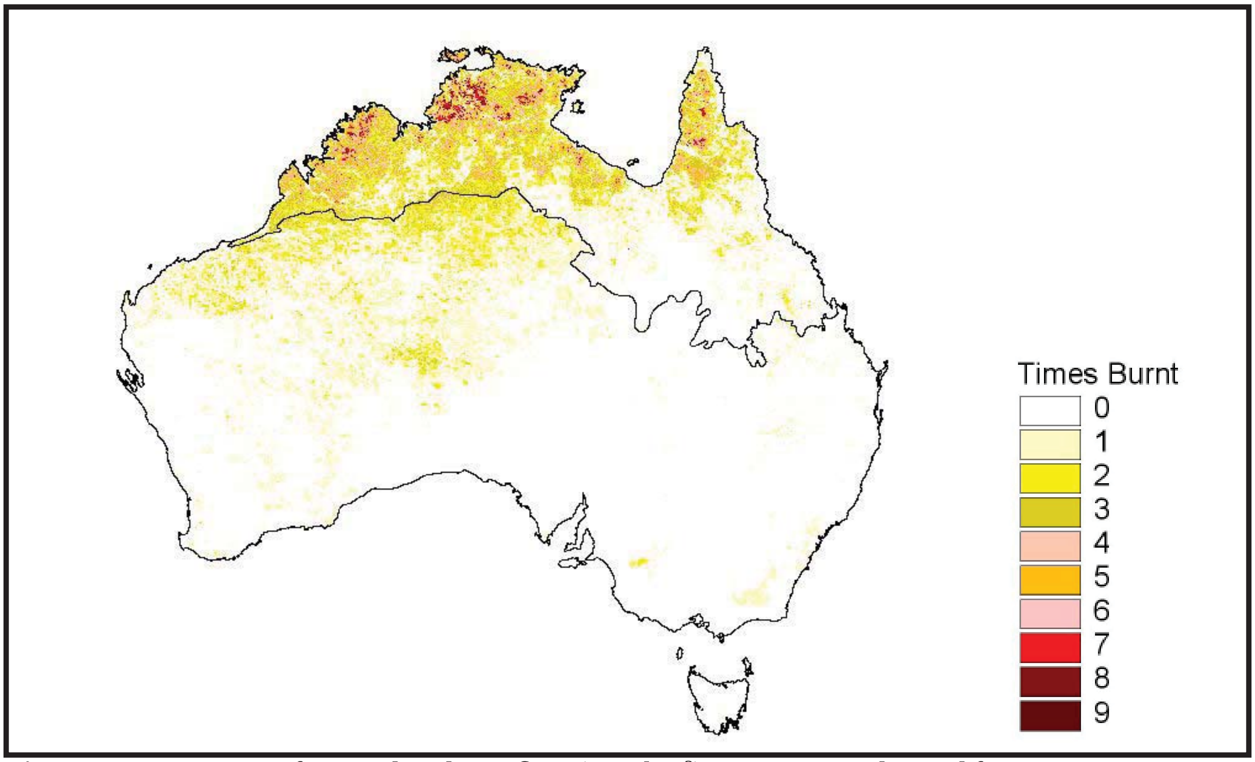

Figure 1. Frequency of Australian large fires (>~4 km^2), 1997-2005, derived from NOAA-AVHRR satellite imagery. North of solid line defines the tropical savannas region.

