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Seasonal Changes in Fire Behaviour in a Tropical Savanna in Northern Australia

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Abstract. In a landscape-scale experiment, fires were lit in replicate catchments 15-20 km^2 in area, either early in the dry season (June) or late in the dry season (September) between 1990 and 1994. For each fire, Byram-intensity was determined in representative one ha areas of *Eucalyptus miniata - E. tetrodonta* open-forest, with a ground stratum dominated by annual grasses. Fuel weights were measured by harvest, fuel heat content was assumed to be constant, and the rate of spread was determined using electronic timers. Fuels consisted primarily of grass and leaf litter, and ranged from 1.5 to 13 t ha^{-1}; in most years, average fuel loads were 2-4 t ha^{-1}. Rates of spread were generally in the range of 0.2-0.8 ms^{-1}. The mean intensity of early dry season fires (2100 kW m^{-1}) was significantly less than that of the late dry season fires (7700 kW m^{-1}), primarily because, in the late dry season, there was more leaf litter, fuels were drier, and fire weather was more extreme. Crown fires, a feature of forest fires of high intensity in southeastern Australia, were not observed in the Kapalga fires. Fire intensity was a very good predictor of both leaf-char height and leaf-scorch height for fires between 100 kW m^{-1} and 10,000 kW m^{-1}, the range in which the majority of experimental fires fell.

Keywords: Australia; *Eucalyptus*; fire intensity; fuel load; fuel moisture; leaf-char height; leaf-scorch height; rate of spread; wet-dry tropics.

Introduction

Frequent fire is a feature of the wet-dry tropical savanna forests and woodlands of the northern part of the "Top End" of the Northern Territory in Australia. Savanna is the dominant vegetation type in northern Australia (Wilson et al. 1990; Gillison 1994) and tens of thousands of square kilometres burn each year during the dry season (Press 1988; Greatz et al. 1992). The vast majority of fires are deliberately lit by humans. The vegetation of the region is predominately open savanna, with a discontinuous overstorey of *Eucalyptus* spp. and a more continuous understorey of annual and perennial grasses, forbs and small shrubs (Wilson et al. 1990; 1995). Press (1988) estimated that in the Alligator and Adelaide Rivers region, more than 50% of all lowland forest systems in all land use categories were burnt during the 1980-85 period. A similarly high figure was described for the Kakadu region by Braithwaite & Estbergs (1985). Russell-Smith (1995) indicated that, between 1980 and 1994, 40-45% of the area of Kakadu National Park (20, 000 km^2) was burnt annually.

The fire-prone nature of this region of tropical Australia, like all tropical savanna regions of the world, is a consequence of the strongly seasonal wet-dry climate. Rainfall is relatively high (1000-1800 mm per annum), 90% of which falls in summer, and the dry season is 6-9 months long. Thus there is a consistent, annual growth of the understorey, followed by a period of desiccation during which fuels may cure and numerous tree species lose some or all of their leaves (Wilson et al. 1995). Grasses are the dominant component of the understorey, with tall annual grasses such as *Sorghum* spp. being especially common. During the transition period from dry season to wet season (the "build-up"), intense electrical storms may occur, and lightning is common. Thus, the meteorological, fuel and ignition conditions necessary for fire, occur annually (Bowman 1988; Bowman et al. 1988; Gill et al. 1990; Gill et al. 1996).

Fire has been used for millennia by local Aboriginal people (Lewis 1989) with historical records suggesting a peak of activity in July at time of European contact (Braithwaite 1991). Fire is used currently as a management tool by most land users within the region (Russell-Smith 1995), and most fires are lit deliberately. Reasons for burning include fuel reduction, promotion of more palatable herbs and grasses, hunting by Aboriginies, and emulation of traditional Aboriginal burning practices. Within the World Heritage Kakadu National Park, prescribed fire is used within the savannas by the managing agency (Kakadu Board of Management 1991; Russell-

Smith 1995, Russell-Smith et al. 1997). Burning commences in the early dry season (April/May), and is mostly complete by August.

There have been several studies of fire occurrence in the savannas of the Top End of the NT (Braithwaite and Estbergs 1985; Press 1988; Graetz et al. 1992). In addition, there have been recent studies of fire weather (Tapper et al.1994; Gill et al. 1996), the nature of Aboriginal burning practices (Braithwaite 1991), and an increasing number of studies on impacts of fire on ecological attributes of Australia's savannas (Bowman et al. 1988; Fensham 1990; Woinarski 1990; Andersen 1991; Cook 1991; Lonsdale and Braithwaite 1991). However, the behaviour of fire with respect to season has not been studied. In this paper we present data on fire behaviour from Kapalga Research Station in Kakadu National Park, with special reference to fuels, intensity with respect to season of burn, and the relationships between intensity and immediate post-fire attributes such as leaf-char height and leaf-scorch height. The fires were lit over a five-year period, as part of a landscape-scale fire experiment (Braithwaite 1990; Andersen 1995; Williams 1995; Andersen et al. 1998) designed to assess the biological impact of a range of fire regimes on soils, flora and fauna.

Methods

Study Site

Kapalga Research Station (12° 45' S 132° 25' E), 700 km^2 in area, is 180 km east of Darwin. Open eucalypt savannas predominate on the well-drained lateritic soils of the drainage divides, which are of low elevation and relief. Floodplain areas are occupied by treeless grasslands, and there are several pockets of monsoon rain forest (Russell-Smith 1992). For the fire experiment, the region was sub-divided into a number of management compartments, 15-20 km^2 in area, which represent the catchments of minor, ephemeral streams which drain into one of the surrounding major river systems - the West Alligator or the South Alligator River (Figure 1). The vegetation of the creek margins is woodland dominated by *Eucalyptus alba* and *E. papuana* (nomenclature follows Dunlop et al. 1990); the understorey consists mostly of perennial grasses. The vegetation of the better-drained soils is open forest dominated by *E. miniata* and *E. tetrodonta*, with the understorey dominated by a mixture of annual grasses such as *Sorghum intrans* and perennial grasses such as *Heteropogon triticeus* (Wilson et al. 1990; 1995).

Fire treatments

Each compartment was subjected to one of four fire regimes (Figure 1):

1. "Early"; burnt annually, once during the early part of the dry season (early June).
2. "Progressive"; burnt annually, with fuel ignited three times (early June, mid-July and late September) during the dry season as the fuels cured; the spatial pattern of burning is roughly concentric, from the outside of the compartment to the inside.
3. "Late"; burnt annually, once during the late dry season (late September).
4. "Unburnt"; fire was actively excluded from each of these compartments. One small (< 1ha) fire was started by lightning early in the wet season on one plot, but was extinguished by subsequent rain. In September 1994, however, one of the unburnt compartments, compartment M, was burnt extensively by unplanned fire.

