Simulating Fire Ecology and Fire Management in Northern Australia

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Abstract: We have developed the FLAMES fire ecology simulation model to better understand the impacts of fire regimes in north Australian savannas. This paper aims to describe the development of the model, using two simulation examples, and indicate future uses of the model. The FLAMES model incorporates existing understanding of the tropical savannas of north Australia and field measurements to simulate the response of tree populations with a grassy understorey to climatic variation, different fire regimes and management options. FLAMES operates on a hectare plot and allows several contiguous plots to be joined to simulate a landscape where flows of water, seeds and litter between adjacent hectares are simulated. In this paper, a single hectare is simulated for an 89-year period using historic, daily rainfall records from 1911 to 1999 for Kunbarllanjnja, Northern Territory, Australia. The two simulations are used to determine what effect varying frequency, timing (early or late dry season) and type of fire have on fire intensity and thus tree survival and the subsequent structure of the savannas.

Keywords: Fire; Savanna; North Australia; Model; Trees

1. INTRODUCTION

Fire regimes are key determinants of vegetation structure in tropical savannas. Across many regions of North and South America, Africa and Australia, the cover of woody vegetation has increased since Anglo-European settlement, and this is believed to be largely due to changed fire regimes [Archer and Stokes, 2000; Dyer and Mott, 1999; Burrows et al., 1998]. These changes in fire regimes include diminished fire frequency, active exclusion of fires and reduced average fire intensity. In contrast, fire regimes are believed to have become more, rather than less severe following European settlement in much of the high rainfall belt of Australia's Northern Territory [Russell-Smith et al., 1997 and 1998]. In order to investigate the long-term implications of different fire regimes, we have developed a modelling tool (FLAMES) to predict the effects of individual fires over long periods of time, across a landscape, and for different soil types and rainfall levels.

In this paper, we describe the development of this model and apply it to extrapolate results of the Kapalga fire experiment [Andersen et al., 1998] to other fire management scenarios. Specifically we compare the effects of varying the frequency and timing of fronting fires and we examine the effects of ignition style under a typical fire regime for the region.

2. OVERVIEW OF THE FLAMES MODEL

2. 1 The Landscape

The landscape in FLAMES comprises an array of contiguous cells. We usually consider the cells to be one-hectare units but potentially, they could be of any area. Two binary raster map files define the landscape. They are 1) a digital elevation map giving the elevation at the centre of each cell and 2) a land unit map with each cell having a specified type of land unit [Karfs, 1999]. These maps define the maximum area in terms of rows and columns of cells on which the simulation can be performed.

The land units comprise: a name, an index which defines the link to the land unit map, a soil type, a list of initial populations of component tree species and a list of initial biomasses of component grass species. Currently, the interactions between cells comprise surface flow of water, with future developments to include seed dispersal and movement of litter, soil and nutrients.

2.2 The Cell

FLAMES applies a nominated fire management regime to a one-hectare population of trees with a grassy understorey (Figure 1). As all processes are simulated at this scale, the cell provides the smallest unit of area. The physical environment is parameterised with daily rainfall records and mean daily 9am and 3pm temperatures, humidities and wind speeds (schotastically determined) for each month as well as soil depth, water holding capacity and elevation. Rates of fire spread are calculated from predefined weather conditions and fuel characteristics [Cheney et al., 1998; Catchpole et al., 1992; Noble et al., 1980], and together with calculated fuel loads generate Byram fire line intensities [Byram, 1959]. The total fuel load depends on the production of grass and tree litter, which varies with total tree basal area according to defined algorithms, and the amount of decomposition [Olson, 1963].

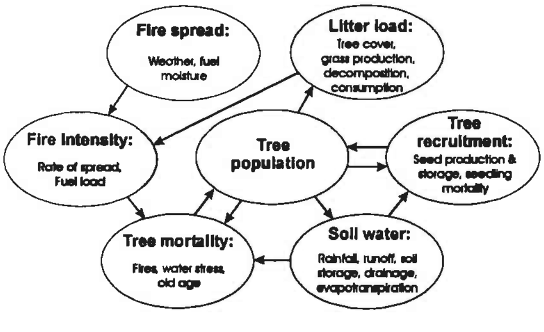

Figure 1. Flow diagram of dynamics within each landscape cell in FLAMES.