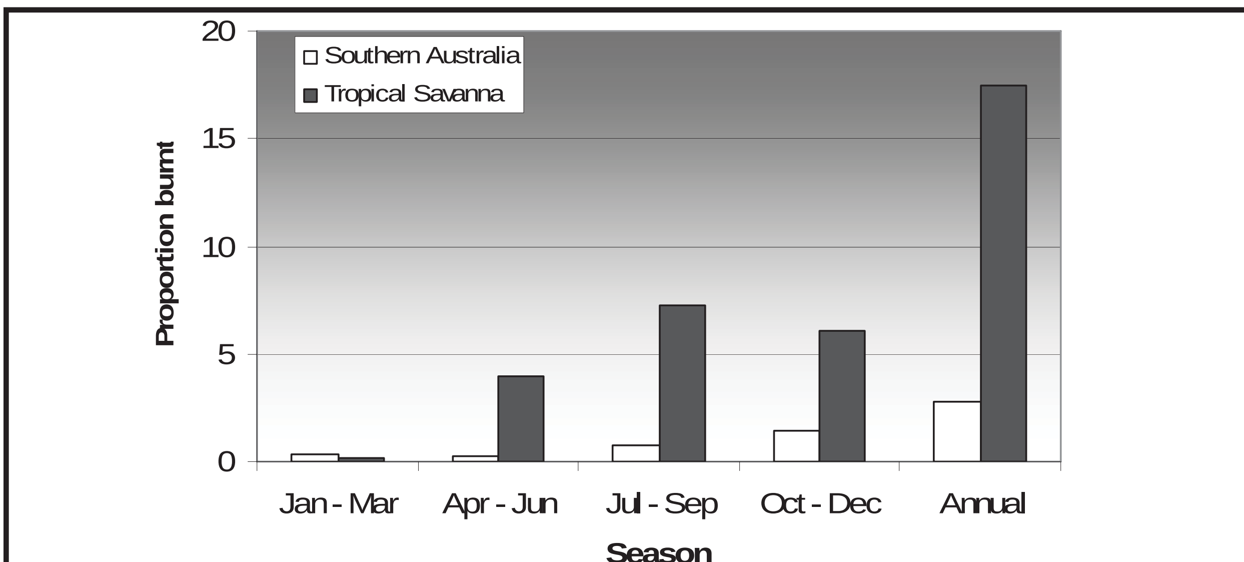

Figure 2. Mean quarterly and annual proportion of Tropical Savannas (1.9 M km^2) and Southern Australia (5.8 M km^2) regions fire affected over the period 1997-2005.

Patterning of fire extent in the tropical savannas region is associated broadly with two landscape-scale features: 1) rainfall quantity and seasonality, and 2) landuse intensity. For example, using rainfall distribution data for the NT savannas region (Figure 3), the mean proportion of respective rainfall isohyet classes that was fire affected over the period 1997-2005 increases generally with increasing mean annual rainfall (Figure 4), reflecting the influence of rainfall-driven ground cover fuel availability as previously discussed.

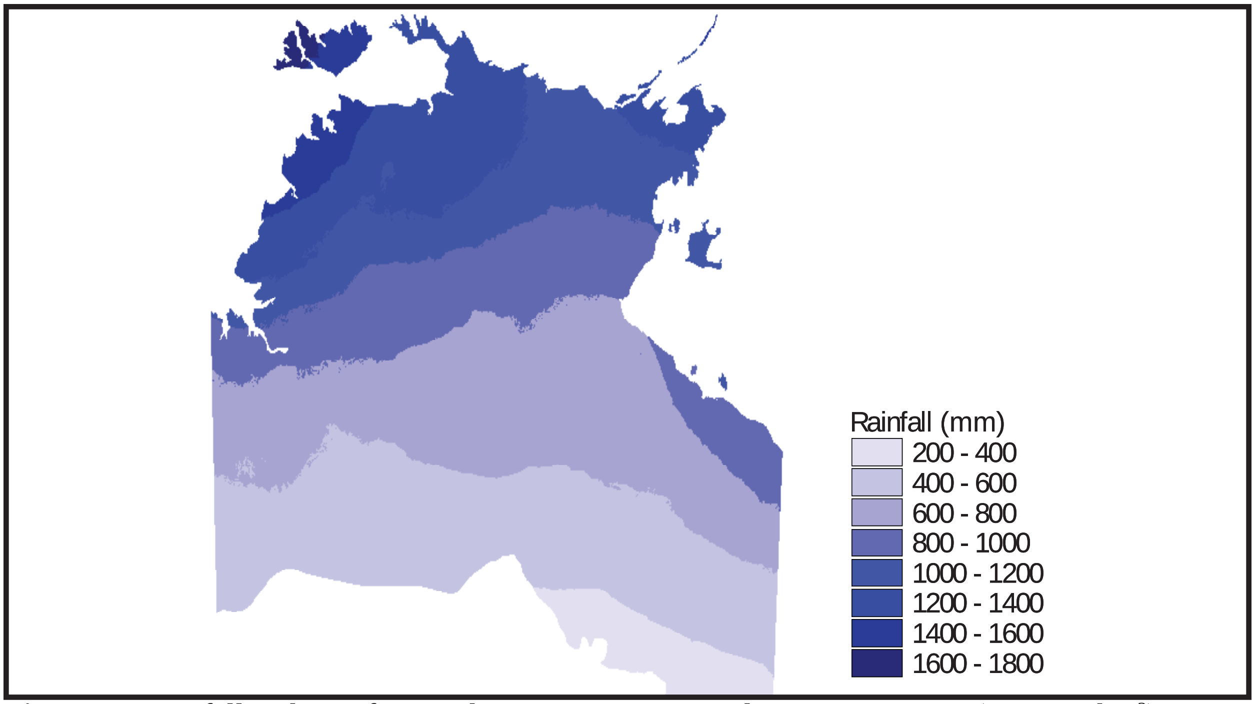

Figure 3. Rainfall isohyets for Northern Territory tropical savannas region (630,000 km^2).