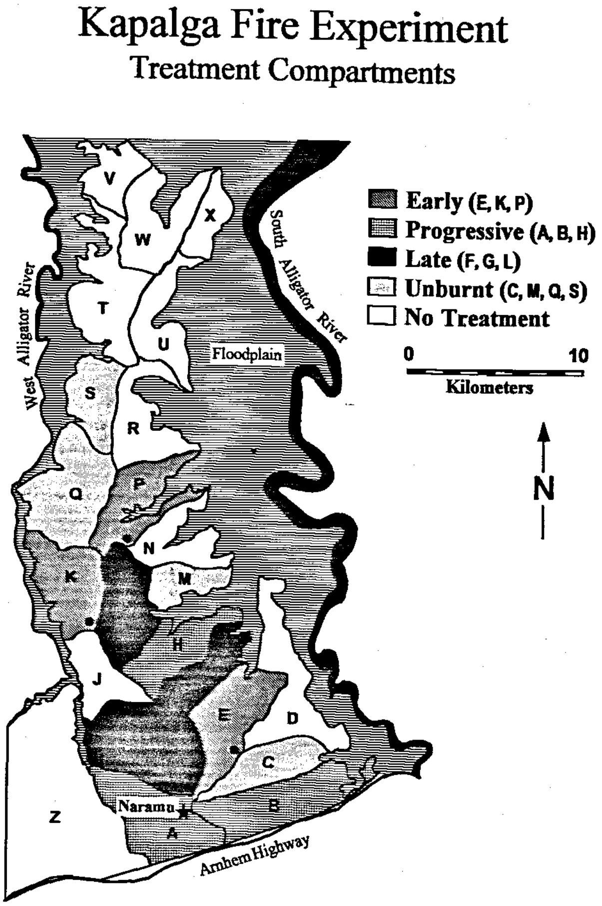

Figure 1. Map of Kapalga Research Station showing location of compartments and their respective experimental fire regimes. The locations of the sites used to measure fire intensity are indicated by the black dots. The letters indicate the local compartment names. The position of the letters within each compartment indicates the approximate position of the permanent 700 m reference transects, along which measurements of the area of ground stratum burnt were made (see Methods). Naramu camp, where meteorological measurements were taken, is indicated.

These regimes represent the range of fires which are typically lit over the course of the year in the Top End of the Northern Territory. Burning early in the dry season is the preferred practice of a number of land management agencies. The Northern Territory Bushfires Council promotes early dry season burns as a means of fuel reduction (Anon. 1993). The Australian Nature Conservation Agency, the agency responsible for managing Kakadu National Park, also prefers to burn early in the dry season (Kakadu Board of Management 1991). The progressive regime, although not discussed in this paper, is an attempt to simulate the spatial and temporal pattern of burning as thought to have been practised by local Aboriginal people (Braithwaite 1991). Late dry season fires are generally looked upon as detrimental to both property and wildlife values; fuel reduction burning early in the dry season is thus practised largely to reduce the likelihood of late dry season fires (Russell-Smith et al. 1997).

The data presented in this paper pertain to the early- and late- fire regimes, for fires ignited annually between 1990 and 1994, in the *E. miniata/tetrodonta* woodlands (Figure 2). For each fire regime, there were three replicates (compartments E, K and P for the early regime; F, G and L for the late regime; Figure 1).

Most fires were lit between 1130 and 1500 hrs. This period corresponds to the time of peak daily wind speed (Gill et al. 1996), highest temperature and lowest humidity. Time of ignition was kept as constant as possible so that the diurnal changes in critical fire conditions -namely temperature, relative humidity, wind and fuel moisture - were not confounded with seasonal changes in the same fire weather variables. Temperature, relative humidity, wind speed and direction were monitored at the time of each fire, either near the site of measurements, or at Naramu camp, 2-15 km from the site of ignition. Fires were lit from vehicle-based ground crews, and controlled by a series of double fuel-breaks between compartments (wherein the vegetation was burned to remove fuel), combined with back burning along the down-wind sides of the compartments. In this way, adjacent compartments with different fire regimes (especially the unburnt ones) were protected from potential escapes of our prescribed

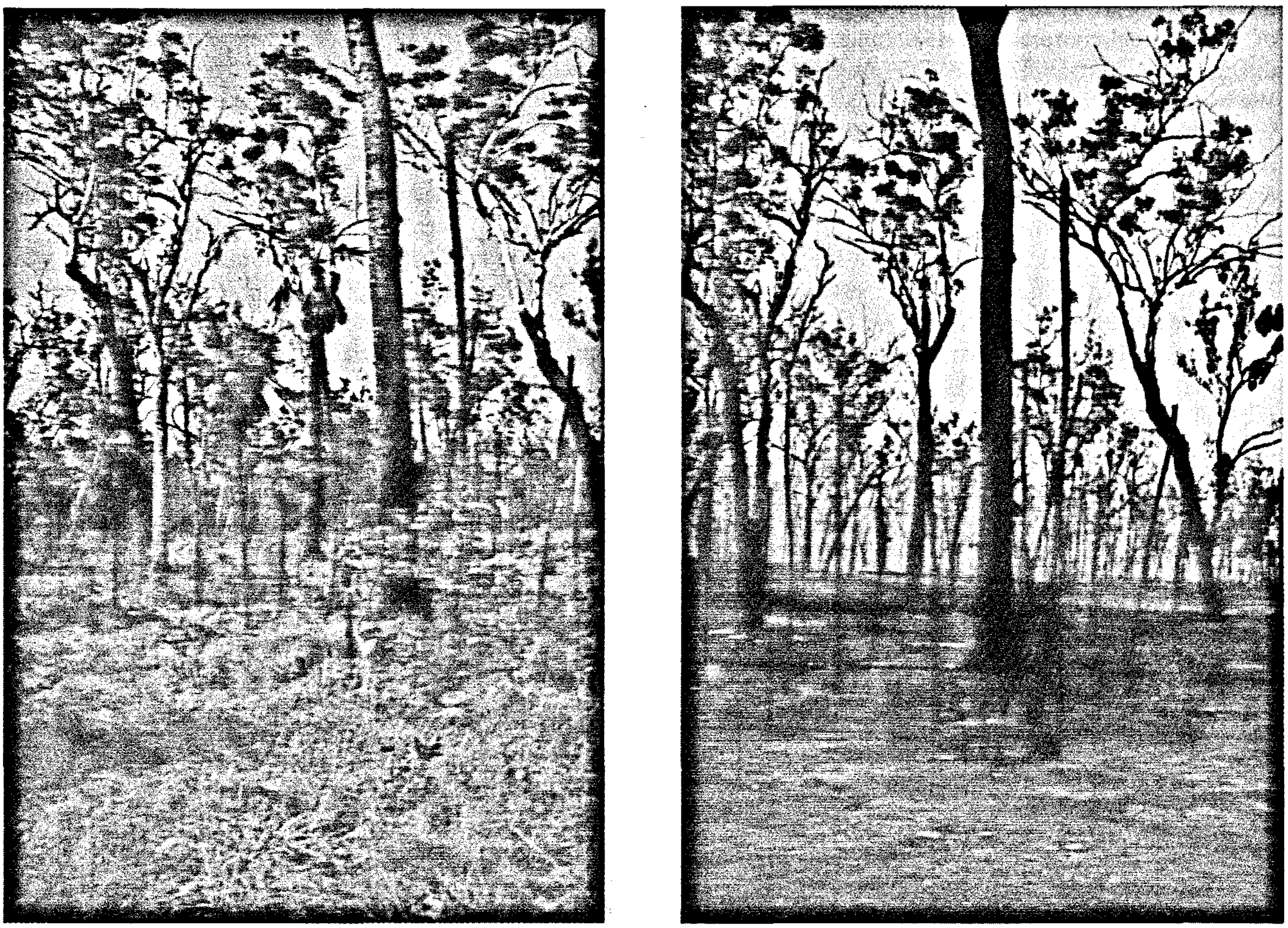

Figure 2. Typical *E. miniata / E. tetrodonta* woodland, before (a) and after (b) a 3000 kWm^{-1} early dry season fire.