In FLAMES, the fire shape can be considered either as a linear fronting fire, or as a simple ellipse (Figure 2). The linear fronting fire could occur if a land manager ignited a line perpendicular to the wind direction along an upwind boundary of a constrained area. If linear fronting fires are simulated in FLAMES, the fire will always spread at the quasi-steady maximum rate for the given weather and fuel conditions. The simple ellipse on the other hand provides a good description of the perimeter of an unconstrained wildland fire [Catchpole et al., 1992]. An elliptical fire shape implies a variation in spread rate at different angles to the prevailing wind direction. In FLAMES, if the elliptical fire option is selected, we calculate the rate of spread from the frequency distribution of particular rates of spread around the circumference of the ellipse using equations of Catchpole et al. [1992] and Luke and McArthur [1978].

The tree population is modelled using a cohort based model where individuals are subject to recruitment, growth and mortaility. Trees grow in diameter at a rate that can be set for up to three population strata. They survive fires according to defined survival functions that depend on fire intensity and tree diameter and have been developed from field measurements at Kapalga, Kakadu National Park, Northern Territory [Williams et al., 1999; Williams unpublished data]. Trees regenerate both from modelled seed production and from their ability to resprout from lignotubers following stem kill by fires.

A tipping bucket water balance model interacts with tree and grass water use to provide upper limits to vegetative biomass and to allow the impacts of drought to be simulated.

The outputs are demographic and structural descriptions of the tree population as well as vegetation biomass, fire intensities, fluxes of carbon, greenhouse gas emissions, and the water budget.

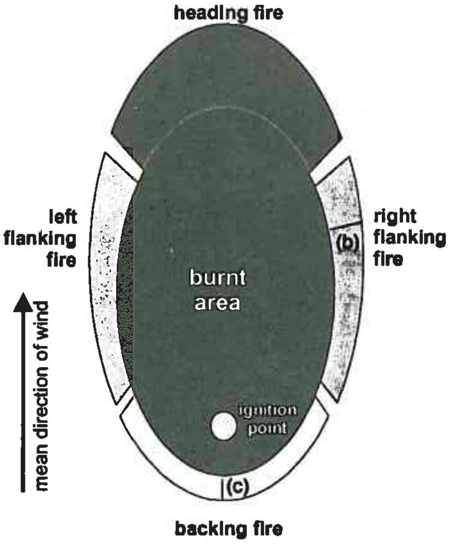

Figure 2. An idealised burnt ellipse showing (a) a heading fire of greatest intensity, (b) a flanking fire and (c) a backing fire of low intensity from which the probability that a particular landscape patch will be burnt at given intensity is calculated.

3. KAKADU CASE STUDIES

3.1 Background

Over the period 1980-1994, about 56% of the lowland savannas of the Kakadu National Park burnt annually, with most fires being lit by people [Russell-Smith et al., 1997]. Of these fires, the majority (59%) occurred in the early dry season (before August). Much of the rationale for fire management is to use fires early in the winter dry season to reduce the occurrence of more intense fires later in the dry season. The relative effects of seasonality and frequency of fires are a key research question to help address sustainable management of the region. CSIRO conducted a fire experiment at Kapalga in Kakadu National Park from 1990 to 1995 [Andersen et al., 1998]. This experiment examined the effects of annual fires early (June) and late (Sept) in the dry season.

3.2 Simulation Details

We used FLAMES model in two series of simulations: 1) Kapalga extrapolation and 2) Kakadu lowlands extrapolation. In the Kapalga extrapolation, we examined the effects of varying frequencies of fronting fires from one in ten years to nine in ten years under three fire weather conditions ranging from relatively benign (typical of mornings in May), through to the increasingly severe fire weather condition (typical of afternoons in June and September). In the Kakadu lowlands extrapolation, we examined the long-term effects of the fire regime described for the Kakadu lowlands (1980 – 1994) [Russell-Smith et al., 1997] where fires occur in 55.5% of years, with 33% of years having early dry season fires (we assume June) and the remainder being late dry season (we assume September). For these simulations, we compared a regime of fronting fires with a regime of point sourced or elliptical fires wherein fires spread in an elliptical pattern and there is a predictable likelihood that any part of the landscape could be burnt by flanking fires of relatively low intensity [Catchpole et al., 1992].