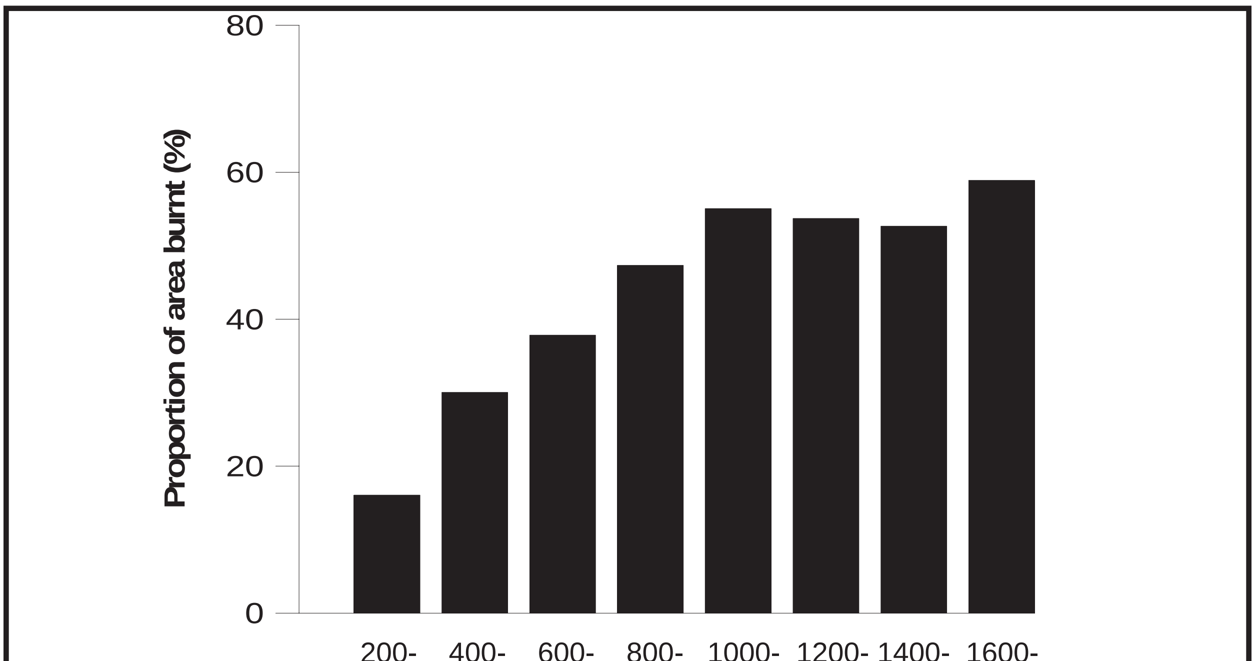

Figure 4. Mean proportion of respective rainfall isohyet classes burnt in the Northern Territory, 1997-2005.

Landuse intensity is imprinted also on this general climate-fire gradient; however, it should be noted that key pastorally productive rangeland areas are associated more with fertile heavy textured soils derived from basalts, limestone, and alluvia, as opposed to any specific rainfall regime. Using detailed property fenceline mapping data (as an expression of landuse intensity) available for sparsely settled areas of the NT (Figure 5), for some local regions at least we can discern clear relationships between extent of burning and fenceline density (e.g., Victoria River District and Gulf in Figure 6). On average, 44.4% of the fenceless Aboriginal-owned Arnhemland, which comprises 32,000 km^2, has burnt annually over the 1997-2000 period.