fires. Once the compartments were fully secured, a single-line head fire, 2-5km long, was lit on the windward side of the block, and allowed to burn until it went out within the compartment. Because the compartments were large (20 km^2) the backburning fires did not interact with the forward burning fires at our measurement sites.

Fire Measurement

Byram fire-line intensity (Byram 1959) was determined for most of the experimental fires lit between 1990 and 1994. Measurements were made within a single, relatively uniform area of approximately one ha within each compartment, within 200 m of the windward (usually southern) side of the compartments, where safe access and egress could be made (Figure 1). Sites were also chosen for continuity of fuel, such that all fine fuels would be consume within the one ha measurement site. All fire intensity measurements were made on the main heading fire of each compartment, within 1-2 minutes of its ignition. Safety considerations dictated that measurements could not be made in the centre of such large compartments.

Fire line intensity, I, is a measure of the energy release along the fire front, (Byram 1959) and is defined as the product of the heat yield of the fuel (H), the weight of standing fuel consumed in the flaming zone (w), and the rate of forward spread of the fire line or perimeter (r). We used a value 20,000 kJ kg^{-1} for H, although there is variation in the literature in the value of H. In northern Australian savannas, similar to those in which the present experiment was conducted, Bowman and Wilson (1988) measured energy contents (= heat of combustion) of 16,000-22,000 kJ kg^{-1} for the dominant fuels. Luke and McArthur (1978) suggest an average of 20,000 kJ kg^{-1} for heat of combustion, but recommend 16,000 kJ kg^{-1} for heat yield. However, other literature suggests that values of H greater than 16,000 kJ kg^{-1} are either used or recommended in the calculation of intensity - e.g. Alexander (1982) 18,700 kJ kg^{-1}; Johnson (1982/3) 20,700 kJ kg^{-1}; van Wilgen et al. (1985) 20,000 kJ kg^{-1}; Stocks (1989) 17,000 - 18,000 kJ kg^{-1}; Cheney et al. (1992) 17,000 kJ kg^{-1}; Noble (1991) 20,000 kJ kg^{-1}; Engle and Stritzke (1995) 17,300 kJ kg^{-1}. Given the range and lack of consistency between studies in the value of H, and, in the view of the authors, the misleading precision implied by values rounded to the nearest 100 kJ kg^{-1}, 20,000 kJ kg^{-1} is within the range of reported vales, and is easy and convenient to apply.

The weight of fine fuels (<6 mm minimum diameter) was determined directly by five or six 0.25 m^2 quadrats within each sample site. The fresh weight of the fuel samples was determined within one hour of cutting; samples were returned to the laboratory, where oven dry weight (ODW) and % moisture content (as % ODW) were subsequently determined. (Fuel moisture was not determined from the cut fuel samples in 1990). Fuels were sorted into grass, leaf and twig components, and each component expressed as a percentage of ODW.

Rate of spread was measured using a series of electronic temperature residence time meters (TRTMs) over a representative 1 ha area, as described briefly below, and in more detail by Moore et al. (1995). The TRTMs consist of a stop watch connected to a thermocouple. The watch section of the device was buried, with only the end of the thermocouple protruding above ground. Prior to burial, all TRTMs were activated synchronously, and were then buried as above in a series of near-equilateral triangles, with sides 10-100 m in length, following Simard et al. (1984). At any given point the passing of the fire front (i.e. the rapid rise in temperature above a critical point, usually ca. 200° C) is sensed by the thermocouple, and an electronic signal is sent to the stop watch, which stops recording, and displays the "stop time". The difference in "stop time" between one point and the other two points in a triangle can then be determined, and the average rate of spread between these three points determined algebraically, following formulae given in Simard et al. (1984). Temperature residence time - the time during which flames, above a critical temperature, remain at a point - is also determined by the meters (Moore et al. 1995), but will not be considered here.

There were some missing values in the data set. Intensity measurements were not recorded for two of the early fires (in compartments E and P) in June 1990. Data from the June fires of that year from two nearby compartments of the progressive fire treatment (H and B) were used as substitutes. The fires in these latter compartments were lit in similar habitats (*E. miniata / E. tetrodonta* forest and woodland) and under similar conditions as were fires of the early regime. During the burning of Compartment E in June 1990, the fire jumped several fuel breaks, and accidentally burned Compartment F (a late compartment). Thus, for the late regime in 1990, there were only two replicate fires. In all fires, the fine fuel was totally consumed at the sites of measurement of rate of spread, thus consumption factors did not need to be applied in the calculation of intensity.

Post-fire indices of fire intensity: leaf-scorch height, leaf-char height and the percentage area of ground-stratum burnt

The immediate impacts of fire can be used as indicators of fire behaviour. Thus, leaf-scorch height may be used as a post-fire index of fire characteristics such as flame height (Luke and McArthur 1978; Cheney et al. 1992; Burrows 1995), and intensity (van Wagner 1973; Rothermel and Deeming 1980; Burrows 1995; Engle and Stritzke 1995). Leaf-char height (the height above ground of blackened leaves) may be used as a surrogate for flame height (Gill and Moore 1994). Following each fire, average char and scorch heights were measured on saplings and adult trees respectively, within the one ha plot from which fire intensity measurements were calculated. For char height, the height above ground of charred (blackened) leaves was measured, using range poles, on saplings, 3-6m tall, within 24 hours of the fire. Charring was assessed only on leaves which were at least 0.5m, horizontally, away from the stem; leaves which were blackened, but close to the stem, were not assessed, as such charring may have been due to stem-flaming, and not the passage of the main, flaming front. Ten to twenty saplings per fire were thus assessed, and an average post-fire char height was thus determined for each fire. Scorch heights were measured using a clinometer (to ± 1 m) within each fire-measurement plot, 1-2 days after each fire. Scorch height was taken to be the maximum height of scorch within a given tree canopy. Mean scorch height per plot was calculated from the individual scorch heights of 10-20 trees.

