FUEL DYNAMICS AND FIRE BEHAVIOUR IN SPINIFEX GRASSLANDS OF THE WESTERN DESERT

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Abstract
Spinifex grasslands, characterised by the dominance of perennial hummock grasses of the genus *Triodia*, cover some 43% of Western Australia. They occur in the semi-arid and arid regions of the State and occupy a diversity of landforms including sand plains, gibber plains, dune fields and rocky hills. The combination of the physical structure of the hummocks and the often extreme weather conditions makes spinifex grasslands highly flammable. Historically, lightning and burning by Aboriginal people were the main causes of fire. Today, most fires are started by lightning, although human-caused ignitions are significant near settlements, on pastoral leases and along travel routes. The primary fire management objectives for spinifex grasslands occurring on the extensive conservation reserve network are to conserve biodiversity and to protect human life, property and cultural values. An ability to predict fuel maturation and fire behaviour is fundamental to proactively managing fire in these landscapes, such as implementing patch-burn strategies and buffer burns to benefit biodiversity and to limit the impact of wildfires. In this paper we present remote sensing (satellite imagery) techniques for quantifying post-fire vegetation/fuel recovery, models of post-fire fuel development and a revised empirical model for predicting threshold fuel and weather conditions for fire initiation and subsequent spread over a broad range of fuel and weather conditions.

Introduction
There is now compelling evidence that fire regimes in much of the spinifex grasslands have changed with the cessation of traditional Aboriginal burning from a fine grain mosaic of burnt patches at different seral states to a coarse grain, simplified mosaic of infrequent, large wildfires (Burrows and Christensen 1991, Burrows *et al*. in press). This, together with predation by introduced predators, has probably contributed to the alarming decline in native fauna, particularly medium sized mammals and some ground-nesting birds (Johnson *et al*. 1989, Burbidge and McKenzie 1989, Morton 1990). Management intervention by the reintroduction of fire to re-create a fine-grained mosaic of different post-fire seral states and to break up the run of major wildfires, is a desirable strategy in many areas. However, fire management is constrained by limited resources, the vastness and remoteness of many nature conservation reserves, poor accessibility and imperfect knowledge of fire behaviour and fire effects. An understanding of fuel dynamics, especially changes in the structure and quantity of spinifex grassland fuels with time since last fire is important for understanding fire hazard, fire behaviour and for planning prescribed burning operations. This study aimed to improve an understanding of fuel dynamics and the predictability of fire behaviour, particularly threshold conditions for fire start and spread, over a wide range of fuel and weather conditions. The fire behaviour research reported here was conducted in spinifex communities in the Great Sandy Desert, building on the earlier work of Griffin and Allan (1985) and Burrows *et al*. (1991).

Materials and Methods
The spinifex fire behaviour model was derived from field experiments undertaken in the two remote regions of Western Australia described below. Modelling incorporated data from 41 experimental fires previously conducted in the Gibson Desert and reported by Burrows *et al*. (1991). These data were supplemented by a further 42 experimental fires carried out in the Great Sandy Desert over the period 1992-1994.

The experimental methods employed to develop the models are similar to those published by Burrows *et al*. (1991), so will not be explained in detail. Prior to igniting the fires, measures of the structure (height, cover and patchiness) and biomass of the spinifex grassland to be burnt were made by intensive sampling along a series (3-4) of 100 m continuous line transects. Spinifex grasslands are usually a simplex (single layer) elevated fuel dominated by hummocks of spinifex of more-or-less uniform structure (for a given time since last fire) interspersed with low soft grasses and occasional small shrubs and trees. Along each transect, the distance of each of bare ground, spinifex hummock, soft grasses and other vegetation intercepted by the line, was recorded in continuous sequence. Where vegetation was intersected along the transect, it was categorized as either spinifex, soft grasses, herb, litter, woody shrub or ‘other’, and the continuous distance of the cover type along the transect, and its height above ground, was

recorded. This enabled vegetation cover (% by vegetation classes) and proportion (%) of bare ground, and patch dimensions, to be calculated. These measurements were used to model fire behaviour and to assess the suitability of using Landsat satellite imagery for determining post-fire vegetation cover (% ground cover) by sampling fuels in a range of fire scars of different but known ages (time since last fire). Actual cover measures were correlated with a Landsat image determination of a ‘cover index’. Fuel weight (oven dry) was sampled by removing all fine (<6 mm diameter) live and dead vegetation from 1m x 1m quadrats placed at 10 m intervals along the line transects. Additional fuel studies were carried out in spinifex grasslands at Lorna Glen, an ex-pastoral lease in the southern part of the Little Sandy Desert some 180 km NE of Wiluna.