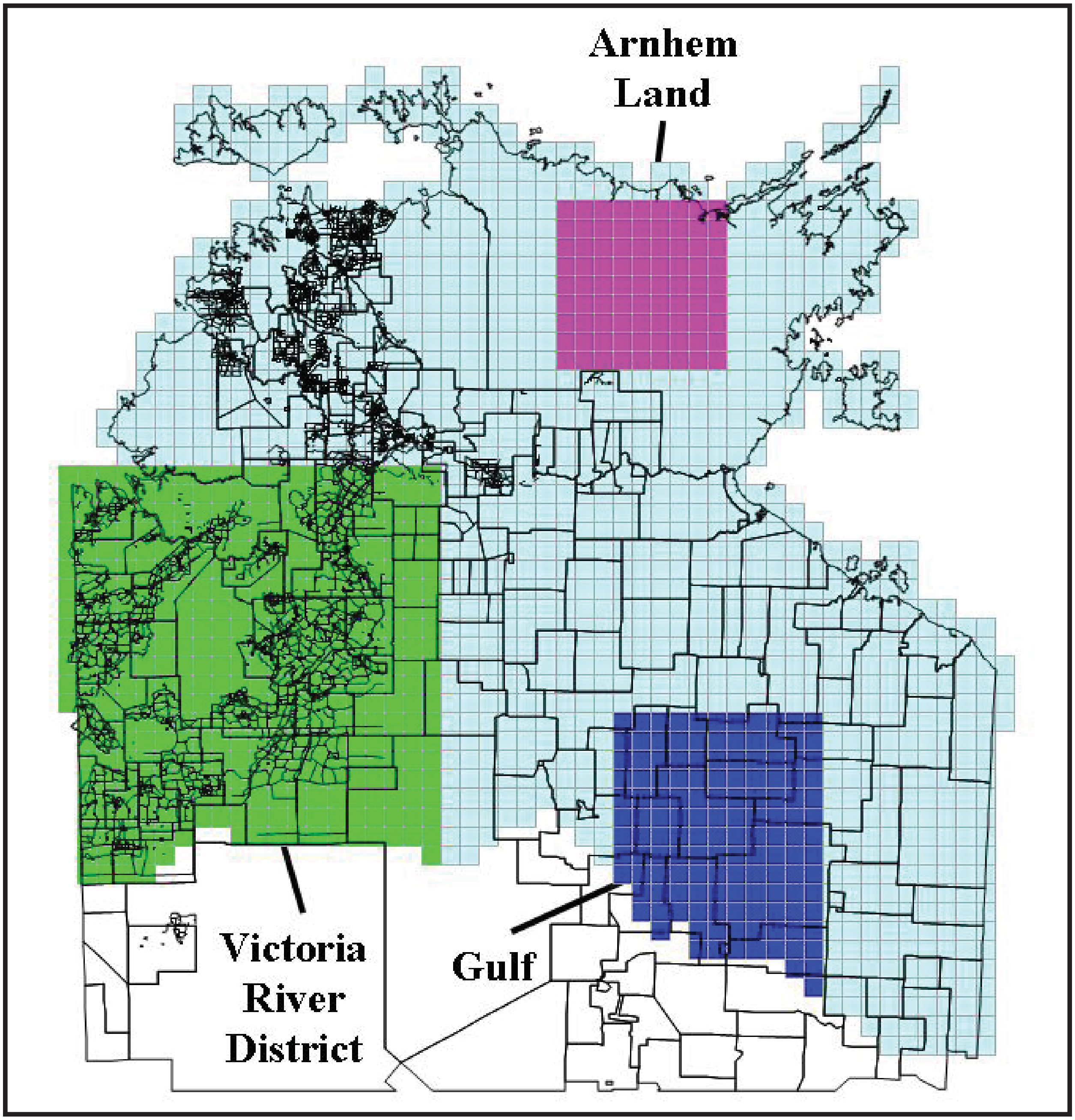

Figure 5. Fenceline and cadastral mapping for the northern NT (source: Northern Territory Government, 2006).

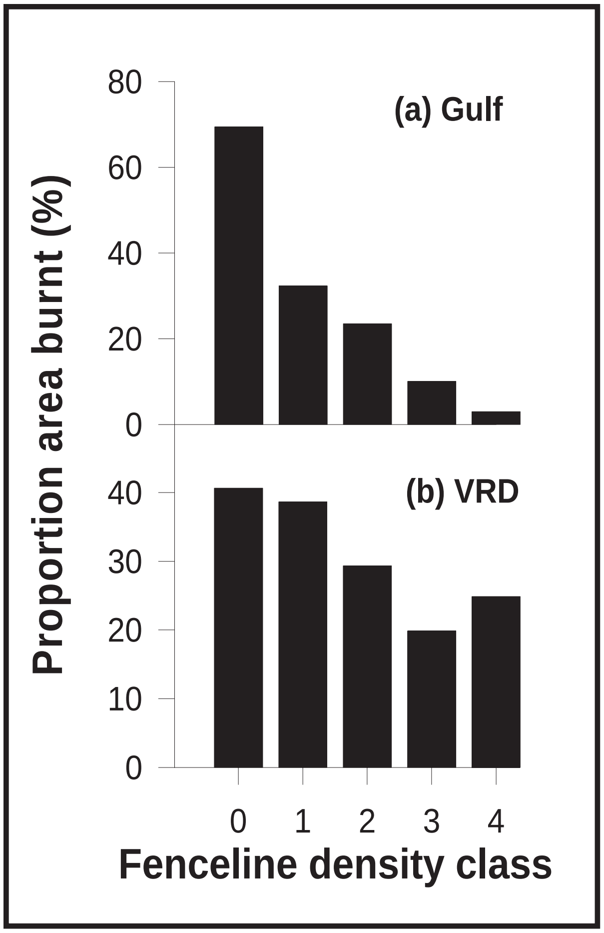

Figure 6. Proportion of 20 x 20 km cells burnt in (a) Gulf (54,800 km^2), (b) Victoria River District (160,400 km^2) regions of the NT, with respect to fenceline density, where 0 = no fencing, 1 = < 50 km fencing, 2 = 50-99.9 km, 3 = 100-149.9, 4 > = 150 km fencing. Refer to Figure 5 for geographic location of areas.

The above assessments conform generally with a recent analysis of Australia-wide fire patterning derived from 8 years (1997-2004) of AVHRR fire mapping, with respect to 10 rainfall regions (defined by 36 years of quarter rainfall data). That continental assessment showed that mean annual extent of large fires was linearly related (r^2 = 0.98) to rainfall seasonality (defined as the ratio of mean annual rainfall in the highest : lowest quarter [Russell-Smith *et al*. 2007]). Statistical modelling of fire extent with a variety of other derived data surfaces (rainfall patterns, vegetation productivity, vegetation type, fuel type, lightning incidence, elevation, surface roughness, cadastral density, land use) confirmed the powerful influence of climatic regimes. The best landscape model explained approximately 70.1% of null deviance, and of which the great majority (60.0%) was accounted for by rainfall patterning. While noting that there were likely to be associations between intensity of landuse and fire incidence in local situations (e.g., as in Figure 6), at the spatial scale of the analysis of fire incidence, no clear associations were detected.