The percentage area of ground stratum which is consumed by fire may also be used as a potential post-fire index of intensity. It is also both a determinant of, and an index of, post-fire habitat heterogeneity (Braithwaite 1995). To determine the area of ground stratum which was burnt by each fire in the wider compartment, the relative area of burnt and unburnt patches of understorey was assessed along permanent transects located towards the centre of each of the fire-compartments (Figure 1). As 100% of the fuel was consumed at each of the fire-measurement sites, irrespective of fire intensity, the other locations were necessary for this component of the study. Moreover, we wished to gauge how patchy the various fires were in the wider compartment, and relate variation in such patchiness to the intensity of the fires as measured at our reference sites. We therefore assessed such patchiness along a series of 700 m reference transects which were 1-3 km away from the site at which fire intensity was measured (Figure 1). These transects were representative of the compartments as a whole, and were the sites where fire impact was determined on other biological variables, such as ground stratum composition, tree phenology and tree demography (e.g. Williams 1995; Wilson et al. 1995). Using a line intercept method (Mueller-Dombois and Ellenberg 1974), we determined the fraction of the ground stratum, or percentage area, which was burnt. Measurements were taken along the transects one day after the fire. Percentage area burnt was defined as:

(intercepted length of burnt ground stratum
vegetation)/(total transect length) x 100%

Statistical analyses

The variation in fuel load, fuel moisture, fuel composition (% grass, % leaf litter etc.) and fire intensity with respect to fire regime (early or late) and year (1990-1994) was examined using a split-plot design. Block (compartment) was the random factor, and year was the split factor. For these analyses, there was one missing value (Compartment F in 1990). Percentage data were arcsin-transformed prior to analysis. The relationships between fire intensity, leaf-char height, leaf-scorch height, and percentage area burnt were examined using non-linear regression. Power functions, of the type $y = A + B.R^x$ were fitted to the data, where A, B and R are estimable parameters. The functions were then converted to the equivalent exponential expression: $y = a + be^{cx}$. Fire intensity was the independent (x) variable, and char/scorch was the response (y) variable. For scorch height and char height, several additional fires lit in June 1990 which were not included in the split-plot ANOVAs, were included in the regression analyses. All analyses were performed on GENSTAT 5.1.

Results

Fuels

There was substantial variation in the fuels during the course of the experiment, with respect to loads, composition and moisture contents, both between fire regimes and between years (Tables 1 and 2; Figure 3). Average fuel loads varied from about 2 t ha^{-1} to about 10 t ha^{-1} (Figure 3.) Fuel loads were significantly higher in the initial year of burning (1990) than in later years (1991-94), wherein there was no significant difference between years. Fuel loads were consistently lower on the compartments of the early regime (Figure 3), with the average fuel load on these compartments (3.2 t ha^{-1}) significantly lower than that of the late regime (5.0 t ha^{-1}, Table 2). Fuels were primarily grass (Table 1), although the proportion of leaf litter in

Table 1. Fuel characteristics by fire treatment by year. Values are average percentage (± SE; by oven dry weight) for fuel moisture, grass content, tree leaf content and twig content, for each fire regime (early dry season; late dry season) for each year (1990-995). For each mean, n=3, except for the late compartments, 1990, when n=2. Average figures (pooling years) for the early dry- and late dry season fire treatments are given in the last two rows.

Fire Regime	Year	% Moisture	% Grass	% Leaf	% Twig
Early	1990	NA	75 ± 5.0	15 ± 4.0	10 ± 3.0
Early	1991	21 ± 2.3	69 ± 6.9	14 ± 4.4	17 ± 3.1
Early	1992	20 ± 1.1	72 ± 7.9	22 ± 8.0	6 ± 1.2
Early	1993	17 ± 1.9	71 ± 9.1	21 ± 8.0	7 ± 1.6
Early	1994	19 ± 1.5	71 ± 9.2	22 ± 8.2	7 ± 1.6
Late	1990	NA	30 ± 2.7	60 ± 2.4	10 ± 0.3
Late	1991	14 ± 0.7	31 ± 4.7	55 ± 5.5	14 ± 1.1
Late	1992	13 ± 0.4	51 ± 6.2	35 ± 4.6	14 ± 4.4
Late	1993	7 ± 2.7	43 ± 6.4	45 ± 5.6	13 ± 1.8
Late	1994	11 ± 0.9	51 ± 6.1	38 ± 6.1	11 ± 2.0
Average Early	All	19.3 ± 0.8	71.5 ± 3.5	18.8 ± 3.2	9.7 ± 1.4
Average Late	All	11.1 ± 0.9	41.1 ± 3.4	46.7 ± 3.2	12.2 ± 1.1

Table 2. Summary of P-values for effects of fire-season and year on fuel characteristics at Kapalga. Design is a split-plot ANOVA, with year as the split factor. DF = degrees of freedom. Dependent variables are: FUEL, total fuel load (t ha^{-1}), %GRASS, % grass in fuel; %LEAF, % leaf litter in fuel; %MOIST, % fuel moisture (DF = 3 for year and fire.year); INTENSITY, fire intensity. NS = non-significant ($P > 0.05$).

Source of Variation	DF	Fuel	% Grass	% Leaf	% Moist	Intensity
Compartment Stratum						
Fire Season	1	0.03	0.05	0.05	0.01	0.001
Residual	4					
Year stratum						
Year	4	0.001	0.001	0.002	0.02	0.02
Fire.Year	4	NS	0.001	0.001	NS	0.01

the fuel was significantly higher in September (47%) than June (19%; Table 1). Fuel moisture content was significantly lower in the late regime than in the early regime, with the fuels in 1993 significantly drier than those of other years (Tables 1 and 2).

Fire Intensity

The seasonal and inter-annual patterns of average fire intensity for the early and late regimes for the years 1990-1994 are given in Figure 4. The average weather conditions at the time of the fires for each regime for each year (1990-1994) and overall are given in Table 3. Average fire weather was more extreme at the time of the late fires than the early fires, with stronger winds, higher temperatures and lower humidities, although the seasonal differences were less pronounced in 1991 and 1992 than in other years. Fire intensities ranged from 500 kW m^{-1} to 18,000 kW m^{-1}. The peak fire intensity was recorded on one of the late-regime compartments (Compartment G) in September 1990. The fires of 1990 were more intense than all other years, although there was no significant difference between years over the period 1991-1994. The mean intensity of early fires over the whole study period (2100 kW m-1) was significantly lower, by a factor of nearly four, than that of the late fires (7700 kW m^{-1}; Table 4). There was, however, annual variation in this pattern, as indicated by the significant year.fire interaction (Table 2). In 1991 there was no significant difference in the average intensity of the early and late fires. In all other years late fires were at least three times more intense than the early fires.