We parameterised the four dominant tree species of the Darwin region, *Eucalyptus miniata*, *Eucalyptus tetrodonta*, *Eucalyptus porrecta* (Myrtaceae) and *Erythrophleum chlorostachys* (Caesalpinaceae) using available data on their daily water use, seed production, litter production, fire survival and growth [O'Grady et al., 1999; Williams et al., 1999; Hatton et al., 1998; Setterfield, 1997; Williams et al., 1996; Brennan, 1996; Setterfield and Williams, 1996; Cook unpublished data]. Savanna vegetation dominated by these species covers more than 90 000 km^2 of the Northern Territory [Wilson et al., 1990]. Grass production was modelled from tree to grass ratios using a relationship based on the equations of Scanlan and Burrows [1990] and calibrated with local data [Cook, 1994; Andrew and Mott, 1983]. Grass water use was estimated from the water use efficiency of native perennial Sorghum species of north Australia [Hammer et al., 1997].

In this paper, we only describe the results of simulations at the one-hectare scale, and do not apply the model to a whole landscape. We run the simulation from 1911 to 1999 using historic daily rainfall records for Kunbarllanjnja, Northern Territory.

4. RESULTS

4.1 Kapalga Extrapolation

The average intensity of fires simulated by the FLAMES model was greatest for September fires and least for May fires (Figure 3). Average intensities decreased with increasing fire frequency, because of decreasing fuel loads. However the maximum intensities showed less variation among fire frequencies.

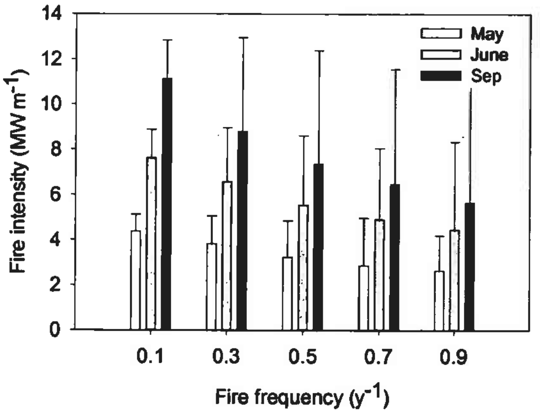

Figure 3. Simulated changes in average fire intensity under average fire frequencies ranging from one to nine per decade (0.1 to 0.9 y^{-1}) and three fire seasonalities. The whiskers give the maximum intensity observed over the 89 year simulation.

Across all fire seasonalities, the total basal areas of trees resulting from 89 years of the imposition of the fire regimes declined with increasing fire frequency (Figure 4). The decline was most marked under September fires when fire weather is most severe, and was slight under the relatively benign fire weather conditions of May mornings.

The changes in total basal area over time vary with fire seasonality. In all cases, total basal area declined rapidly over the first few years. At a fire frequency of 0.5 y^{-1}, total basal area under May fires fluctuated between about 10 and 12 m^2 ha^{-1} (Figure 5). Under June and September fires, the total basal areas declined by about 0.05 and 0.06 m^2 ha^{-1} y^{-1} respectively over the period of the simulation.

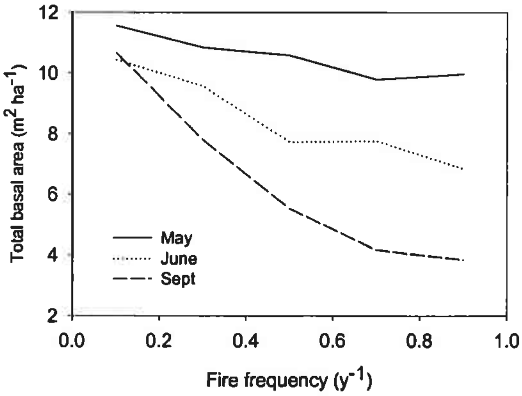

Figure 4. The resulting total basal areas of trees in 1999 following commencement of various simulated fire regimes in 1911.

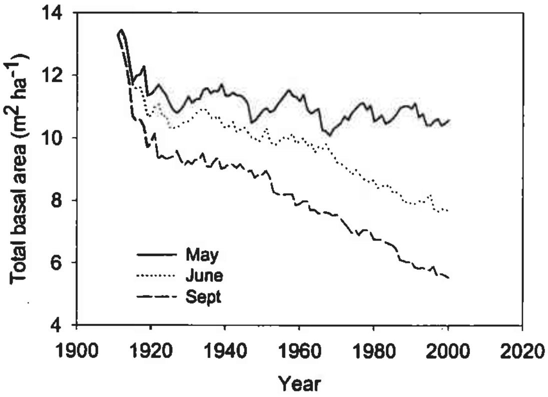

Figure 5. Simulated changes in total basal area of trees from 1911 to 1999 under a fire frequency of 0.5 y^{-1} and three fire seasonalities.