For Australia as a whole, and for northern Australia generally, more fire was observed in years with above average rainfall in the preceding one or two years, and, interestingly, areas burned were also greater in cells that had greater areas burned in the preceding one or two years (Russell-Smith *et al*. 2007). These latter data support the notion that burning patterns at sites or in local regions with a history of anthropogenic fire are more likely to experience additional fire in the future, rather than the perhaps more intuitive association that prior fire reduces fuel loads and consequently reduces fire risk and size.

COMPONENTS OF PATCHINESS

It is axiomatic that spatial detection of patchiness increases with finer resolution optical imagery. For example, Yates and Russell-Smith (2002) provide a detailed comparison of annual fire size distributions derived from AVHRR vs. LANDSAT imagery for three north Australian LANDSAT scenes. While >90% of individual fires were found to be omitted from AVHRR fire mapping given their small size, such fires constituted <3% of total area burnt. Similar observations concerning the influence of small numbers of fires contributing a large proportion of fire-affected area are widely reported both from savannas (e.g., Kasischke and French 1995, Keeley *et al*. 1999, Smith *et al*. 2007). As considered in the Introduction, various studies have been undertaken in the Australian tropical savannas to better understand fire patchiness for a variety of ecological and associated land management purposes.

Spatial extent—ground-based studies of fire extent/patchiness have included measurements associated with 500 m to 750 m transects sampling small water catchment-scale compartments associated with experimental fire treatments in lowland eucalypt-dominated savannas (Williams *et al*. 2003), and 400 m to 1,280 m transects sampling fires at different times of the year in different structural vegetation types in mostly rugged, rocky sandstone terrain (Price *et al*. 2003; J. Russell-Smith, Bushfires NT, Darwin, unpublished data). Data presented by Williams *et al*. (2003: Figure 3.5c) indicate that even some lowland savanna fires with fire-line Intensities of as much as 4 MW m^{-1} were observed to leave at least 10% of ground cover unburnt; generally, however, fires >2 MW m^{-1} left <<10% unburnt. Available patchiness data for vegetation types occupying rocky sandstone savanna terrain indicate that, as one would expect, early dry season fires are more patchy—even when late dry season transects were substantially rockier (Table 1). Price *et al*. (2003) also provide a statistical assessment of patch size distributions. In reality, patchiness data are likely to be highly variable (e.g., reflecting weather, curing and fuel load conditions) and thus substantially more data sets are required. These data are fundamentally useful, however, for providing calibrations of the amount of patchiness inherent when mapping burnt (or, better stated, 'fire affected area') spatial extent from remotely sensed imagery at different scales.

Table 1. Fine-scale patchiness of fires on the Arnhem Land plateau in early and late dry seasons.

Season	Source	Replicates	Patchiness (% burnt)	Weighted mean
Early	Price *et al.* 2003	1300	74.9	70.9
	Russell-Smith *et al.* unpublished data	669	63.3	
Late	Price *et al.* 2003	556	84.6	88.9
	Russell-Smith *et al.* unpublished data	280	97.6	

Temporal patchiness—Temporal changes in patchiness have been explored mostly through compilations of fire frequency (e.g., Figure 1) and associated interval mapping at AVHRR- and, especially for regional ecological assessments, at LANDSAT-scales (e.g., Press 1988; Russell-Smith *et al*. 1997; Gill *et al*. 2000, 2003; Edwards *et al*. 2001; Williams *et al*. 2002; Bowman *et al*. 2003, 2004; Fisher *et al*. 2003; Yates and Russell-Smith 2003; Vigilante *et al*. 2004; Felderhof and Gillieson 2006). For example, using 10 years of LANDSAT-derived fire mapping for a 9,000 km^2 mesic savanna property, Gill *et al*. (2003) explore the frequency distributions of three types of fire-created patch: 1) unburnt 'islands' within burnt areas, 2) patches created with respect to time-since-last-burnt, and 3) patches describing particular intervals between fires. They found that all three frequency distributions describing number of patches vs. area were log-log linear.

Burnt patch size also increases significantly with the progression of the dry season (e.g., Russell-Smith *et al*. 1997, Price *et al*. 2003). For example, in a comparison of patch size distributions mapped from AVHRR and LANDSAT imagery for a 23,000 km^2 area over the period 1997-2005, Yates *et al*. (2008)

describe annual average maximum sizes of patches as ranging from: LANDSAT—266 km^2 in the first quarter, to 2,459 km^2 in the fourth quarter; AVHRR—687 km^2 in the second quarter (incomplete data were available for the first quarter), to >2,000 km^2 in both third and fourth quarters.