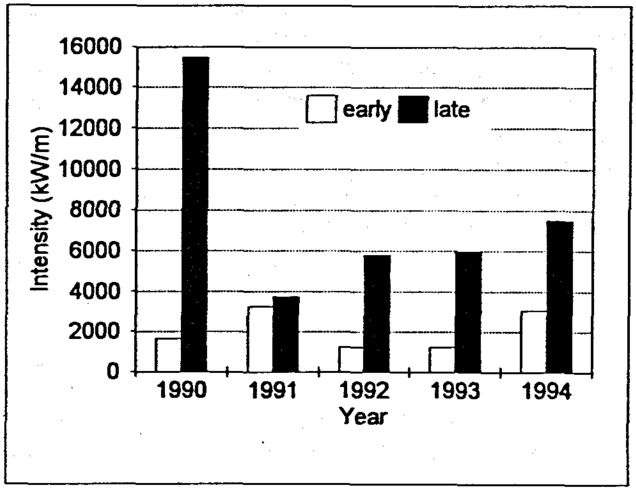

Figure 4. Average fire intensity (kW m^{-1}) for the period 1990-94 on the early fire treatment, or late fire treatment at Kapalga Research Station, Kakadu National Park. For each mean, N=3, except for the late compartments, 1990, when N=2.

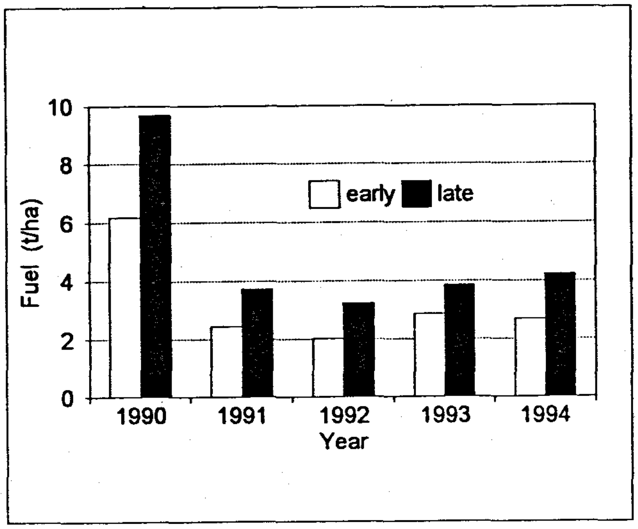

Figure 3. Average fuel loads (t ha^{-1}) for the period 1990-94 on the early fire treatment, or late fire treatment at Kapalga Research Station, Kakadu National Park. For each mean, n=3, except for the late compartments, 1990, when n=2.

Rates of spread varied over an order of magnitude, from < 0.1 ms^{-1} to 1.8 ms^{-1}, but were generally between 0.4 and 0.8 ms^{-1} (Table 4). Annual variation was significant, with rates being higher in 1994 than all other years. Seasonal variation was also significant, with spread rates lower in the early fires than the late fires. Temperature residence times (data not presented) were generally of the order of 30-60 s. All fuel was consumed at each of the measurement sites. Crown fires did not occur during any of the Kapalga fires. However, "torching" (the ignition of foliage of individual trees) was observed in the tree-legume *Erythrophleum chlorostachys* and the palm/palm-like genera *Livistona* and *Pandanus* during several of the higher-intensity fires.

Table 3. Summary weather characteristics for the early and late fire treatments, as measured at the time of the fires, at Naramu Camp, Kapalga, 2-15 km from each experimental fire site. All values refer to the conditions at the time of the burns. Columns: wind direction; wind speed (m s^{-1}); air temperature (°C); relative humidity (%), for the early (June) and late (September) fire regimes, 1990-1994. Averages are for the period of the experiment (1990-94) and the long term data for 0900 hrs and 1500 hrs for the town of Jabiru, 50 km from the study site.

Year	Wind direction		Wind Speed		Temperature		Humidity	
	Early	Late	Early	Late	Early	Late	Early	Late
1990	SE	SE	0.3	1.1	23.7	34.0	45.3	28.0
1991	SE	ENE	1.5	1.4	28.0	34.7	44.3	38.7
1992	SE	E	3.4	3.4	29.6	33.6	36.3	34.3
1993	ESE	SE	2.5	2.4	28.7	33.1	45.7	34.0
1994	SE	SE	2.3	3.3	32.7	35.3	31.3	13.7
Averages								
1990-1994	SE	ESE	2.0	2.3	28.5	34.1	40.6	30.6
0900 hrs	SE	ESE	1.5	1.8	24.1	27.0	57.0	59.0
1500 hrs	SE	ESE	2.0	3.0	30.3	35.1	34.0	24.0

Fire Intensity, leaf-char height, leaf scorch height and percentage area burnt

The relationships between fire intensity and both leaf char height, leaf scorch height and percentage ground stratum consumption were variously curvi-linear (Figures 5-7). The relationship between intensity, leaf char height, leaf scorch height and percentage area burnt were described by the following equations:

$$\text{Leaf Char} = 3.7 - 3.63\,e^{-0.000182\,\text{INTENSITY}};\ r^2 = 0.89 \text{ (Figure 5)}$$

$$\text{Leaf Scorch} = 21.2 - 17.6\,e^{-0.000287\,\text{INTENSITY}};\ r^2 = 0.85 \text{ (Figure 6)}$$

$$\text{Area Burnt} = 98.9 - 59.5\,e^{-0.000837\,\text{INTENSITY}};\ r^2 = 0.61 \text{ (Figure 7)}$$

Char height following the two most intense fires (13,000 and 18,000 kW m^{-1}) was relatively low; the char height for latter value (2.5 m) was clearly an outlier, and was omitted from the regression analysis. Leaf scorch occurred to the base of the canopies of the taller trees (ca. 10-12 m) tops in fires of ca. 3000 kW m^{-1}, and to the tops of the tallest trees (20-22 m) at intensities of about 10,000 kW m^{-1} or more. We included the scorch height associated with the most intense fire in the final regression model, even though this value (22 m, i.e. maximum tree height) is an under-estimate of potential scorch height for an 18,000 kWm^{-1} fire, because it is the actual scorch height for a high intensity fire as measured in the field. We fitted a model excluding this data point, but the estimates of all three of the parameters and the r^2 differed by only 1% from the above values in each case. Ground stratum consumption was greater than 90% above intensities of ca. 2000 kW m^{-1}. The observed values of char height and scorch height are substantially lower than those predicted by Rothermel and Deeming (1980; flame/char height) and van Wagner (1973; scorch height), as indicated on Figures 5 and 6 respectively.

Discussion

Seasonal and annual patterns of fuels and fires

Just as the climate of northern Australia is highly seasonal (McDonald and McAlpine 1991; Gill et al. 1996), so too is the pattern of fuels and fires. Fuel loads, fuel composition, fuel moisture, local fire weather and fire intensity all showed distinct and consistent differences between the early dry season and the late dry season. There was also substantial inter-annual variation in these fire parameters.

Table 4. Mean values (by year and by season of burn) for fuel load, rate of forward spread and fire intensity. Columns are years (1990-1994; pooling seasons) or seasons (Early or Late; pooling years). Rows are fitted (mean) values fuel and fire parameters, derived from Generalised Linear Models for the various fuel/fire parameters: Fuel load (t ha^{-1}), rate of spread (R/Spread) (ms^{-1}) and Fire Intensity (kW m^{-1}). Standard errors (SE) of differences between treatment means indicated (YearSE, between years; SeasonSE, between season of burn); means differing by 2SE units are significantly different ($P < 0.05$).

