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Tree mortality in relation to fire intensity in a tropical savanna of the Kakadu region, Northern Territory, Australia

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ABSTRACT

Frequent fire is a feature of the tropical savannas of the Kakadu region of the Northern Territory. In a landscape-scale experiment at Kapalga Research Station in Kakadu, fires have been lit experimentally in catchments 15-20 km^2 in area, both early in the dry season (June) and late in the dry season (September) between 1990 and 1993. In *Eucalyptus miniata* - *E. tetrodonta* forest the mean intensity of early dry season fires (4200 kW m^{-1}) was less than that of the late dry season fires (7800 kW m^{-1}), although there was considerable spatial and yearly variation. In 1991-92, two years after the commencement of the fires, tree mortality was greatest in compartments burnt late in the dry season (15.4 per cent), intermediate in compartments burnt early in the dry season (7.6 per cent) and least in the unburnt compartments (3.5 per cent). Season of burn, however, was not a statistically significant predictor of tree mortality; maximum fire intensity (fitted as a co-variate) explained the majority of the variation in tree mortality. Measurement of fire intensity, which can be used as a co-variate in experimental fire-effects studies, is thus a vital component of fire experiments where season of burn is a factor within the design.

INTRODUCTION

Frequent fire is a feature of the tropical savanna forests and woodlands of the 'Top End' of the Northern Territory. Tens of thousands of square kilometres burn each year during the dry season (Press 1988; Graetz *et al.* 1992), and 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). Press (1988) estimated that in the Alligator and Adelaide Rivers region, over 50 per cent of all lowland forest systems in all land use categories carried fire during the 1980-1985 period. The fire-prone nature of the region is a consequence of the strongly seasonal climate. Summer rainfall is relatively high (800-1800 mm) and supports consistent annual growth of the understorey. The dry season is long (6-9 months), hence fuels cure each year. Fire has been used for millennia by local aboriginal people, with a 9.5 month fire season, and a peak of activity in July (Braithwaite 1991). Fire is used currently as a management tool by most land users within the region, and most fires are deliberately lit. Reasons for burning include fuel/hazard reduction, promotion of more palatable herbs and grasses, and emulation of traditional aboriginal burning practices.

Within the World Heritage Kakadu National Park, prescribed fire is used within the savannas and grasslands by the managing agency (Australian National Conservation Agency; Anon. 1989). Burning commences in the early dry season (May), and is mostly complete by August. Braithwaite and Estbergs (1985) estimate that the savannas of Kakadu are burnt two years in every three. Fire, and its effects, have been little-studied in Kakadu. CSIRO is presently conducting a landscape-scale fire experiment in savannas at the Kapalga Research Station within Kakadu National Park. The aim of this experiment is to assess the effects of various fire regimes on the soils, plants, invertebrates and vertebrates of the savannas (see papers by G. Cook, R. Braithwaite, this volume). This paper presents data on fire behaviour with respect to season of burn for the years 1990-1992, and effects of fire on tree mortality.

METHODS

Study Site

Kapalga Research Station is 180 km east of Darwin and occupies some 700 km^2. Open eucalypt savannas predominate on the well-drained lateritic soils of the drainage divides. Floodplain areas are occupied by treeless grasslands, and there are several pockets of monsoon vine forest. For the fire experiment, the region has been subdivided into a number of management compartments, which represent the catchments of minor streams which drain into the surrounding major river systems - the West Alligator and the South Alligator Rivers. Each compartment is 15-20 km^2 in area. Within each compartment a permanent, reference transect, 700 m long, has been established along a topographic-soil-moisture gradient, from the more poorly-drained shallow sands of the creek margins, to the better drained loamy soils of the drainage divides; relief along the transects is 10-30 m. The vegetation of the creek margins is woodland dominated by *Eucalyptus alba* and *E. papuana*; the understorey is mostly perennial grasses. The vegetation of the better-drained soils is open forest of *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.*

Fire Treatments

Each compartment is subject to one of four fire regimes:

(1) 'Early dry season'; burnt once during the early part of the dry season (June).
(2) 'Progressive'; burnt 3 times (June, July and September) during the dry season as the fuels cure; the spatial pattern of burning is concentric, from the outside of the compartment to the inside.
(3) 'Late dry season'; burnt once during the late dry season (September).
(4) 'Natural'; unburnt control; fire is excluded from these compartments, although one or two small scale (< 1 ha) fires have been detected over the study period.

For each of the early, progressive and late fire regimes, there are three replicate compartments; the natural regime has four replicates. Fires are lit from vehicle-based ground crews, and controlled by a series of double-fuel breaks between compartments. The burning regimes commenced in June 1990, and have been applied annually since then. The data presented in this paper are from each of the three early and three late compartments and three of the four natural compartments.