A further recent application, using temporal sequences of LANDSAT-derived fire mapping, has been to describe landscape-scale changes in fire-induced heterogeneity with time, adapting a methodology originally developed for Pilanesberg National Park, South Africa (Brockett 2001). The study involved the application of three heterogeneity patch-based metrics (*sensu* Turner *et al*. 2001), for assessing fire-induced heterogeneity changes in the 20,000 km^2 Kakadu National Park, over the period 1981-2000 (Price *et al*. 2005). Heterogeneity indices were calculated from assembled fire history data for the central 1 ha cell of a 5 x 5 cell (25 ha) window; that is, at a spatial scale relevant to the home ranges of many small- to medium-sized native mammals. Two of these indices were first calculated separately for each year, employing different metrics based on the extent of burning occurring in the 5 x 5 cell array, and then averaged for each of four consecutive five-year periods and over all years. The third index was calculated as the sum of the coefficients of variation for four fire regime variability parameters determined likewise for five- and 20-year periods. The study illustrated that ongoing development and refinement of Kakadu's fire management program has reflected incremental increase in fire-induced heterogeneity in successive five-year periods.

Fire severity—Given the large extents of north Australian savanna fires, it stands to reason that there will be very substantial spatial heterogeneity with respect to fire severity within individual fires. To date, however, there has been no concerted effort to use conventional remote sensing indices for mapping fire severity (NDVI—Normalised Difference Vegetation Index, or dNBR—Differenced Normalized Burn Ratio), in Australia's tropical savannas as has been applied elswehere (e.g., Pereira *et al*. 2004, van Wagtendonk *et al*. 2004, Cocke *et al*. 2005, Hamill and Bradstock 2006). In order to assess the relative merits of a range of spectral indices for application to fire severity and intensity mapping, one of us (ACE) is currently undertaking a PhD program that involves direct measurement of electromagnetic reflectance spectra for fire-affected patches in different savanna landscape types.

Rather, seasonality of burning has been used generally as a surrogate of intensity and severity given strong empirical relationships derived from experimental fire studies that show that fires in the EDS typically are substantially less intense than those later in the dry season (Williams *et al*. 1998, Russell-Smith *et al*. 2003b). These findings have been reinforced in a recent study where ten years of photo and associated data records from an extensive fire and vegetation effects monitoring program established in two large north Australian National Parks were used to explore relationships between seasonality and fire severity in a variety of different landform and vegetation types (Russell-Smith and Edwards 2006). Using a three-tiered fire severity scale (low severity—leaf scorch height <2 m; moderate severity—leaf scorch height >2 m, but mid-canopy only scorched; high severity—canopy scorched), data for 719 fires recorded from 178 plots over the period 1995-2004 indicated that the great majority of early dry season fires were of very low severity (fire-line intensities <<1,000 kW m^{-1}), whereas fires later in the dry season were typically of substantially greater severity. Similar trends were evident for vegetation occupying all landform types.

INTEGRATING PATCHINESS WITH BIODIVERSITY AND GREENHOUSE GAS EMISSIONS MANAGEMENT—A CASE STUDY

As considered previously, the savannas of northern Australia comprise a vast, mostly subdued, sparsely settled, fireprone landscape where, over substantial areas and particularly on poorer soils, contemporary fire regimes are dominated by frequent and extensive late dry season wildfires. Such fire regimes are incurring significant impacts on various biodiversity components, including biodiversity hotspots associated particularly with remote and rugged sandstone terrain (Williams *et al*. 2002, Russell-Smith *et al*. 2003, Woinarski *et al*. 2006). Such fire regimes are also the source of nationally significant emissions of the accountable greenhouse gases, nitrous oxide and methane, and annually account for ~2% to 4% (10 Mt to 20 Mt $CO_{2\text{-}e}$) of Australia's National Greenhouse Gas Inventory (AGO 2006). Landscape-scale fire management in these situations, often coincident also with lands under Aboriginal tenure where landowners possess few infrastructural and capital resources, poses significant challenges.

A key region of national biodiversity significance concerns the 34,000 km^2 Arnhem Plateau region in the Northern Territory (Figure 7). This region is included partly within the contiguous Kakadu (World Heritage) and Nitmiluk National Parks to the west, and mostly within Aboriginal-owned Arnhem Land in the east. It comprises very remote and rugged sandstone terrain and is one of four key centres for terrestrial plant diversity in northern Australia (Woinarski *et al*. 2006). Based on fire mapping from LANDSAT imagery for the period 1990-2005, the 24,000 km^2 Western Arnhem Land Fire Abatement (WALFA) project area (Figure 8) has been burnt on average 9.8% in the early dry season and 26.7% in the late dry season, with fire return periods ranging from almost every second year for woodland and open forest habitats, to once in five years for monsoon rain forest (A.C. Edwards, unpublished data).