Year/Season	1990	1991	1992	1993	1994	Year SE	Early	Late	Season SE
Fuel (t ha^{-1})	8.04	3.08	2.64	3.36	3.46	0.82	3.24	4.99	0.6
R/Spread (ms^{-1})	0.51	0.52	0.61	0.51	0.73	0.07	0.37	0.78	0.1
Fire Intensity (kW m^{-1})	8500	3500	3500	3600	5300	1500	2100	7700	290

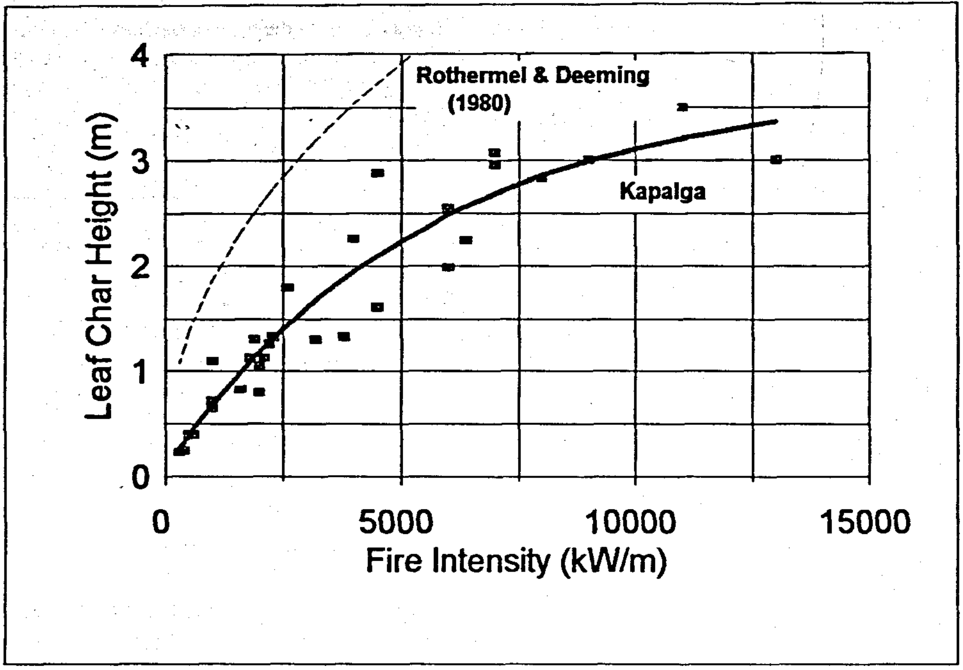

Figure 5. The relationship between leaf char height (m) and fire intensity (kW m $^{-1}$). The solid line is that given by the equation: Leaf char = 3.7 - 3.63 e $^{-0.000182\ \mathrm{Intensity}}$; $r^2 = 0.89$. The dotted curve represents the relationship between intensity and flame height, as predicted by Rothermel and Deeming (1980), from the equation Intensity = 258 (Flame height)$^{2.17}$

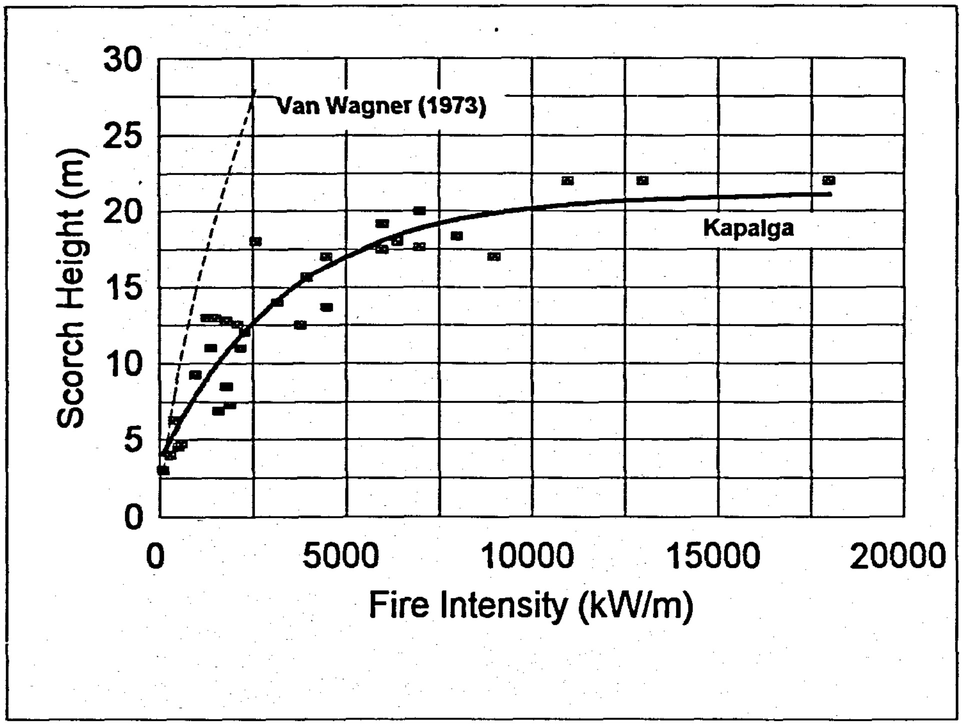

Figure 6. The relationship between leaf scorch height (m) and fire intensity (kW m $^{-1}$).The solid line is that given by the equation: Leaf scorch = 21.2 -17.6 e $^{-0.000287\ \mathrm{Intensity}}$; $r^2 = 0.85$. All points were included in the regression. The dotted curve represents the scorch heights predicted by van Wagner (1973), from the equation Scorch height = 0.148 (Intensity)$^{0.67}$

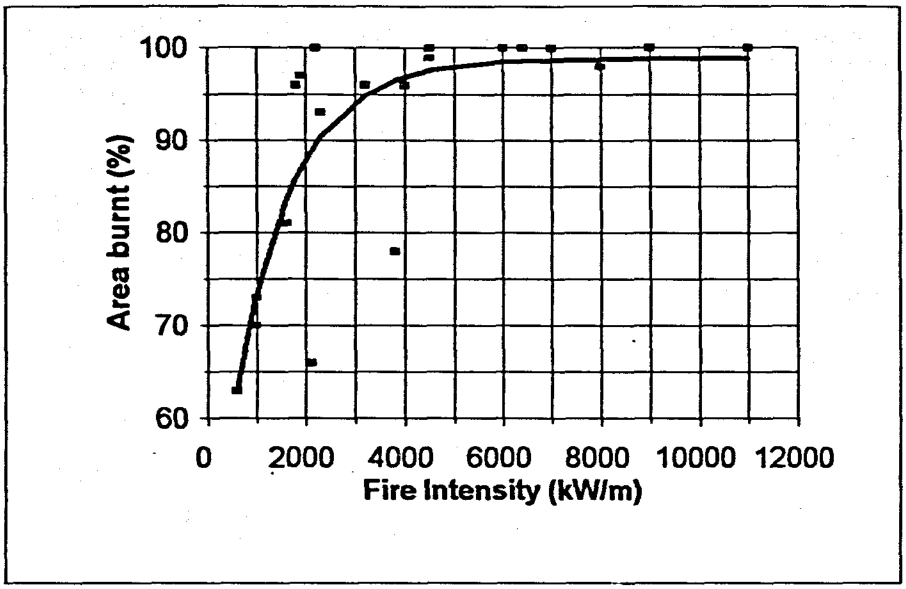

Figure 7. The relationship between percentage area of the ground stratum burnt and fire intensity (kW m^{-1}). The solid line is given by the equation Area burnt = $98.9 - 59.5\ e^{-0.000837\ \mathrm{Intensity}}$; $r^2 = 0.61$.