As evident from the literature and model parameters, the most fire sensitive species was the leguminous tree *Erythrophleum chlorostachys*. The proportion of the total basal area comprising this species declined substantially with increasing fire frequency (Figure 6). The effects of fire seasonality were less marked, and did not follow a consistent pattern.

4.2 Kakadu Lowlands Extrapolation

Under a regime of fronting fires, the mean fire intensity was more than double that under a regime of point-sourced fires (Table 1). The maximum intensity observed over the simulation period was about 30% greater under fronting fires. These differences had important effects on tree populations with the total basal area continuing to decline at about 0.1 m^2 ha^{-1} y-1 over the 89 years of the simulation under fronting fires, but stabilising at around 10 m^2 ha^{-1} after about 20 years under point sourced fires (Figure 7).

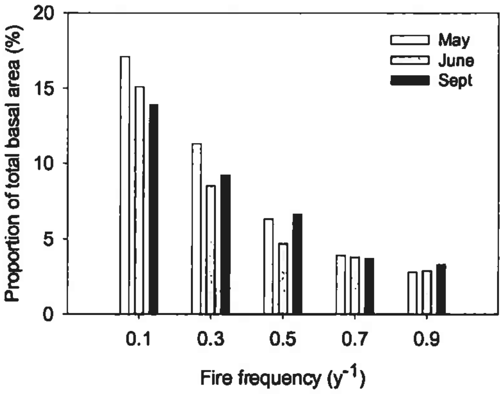

Figure 6. Simulated changes in the proportion of the total basal area comprising Ironwood trees (*Erythrophleum chlorostachys*) under various fire frequencies and and three fire seasonalities.

Table 1. The mean and maximum fire intensities over 89 years of simulation fires in the Kakadu lowlands with a fire frequency of 0.55 y^{-1} of which 41 % occur in June and 59 % in September.

	Ignition style	
Fire intensity (MW m^{-1})	Fronting	Point-source
Mean (s.d.)	6.6 (1.8)	3.0 (2.0)
Maximum	11.0	8.5

5. DISCUSSION

By scaling up from individual trees, the FLAMES model has produced values of total tree basal area at the hectare scale similar to those observed in this region which is about 8 m^2 ha^{-1} [Williams et al., 1996]. As well, the variations in fire intensity are consistent to those measured in the field under similar conditions [Williams et al., 1999].

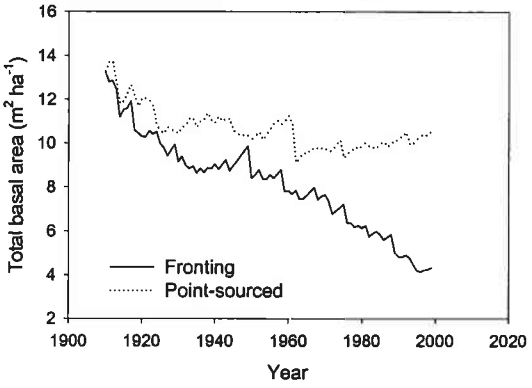

Figure 7. Simulated changes in total basal area of trees from 1911 to 1999 for point-sourced and fronting fires under a fire frequency of 0.55 y^{-1} with 41 % of fires in September and 59 % in June.

FLAMES allows the effects of fire frequency and seasonality to be simulated when field studies to examine these effects are difficult and costly. The results show important effects of both frequency and seasonality on total basal area, but with frequency having a greater impact than seasonality on the relative contribution of a fire sensitive species to the total tree basal area. The current fire regime in the Kakadu National Park lowlands may sustain a basal area of trees at about 10 m^2 ha^{-1} unless the fires are largely fronting. In that case, the trees are likely to slowly decline. Published data on fire occurrence gives no information on spatial distributions of fire intensity. FLAMES highlights the importance of obtaining such data in order to better describe fire regimes.

Future development of the FLAMES model will be through completing various case studies to ensure its reliability in making sound predictions of the impacts of fire regimes. The model will be tested by field validation of a range of case studies.

6. ACKNOWLEDGEMENTS

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