Such high frequencies, particularly of relatively intense late dry season fires (refer earlier discussion), are incurring devastating impacts on regional extensive fire-sensitive plant communities (e.g., monsoon rain forests—Russell-Smith and Bowman [1992], Bowman [1994], heaths—Russell-Smith *et al*. [2001], cypress pine (*Callitris intratropica*) thickets—Bowman and Panton [1993]). Notably, many shrubby heath species, as well as cypress pine, are long-lived obligate seeders and thus susceptible to frequently recurring fires (Russell-Smith *et al*. 2001, Russell-Smith and Edwards 2006). A considerable challenge, therefore, for biodiversity management of Arnhem Plateau fire-sensitive communities is to better understand and deliver spatio-temporal fire patchiness, especially in relation to rapid accumulation of ground- and shrub-borne fuels.

Parallel research is also being undertaken in the WALFA area to understand and measure the dynamics and quanta of accountable greenhouse gas emissions from savanna fires (Russell-Smith *et al*. 2003a, 2004). Understanding components of fire patchiness is critical to those measurements, particularly the amount of biomass consumed in savanna fires. Following AGO (1994):

$$M = A \text{ x } FL \text{ x } BEF \qquad (1)$$

where: M = mass of fuel burnt in fires (tonnes); A = estimated area of fires, using remote sensing; FL = fuel load; BEF = burning efficiency factor. Of relevance here, the BEF takes into account, and is the product of, two components of patchiness: 1) pyrolysis efficiency—the fraction of fuel actually burnt, and 2) fire patchiness—the fraction of the mapped fire affected area actually burnt. As described

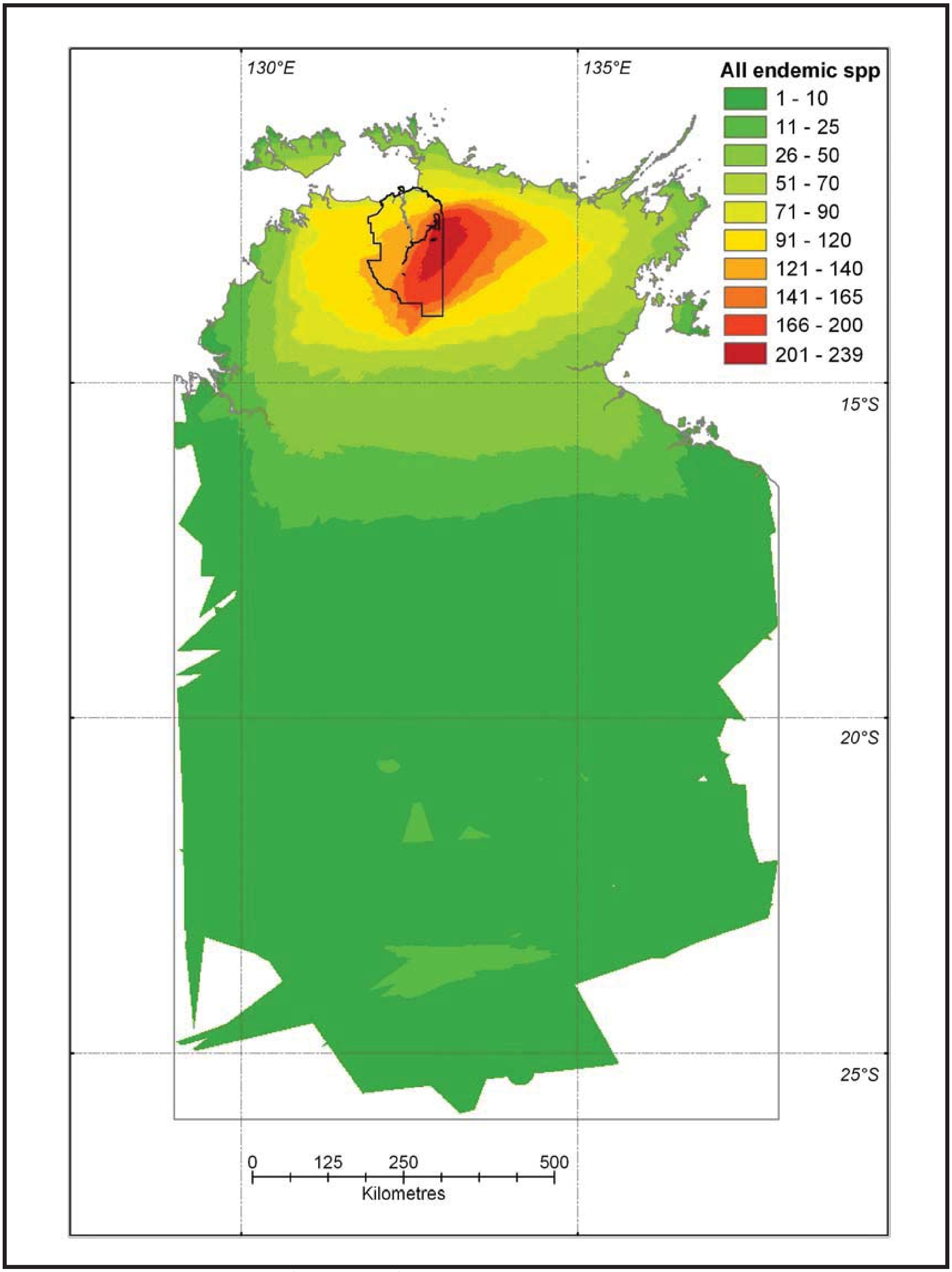

Figure 7. Contour diagram of number of endemic plant species in the Northern Territory. Outline is Kakadu National Park. Refer to Woinarski *et al.* (2006) for details.