The inter-annual variation in fuel loads at Kapalga was primarily a consequence of local fire history. Fuel loads were highest in 1990 because most compartments had remained unburnt for two years prior to the initial fires. The extreme value of 13 t ha^{-1}, on one late fire compartment in September 1990, was the highest recorded within eucalypt-dominated savannas at Kapalga. This value was unusual, as fuel loads recorded on the unburnt, control compartments over the study period were commonly 6-8 t ha^{-1} (Cook et al. 1995; Cook and Williams 1995). However, fuel loads in excess of 10 t ha^{-1} have been reported for eucalypt savanna in parts of humid northern Australia which have remained unburnt for at least four years (e.g. 10-15 t ha^{-1}, Gill et al. 1990; 5-10 t ha^{-1}; Mott and Andrew 1985). At Kapalga, subsequent to 1990, however, on the annually burnt compartments, fuel loads were most commonly between 2 and 5 t ha^{-1}, clearly indicating that annual burning maintained relatively low fuel loads.

The total fuel loads measured at Kapalga (2-10 t ha^{-1}; usually 2-4 t ha^{-1}) were comparable to those reported by Cheney et al. (1993), for a grassland savanna in July/August at Annaburroo, 100 km west of Kapalga (2-6 t ha^{-1}). Bowman and Wilson (1988) measured 6.3 t ha^{-1} at a eucalypt savanna site at Gunn Point, near Darwin, in September.

The seasonal changes in fuel loads and composition (grass:leaf litter ratios) were a consequence of the leaf phenology of the trees within the tropical savanna. Whilst deciduous trees commence leaf fall early in the dry season, semi-deciduous and evergreen species have peaks of leaf fall later in the dry season (Wilson et al. 1995; Williams et al. 1997). Hence, by late in the dry season, fuels are more abundant, with a greater proportion of leaf litter, than early in the dry. The average grass:leaf litter ratio measured for the late dry season in this study (38:48=0.79) was similar to that reported by Bowman and Wilson (1988) for similar forest in September (35:43=0.81). Fuel moisture decreases during the dry as a consequence of senescence of annual grasses, decreases in soil moisture and decreases in relative humidity as the dry season progresses (Gill et al. 1990; Cheney et al. 1993; Gill et al. 1996).

In this study fire intensity varied significantly with season of ignition. Over the years 1990-1994, the average intensity of fires at our 1 ha measurement sites in the early regime (2100 kW m^{-1}) was about one quarter that of fires in the late regime (7700 kW m^{-1}). The average intensity, over the whole compartment, for the early regime is likely to have been lower than 2100 kW m^{-1}, given the incomplete combustion of fuels in the wider compartment, as measured along the 700 m reference transects. The compartment-scale value of fire intensity for the late regime is likely to be close to that measured at the 1 ha sites, as fuels were completely consumed over the whole compartment in all but one of the late fires. This demonstration of seasonal differences in fire characteristics is the first quantitative demonstration of this phenomenon, which, regionally, determines most fuel and fire management strategies in all land uses in the humid wet-dry tropics of northern Australia.

Factors contributing to this pattern of higher fire intensities during the late dry season were undoubtedly the higher fuel loads, and the drier fuels, during the late dry. In addition, the observed pattern is consistent with the observed patterns of temperature and relative humidity at the time of the fires. Midday temperatures were 3-5° C higher, and relative humidities 10-20% lower, at the time of the late fires than at the time of the early fires. This local variation in the seasonal patterns of these important fire-weather variables is consistent with the regional, long-term Forest- and Grassland Fire Danger Indices as determined by Gill et al. (1996) from weather records at nearby Jabiru. The fire danger indices increase from June to September, because of seasonal changes in a number of regional meteorological factors. Afternoon relative humidity decreases progressively throughout the dry season, thus increasing the potential rates of spread (Gill et al. 1990; Gill and Knight 1991; Cheney et al. 1993). Moreover, winds, especially afternoon and evening winds, are, on average, 1 m s^{-1} faster in September than June (Gill et al. 1996).

Fire intensity at Kapalga ranged from <500 to 18,000 kW m^{-1}. However, there have been few other studies in northern Australia or other tropical savannas with which to compare these data. The range of intensities at Kapalga is similar to that of fires in grassland at Annaburroo Station, which can be estimated based on data on fuel load and rate of spread given in Cheney et al. 1993 - Table 3, p. 38). In that study, assuming a value of H of 20,000 kJ kg^{-1}, the experimental fires lit in July/August 1986 ranged from ca. 1100 kW m^{-1} to 23,000 kW m^{-1}.

Whilst the early dry season fires were, on average, about one quarter the intensity of late dry season fires, several fires of relatively high intensity occurred in June 1990, on Compartments E, P and F. These particular fires were estimated to be 5000-10000 kW m^{-1}, on the basis of leaf char- and scorch heights, presumed fuel loads and fortuitous observations of rates of spread. These estimates have not been included in the data analysis, because of their lack of precision, but that such fires occurred indicates quite clearly that relatively intense fires may occur early in the dry season, especially where fuels have accumulated for several years. Gill et al. (1996) indicate that extreme fire danger indices in June can be as high as those in September. Thus, as argued by Bowman (1988) time of year alone may not necessarily be a precise predictor of fire intensity. This has substantial management implications, as in some years relatively intense fires can occur in the early dry season; in others, late dry season fires may be of relatively low intensity, especially if travelling at night under conditions of low wind. The precise conditions determining these fires, and their degree of predictability, require further research.