Fire Measurement

Byram fire-line intensity was determined for most of the experimental early and late dry season fires lit between 1990 and 1993. Intensity, I, is a measure of the energy release along the fire front, and is defined as the product of the heat content of the fuel, fuel standing crop, and the rate of forward spread of the fire line or perimeter; the units are kW m^{-1} (Byram 1959). The mineral-free heat of combustion of the fuel was assumed to be 20 000 kJ kg^{-1}. Rate of forward spread was determined using a series of electronic fire timers over a representative 0.5 ha area, as described by Moore and Gill (this volume). Fuel weight (kg m^{-2}) was determined directly by 5 x 0.25 m^2 quadrats. For those compartments where intensity was not measured directly, intensity measurements were based on rates of spread observed by the fire crews, coupled with empirically derived relationships between fire intensity and canopy scorch height (A.M. Gill, P.M. Moore and R.J. Williams; unpublished data). Based on the experience of the fire crews and those involved in direct measurement, these estimates are considered to be accurate to within 1000 kW m^{-1}, or about 10 per cent.

Tree Mortality

The impact of the fires of 1990 on tree mortality was assessed by determining the abundance of standing dead trees along the permanent transects in each of three of the early, late and natural fire compartments. Measurements were restricted to one widespread vegetation type: open *E. miniata-E. tetrodonta* forest on well drained lateritic soils. The survey was carried out at the end of the wet season (April-May) 1992, two full growing seasons after the initial fires. The total number of trees taller than 3 m in a 200 x 20 m section of each permanent transect in this forest type was counted for each of the three replicate compartments of the natural, early and late fire regimes. For each tree, the following attributes were determined: species, x, y co-ordinates, height, diameter at breast height, and life state (based on presence/absence of epicormic or basal resprouts; trunks without either were scored as dead). Approximately 2000 trees in total were sampled.

Data Analyses

Fire intensity data were analysed by repeated-measures ANOVA, following log transformation. Tree mortality was analysed by GLMs, using a binomial error structure and logit link function; the design strata are displayed in Table 1. Fitted terms included fire intensity (fitted as an explanatory variable), season of fire (early, late, natural) and size class of individual (>3-<6 m, >6-<9 m, >9-<12 m, >12-<15 m, >15 m). The effects of both fire intensity and season of fire were tested against the fire x replicate interaction; the effect of size class

TABLE 1

The design strata of the terms and interactions of the model fitted to the tree mortality data.

TERM	DF
Intensity	1
Season of burn	2
Fire.Rep (=Compartment)	5
Height class	4
Intensity x height class	4
Season x height class	8
Residual	20
Total	44

was tested against the overall residual.

The analyses were conditioned by several limitations of the design. First, the assessments of forest condition (canopy cover and standing dead) were undertaken at the end of the second growing season (1991-1992), that is after two years worth of fires - 1990 and 1991. For the analyses of co-variance, the maximum intensity of the fires applied to a given compartment during either the 1990 or 1991 dry seasons was fitted as the co-variate (explanatory variable). The primary reason for this was that for all but two of the compartments the measured intensities between years varied by between 5 and 15 times, with the fires of 1990 being overwhelmingly more intense. For the two compartments wherein this was not the case, fire intensity was similar between years.

Secondly, one compartment in the late dry fire regime (Compartment F) was accidentally burnt in 1990 at the time of the early dry season fires. It was burnt the following year at the experimentally correct time (September), with an intensity very similar to that of the previous year. To allow for this design problem, two sets of analyses of mortality were undertaken. The first set was based on a non-orthogonal design with respect to season of burn, with three replicates for the natural fire treatment, four replicates for the early dry season fire treatment, and two replicates for the late dry season fire treatment. The second set was based on an orthogonal design, with three replicate compartments per fire regime, as if the accidental burning of Compartment F in June 1990 had not occurred.

RESULTS

Fire Intensity

The average fire intensity for the early and late dry season fires for the years 1990-1992 are given in Table 2. The mean, overall intensity of early dry season fires (4200 $\pm$ 1000 kW m^{-1}) was approximately half that of the late dry season fires (7800 $\pm$ 1750 kW m^{-1}), although there was considerable spatial and yearly variation. The fires of 1990 were the most intense. The peak fire intensity was 18 000 kW m^{-1}, recorded on one of the late-fire compartments (Compartment G) in September 1990. Fires between 7000 and 10 000 kW m^{-1} occurred on the early-fire compartments in June 1990. In 1991, fire intensity was substantially less than that of 1990, in both the early and late fires; there was little difference in the average intensity of the early and late fires during that year. In 1992, the intensity of the early fires was about one-third that of the late fires. Despite the occurrence of several fires of relatively high intensity (>10 000 kW m^{-1}) over this three-year period, crown fires did not occur. Crown scorch, however, was complete in all fires of intensity greater than *ca* 7000 kW m^{-1}.