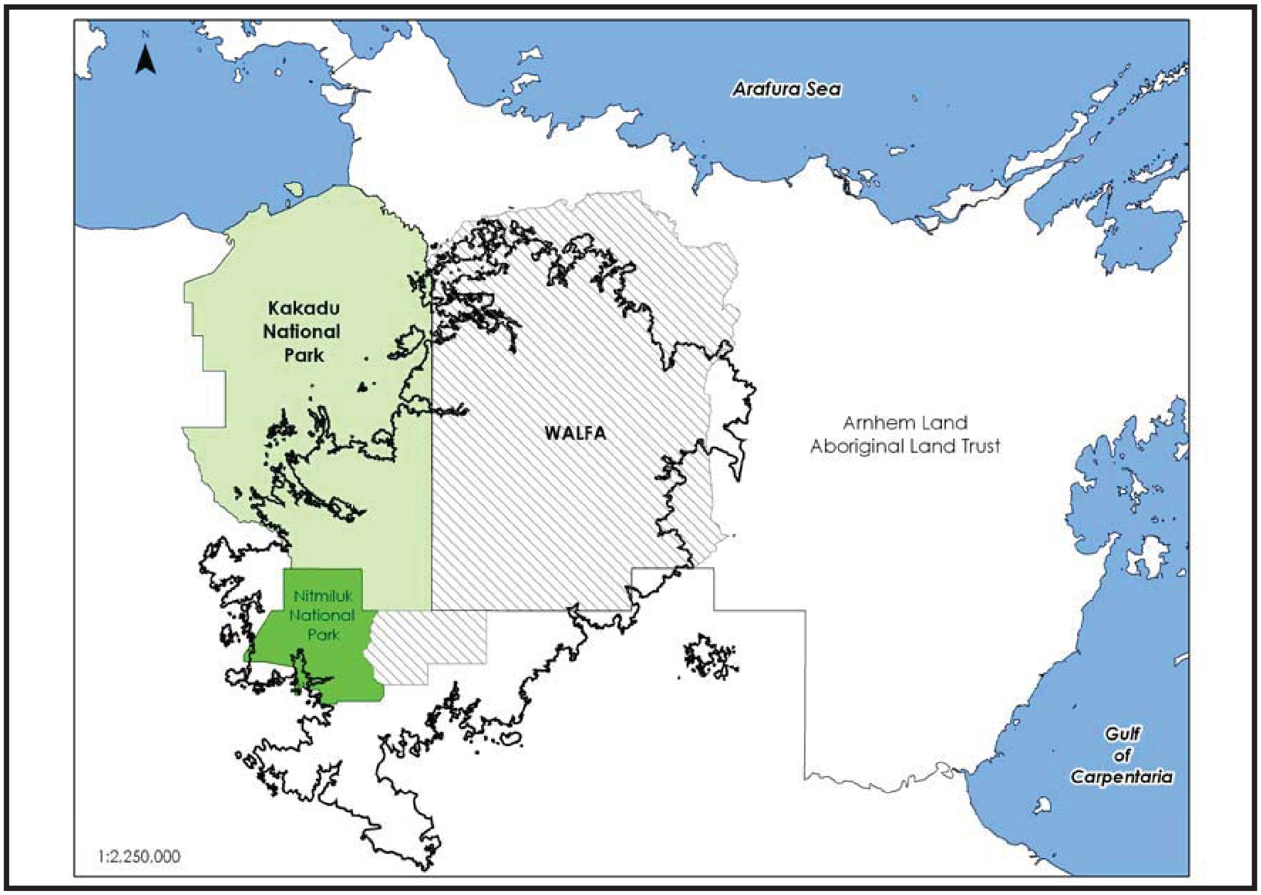

Figure 8. Western Arnhem Land Fire Abatement (WALFA) project area.

previously, fire patchiness has been measured in transect-based studies, under different fire severity (i.e., seasonal) conditions (Table 1). Likewise, the proportion of fuel consumed has been measured extensively in plot-based studies, for fires of different intensity / severity (G.D. Cook *et al*. unpubl. data).

These parallel research and management issues, together with the need for finding sustainable long-term economic solutions to provide employment opportunities for remote Aboriginal communities, have this year been integrated as a multi-decade, greenhouse gas emissions abatement project, funded principally by a multi-national energy corporate as a 'carbon offsets' arrangement. Significant opportunities exist elsewhere in Australia's fireprone tropical savannas (Figure 1) to develop similar multi-beneficial arrangements. Understanding the components and implications of fire-induced patchiness is a key research issue for Australia's tropical savannas.

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