Post-fire indices of fire intensity

Leaf-char height and leaf-scorch height were both closely related to fire intensity, especially over the range of 100-10,000 kW m^{-1}. Both measures therefore have high potential as post-fire indicators of fire intensity, all else being equal, for fires between 100 and 10,000 kW m^{-1} - a range within which 90% of the Kapalga fires occurred. The relatively low, outlying value of char height (2.5 m) for the most intense fire (18,000 kW m^{-1}) may have been due to stronger winds than usual, increasing flame tilt, and thereby decreasing flame height. Flame heights in excess of 4 m were observed directly for the 13,000 and 18,000 kW m^{-1} fires, but high flame angles were also observed. Hence, whilst leaf char height may be expected to be correlated with flame height, this may not always be the case, given variation in local winds, and variation in the size and moisture content of leaves. Percentage area burnt was a less efficient indicator of intensity compared with leaf char/scorch, as evidenced by the lower r^2 value, and the tendency towards maximum values (100%) at relatively low intensities (1500- 2000 kW m^{-1}). However, the relationships indicate fires in excess of ca. 2000 kW m^{-1} will consume virtually all of the ground stratum. These relationships should provide some useful ground-based "rules of thumb" for land managers wishing to monitor the intensity of prescribed burns. For example, fires which produce char heights or flame heights less than 1 m are unlikely to scorch the tallest trees higher than the base of the canopy (ca. 8 m), or, are likely to be patchy with respect to ground stratum consumption. Fires with char/flame heights of 2m are likely to scorch most trees, although not completely, but will consume all the ground stratum. Fires with char/flame heights of 3-4 m will consume all of the ground stratum, and scorch almost all of the tallest trees to the top of the canopy.

Comparative fire characteristics in northern and southern Australia

The environment of northern Australia is very fire-prone. This is due to the combination of a regular wet season, which makes annual production of fine fuels possible, a long dry season which produces fuels flammable for all but a few months of the year, and the existence of potential ignition sources from either human or non-human sources over the whole of period when fuels are combustible. Thus, fire is more frequent in the eucalypt-dominated savanna open- forests and woodlands of northern Australia (every 1-2 years; Stocker and Mott 1981; Braithwaite and Estbergs 1985) than in the eucalypt open-forests and woodlands of southern Australia (probably every 5-20 years; Cheney 1976; Walker 1981).

The overall mean intensity of the 29 fires studied at Kapalga (4900 kW m^{-1}, pooling season and years) and, indeed the peak fire intensity (18000 kW m^{-1}) was low, relative to potential peak intensities of ca. 100,000 kW m^{-1} which may occur during wildfire in the forests of southeastern Australia (Gill and Moore 1990; Gill and Knight 1991). There are several likely reasons for this. First, fuel loads in northern Australian eucalypt savannas do not appear to build up to levels in excess of 20 t ha^{-1}, as do those of the eucalypt forests in temperate, southeastern Australian (e.g.Walker 1981; Attiwill and Leeper 1987; Ashton and Attiwill 1994). Maxima appear to be in the order of 10 t ha^{-1}. Second, relative humidity in northern Australian savannas, even during the peak fire period of September, remains relatively high (>20% during the day; >60% overnight), and almost never reach the low levels as may occur on "blow-up" days in SE Australia, when RH may be as lower than 10 %, and winds may gust at >100 km hr^{-1} (Anon 1984).

There are also apparent qualitative differences between fires in eucalypt forest/woodlands in northern and southern Australia - the relationships between intensity and char/scorch heights appear to be different in the two regions, and crown fires do not appear to occur in northern Australia. Cheney (1990) cautions against comparing fire characteristics and fire impacts between regions where fuel characteristics are different, such as between northern Australia, and southern Australia. However, some consideration of the differences in fire characteristics between the two regions is warranted.

The degree of leaf char and leaf scorch generated by fires of a given intensity in the tropical savannas at Kapalga appears to be substantially lower than that predicted by the response models of Rothermel and Deeming (1980) and van Wagner (1973) for temperate forests in North America, and those measured or predicted for the eucalypt forests of southern Australia. In the temperate Australian forests, char/flame heights of 1-2 m are associated with fires of ca. 200-800 kW m^{-1}. For example, Luke and McArthur (1978 Figure 8.1) suggest 1-2m flames for fires over the range of 200-500 kW m^{-1}. Cheney (1981) and Cheney et al. (1992) indicate similar relationships (1.5 m flame heights for fires of ca. 500 kW m^{-1}; 2 m flames for fires of 750 kW m^{-1}). Flames of ca. 1m for fires in a similar range of intensities (200 - 500 kW m^{-1}) were measured by Nelson (1980) in temperate forests in southeastern USA. In comparison, at Kapalga, fires of 2000-5000 kW m^{-1} were needed to generate flame heights in the 1-2 m range (as indicated by the char heights). Scorch heights showed a similar differential pattern - the Kapalga fires produced lower scorch for given fire intensities than do southern Australian eucalypt forest fires (regardless of whether the actual scorch height in the fire with the highest intensity - 18,000 kWm^{-1} - was lower than the potential scorch height). For example, Cheney (1981) indicated complete scorch of most open eucalypt forests in fires of moderate intensity (500-3000 kW m^{-1}). Burrows (1995) indicated 20-25 m scorch for 1500 kW m^{-1} fires in eucalypt forests in southwestern Australia; similar values were predicted by Cheney et al. (1992) for fires of 1500 kW m^{-1} in eucalypt forests in southeastern Australia. Substantially higher scorch heights than those obtained at Kapalga were predicted for a given intensity by the model of van Wagner (1973). These differences are most likely due to the fuel type and architecture. The fuels of the savannas are mainly grassy, and, as discussed by Cheney (1990 Table 1), flame heights in grasslands fires may be five times lower than those of fires of similar intensity in litter beds in open eucalypt forest. Moreover, the taller and more open nature of grassy fuel may mean that, compared with litter fuels, more colder air is drawn into the combustion zone, thereby reducing the temperature of the convective column. This, coupled with rapid spread, may result in less heat damage to the leaves of trees. The relationship between char height and scorch height in the Kapalga fires (scorch was ca. 8x char height) was also different to that assumed by Davis et al. (1985; scorch = 4x flame height) for similar savanna woodlands in Kakadu National Park.

No crown fires were observed at Kapalga, despite the occurrence of several fires in the order of 10,000 kW m^{-1} over the study period. Fires of such intensity would almost certainly crown in temperate eucalypt forests of SE Australia (Cheney 1990). Reasons for this apparent lack of crowning may include the generally light fuel loads (generally less than 5 t ha^{-1}), the low canopy density of the dominant trees (Leaf Area Index of ca. 1-1.5; Gill et al. 1996; Williams et al. unpublished data), lower oil contents and calorific content of the northern eucalypts compared with southern eucalypts (Webb 1968; Dickinson and Kirkpatrick 1985; Bowman and Wilson 1988), the general absence of a dense mid-stratum of shrubs (Wilson et al. 1995) resulting in a lack of "ladder fuels" (Cheney 1990), and the generally flat terrain (Williams 1991). The rates of spread of the Kapalga fires varied between ca. 0.3 and 5 km hr^{-1}. The upper range, for fires of 7,000-10,000 kW m^{-1}, appears to be far higher than those reported for southern Australian eucalypt forest fires of similar intensity, where spread rates may be 1 km hr^{-1} (e.g. Cheney 1990). This is likely to be due to the higher proportion of fine grassy fuels, in the northern Australian savannas compared with the southern eucalypt forests. Thus, on the basis of the fire characteristics, and the immediate post-fire impacts on the trees, the eucalypt savanna fires of northern Australian are more akin to grass fires than to the eucalypt forest- litter fires of southern Australia.

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