TABLE 2

The average fire intensity (kW m-1; $\pm$ SE) for the early and late dry season fires for the years 1990-1992, and the average (AVG) pooling years.

	1990	1991	1992	AVG
EARLY	8300 $\pm$ 700	3200 $\pm$ 1300	1900 $\pm$ 500	4200 $\pm$ 1000
LATE	13300 $\pm$ 1900	3700 $\pm$ 2100	6300 $\pm$ 1000	7800 $\pm$ 1750

Tree Mortality

Tree mortality, as expressed by the average percentage of standing dead trees taller than 3 m, in relation to season of fire is given in Table 3. For these data, Compartment F (the 'late' compartment accidentally burnt 'early' in 1990) is included within the late dry season regime; averages determined by including the data from Compartment F within the early dry season fire regime were within 3 per cent of these figures. Mortality was greatest in the late-burnt compartments (15.4 per cent); the comparative figures for the early-burnt and unburnt compartments were 7.6 per cent and 3.5 per cent (Table 3). There was substantial within-treatment variation, however, and the effect of season of fire on mortality was not significant (p>0.1; 2,5 Df). Analysis of co-variance, however, with maximum fire intensity over the 1990-1991 period as the explanatory variable, indicated that the effect of fire intensity on tree mortality was significant (p<0.05; 1,5 Df); both non-orthogonal and orthogonal ANCOVAs gave similar results.

TABLE 3

Tree mortality, as expressed by the average percentage ($\pm$ SE) of standing dead trees taller than 3 m which were dead in April 1992, by fire treatment (Natural or unburnt control, Early dry season fire, Late dry season fire). Figures are fitted values, based on GLMs which include fire intensity and tree size as terms, pooling height class.

	FIRE TYPE	
Natural	Early Dry season	Late Dry season
3.5 $\pm$ 0.9	7.6 $\pm$ 3.6	15.4 $\pm$ 7.3

Tree mortality was also significantly affected by tree size (Fig. 1) and species (Table 4). Mortality was greatest in the smallest size class (3-6 m) and least in the largest size class (>15 m). Mortality was also affected by species, being less in the canopy dominants - *Eucalyptus miniata and E. tetrodonta* - than in the canopy subdominants such as the leguminous tree *Erythrophleum chlorostachys.*

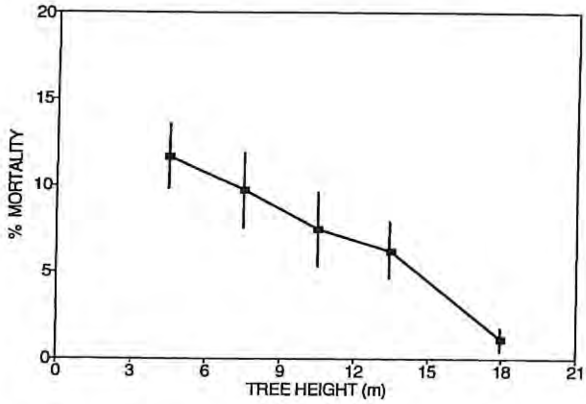

Figure 1. Tree mortality as a function of tree size. Figures are fitted values (+ SE), pooling season of fire and species. Tree heights are the mid-points of the height classes indicated on the X-axis.

TABLE 4
Fitted values of mortality by species, based on GLMs which include fire intensity and tree species as terms.

SPECIES	MORTALITY
Eucalyptus miniata	2.6 + 0.7
Eucalyptus tetrodonta	3.2 + 0.9
Erythrophleum chlorostachys	5.2 + 1.9

DISCUSSION

Fire Behaviour

The environment of northern Australia is extremely fire-prone. This is because of the combination of a regular wet season which makes annual production of fine fuels possible, a long dry season which makes 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 forests and woodlands of northern Australia (every 1-2 years) than in those of southern Australia (every 5-20 years: Cheney 1976; Stocker and Mott 1981; Walker 1981).

Measured fire intensity ranged from <500 to 18 000 kW m^{-1}; the latter was the most intense fire measured in northern Australia. Fire intensity at Kapalga was low, however, relative to potential peak intensities of *ca* 100 000 kW m^{-1} which may occur during wildfire in the forests of south-eastern Australia (Gill and Knight 1991). In the present study fire intensity varied with season of ignition. Over the years 1990-1992, the average intensity of fires in the early dry season (June) was less than that of those in the late dry season (September), which is consistent with the seasonal pattern of both Forest and Grassland Fire Danger Indices as determined by Gill *et al.* (1987, 1990). This is due to a number of factors. By the late dry season there is more fine fuel, primarily as a consequence of increased leaf-fall in the trees, both deciduous and evergreen. Afternoon relative humidity decreases progressively throughout the dry season, thus increasing the potential rates of spread (Gill *et al.* 1987; Gill and Knight 1990). However, despite the clear association between season of burn and fire intensity, in the present study there was substantial variation in fire intensity, both temporally and spatially (see also Bowman 1988) indicating that season of burn is not a precise predictor of fire intensity.

Effects of Fire on Savanna Trees

There are some aspects of this study which must be taken into account when assessing the effects of fire on savanna trees. In this study, as in that of Lonsdale and Braithwaite (1991), the effects of fire on the savanna trees have been determined by a single-time study of forest condition after fire, but without pre-fire measures of forest condition. Further, this study is in effect one of assessing the effects of fire following a set of relatively intense fires in the first year of the experimental burning - 1990 - and a set of generally low intensity fires in 1991. The fires of 1991 were of much lower intensity (5-15 times less intense) than those of 1990 in all but two cases. In these two cases, the fires of 1991 were about the same as those of 1990. Independent measurements of tree mortality on other reference plots following the 1991 fires indicate that tree mortality was minimal (R.J. Williams, unpublished data). Hence it is highly likely that the main patterns of stand condition measured on the experimental compartments at the end of the 1991-1992 growing season reflect the effects of the fires of 1990, rather than the combined effects of the fires of 1990 and 1991.

The effects of fire on patterns of tree mortality depended on interactions between fire intensity, tree size and tree species. Of the fire variables (fire intensity and season of burn), intensity was a more powerful predictor of overall tree mortality than was season, which explained less than 5 per cent of the variability in tree mortality. This does not imply, however, that season is unimportant, and the interaction between season and intensity is likely to be ecologically significant. For example, in most woody species the majority of flowering and leaf flush occurs between September and November (Brock 1988; Wilson *et al.*

1995), hence fires in the late dry season are likely to impact on these processes.

Tree mortality was also affected by tree size and species. Mortality increased with decreasing tree size, and was lower in the dominant eucalypts - *E. miniata* and *E. tetrodonta* - than in canopy subdominants such as *Erythrophleum chlorostachys*. Thus, fire has considerable potential to affect the species composition of savannas, given such differential susceptibility to fire of the major trees, both by species and by size. The reasons for this are at present unclear, but the relationship between bark thickness and species susceptibility are currently being investigated.

Management Implications

The major management implications derived from this study are that, first, season of fire is not necessarily a precise predictor of fire intensity; in some years, relatively intense fires can occur in the early dry season. The conditions determining these fires, and their degree of predictability, require further research. Second, single intense fires may have dramatic and long-lasting effects on forest structure and composition. There is some evidence that following the most intense fires of 1990, regeneration in tree saplings (less than 3 m tall) was stimulated on all burnt compartments. On the other hand, rates of recruitment from this below-3 m fraction of the tree population to the above-3 m fraction has been insufficient over the 1991-1993 period to replace losses due to the fires of 1990 (R.J. Williams; unpublished data). The old-growth stems of adult trees, and the actively growing sapling stages are both important components of long-term pools and fluxes of both nutrients and carbon. Increased loss of these components of the forest due to high intensity fire may lead to depletion of nutrient supplies (especially nitrogen) and a decreased store of carbon (see G. Cook *et al.;* this volume).

It is virtually impossible to prevent fire from occurring in the savannas of northern Australia. Therefore, the occurrence and impacts of different fire regimes on forest regeneration, given the variation in both timing and intensity of fire, requires further study, to understand the impacts of both fire regimes, and individual fires. In particular, there is need for long term monitoring of both post-fire seedling establishment and tree mortality; such studies are in progress at Kapalga.

In fire-impact studies, especially where season of burn is a factor in the design, measurements of fire behaviour are critical to interpretation of biological response. Direct measures which reflect the amount and rate of heat energy released in the vicinity of plants are discussed elsewhere in this volume by Burrows and Tolhurst. However, fire intensity - an integrated measure of energy release - is a convenient measure of fire behaviour, suitable for large-scale fire experiments such as the Kapalga experiment. Equipment such as that described by Moore and Gill (this volume), and the empirical relationships between intensity and post-fire attributes such as scorch height, are useful aids in this task.

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