Moisture content of the spinifex hummocks was determined by taking a cross section (profile) of material from 6-10 hummocks prior to each experimental fire and oven drying the sample. Weather conditions during the experimental fires were recorded by both an on-site automatic weather station and hand held instruments. Wind speed, wind direction, air temperature and relative humidity were measured at ~2m above ground (see Burrows *et al.* 1991). Experimental fires were lit by a 100-200m line of fire. The position of the fastest spreading part of the fire (headfire) was marked at regular time intervals with metal tags, which were later surveyed to enable the fire’s rate of spread to be calculated. Not all fires sustained spread and analysis focussed on; a) determining threshold conditions of fuel and weather for fire spread and b) predicting rate of spread when these were met or exceeded.

Field Sites

Fuel dynamics and fire behaviour studies were conducted in hummock grassland communities in the Gibson and Great Sandy Deserts of Western Australia. A description of the Gibson Desert study area is provided by Burrows *et al.* (1991). In summary, and as described by Beard (1969), the Gibson Desert is ‘characterized by laterite plains, a monotonous and gently undulating topography floored with ironstone gravel and vegetated with poor spinifex (mostly *Triodia basedowii* and *T. schinzii*) and stunted mulga (*Acacia anuera*)’. Spinifex communities growing on the buckshot plains in the Gibson Desert are generally sparser, shorter and lower in biomass (‘poorer’) than those that occur on the sand plains and dune fields that characterize much of the inland arid zone, including the Great Sandy Desert. Fire behaviour studies were also carried out in the Rudall River National Park, which at 1,283,706 ha is the largest national park in Western Australia and one of the largest in the world. The park is situated in the south-western portion of the Great Sandy Desert. The climate of the region is classified as desert based on the Koppen classification system. Mean annual rainfall is ~225mm mainly derived from summer thunderstorms and cyclone activity between November and March. Mean daily maximum temperatures range from 41^{o} C to 25^{o} C. Vegetation on the eolian sand plains and dune fields of the study area is dominated by spinifex (*Triodia pungens*, *T. wiseana* and *T. schinzii*), with scattered small shrubs and trees (predominantly species of the genera, *Grevillea*, *Acacia*, *Hakea*, *Eremophila* and *Eucalyptus*). Spinifex cover mostly varies from 30-50%, ranging in height from 0.2-0.4 m, with scattered trees and shrubs to 3 m.

Analysis

Models were developed by applying various linear and non-linear regression techniques to determine the best statistical relationships between dependent (fire behaviour) variables and independent (fuel and weather) variables. Logistic regression modelling (SAS 2003), a conditional distribution of a binary output variable y given a input vectors, was used to determine the probability of fires spreading.

Results and Discussion

Space-for-time fuel sampling showed that fuel weight increased with time since fire (Figure 1), plateauing at about 10-12 t ha^{-1} some 18-20 years after fire. Changes in the cover of spinifex, other plant species and of bare ground with time since fire are shown in Figure 2. In the early years post-fire, vegetation cover was very sparse, although on some sites, and following rain, the cover of annual herbs and grasses temporarily increased the overall cover of vegetation. Figure 2 shows the increasing dominance of spinifex cover with time since fire, which reached a maximum of about 40% some 18-20 years after fire. By this stage, other plant species comprised about 5% of the total cover, with some 55% of the sand plain being bare ground. The height of spinifex clumps also steadily increased with time, plateauing at about 35 cm some 18-20 years after fire (Figure 3). This pattern of post-fire fuel development is consistent with other studies (Griffin 1992, Griffin *et al.* 1990, Allan and Southgate 2003), who also note that the rate of change in biomass and fuel composition and structure are strongly influenced by rainfall. The profile moisture content of spinifex clumps of varying age, but sampled at about the same time, decreased with the age of the clump, reflecting the increasing proportion of drier dead material and decreasing proportion of wetter green live material in the hummocks (Figure 4).

These data demonstrate how the flammability of spinifex grasslands increases with time, not only due to increasing cover and weight of flammable vegetation, but also due to decreasing moisture content and an increasing proportion of drier dead material accumulating in the hummocks. We were able to develop a significant linear relationship between a satellite-derived measure of vegetation cover index and actual ground cover (%) as shown in Figure 5, meaning that vegetation cover (%) can now be reliably estimated from satellite imagery.

Figure 1: Fuel weight with time since fire based on space-for-time sampling in spinifex grasslands.

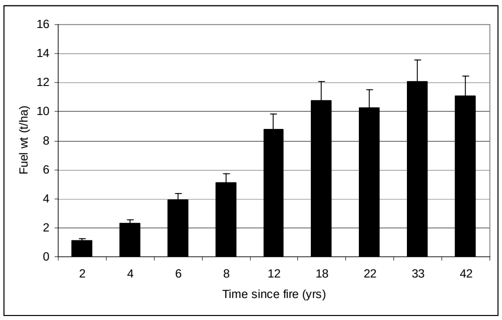


Figure 2: Cover of vegetation and bare ground with time since fire.

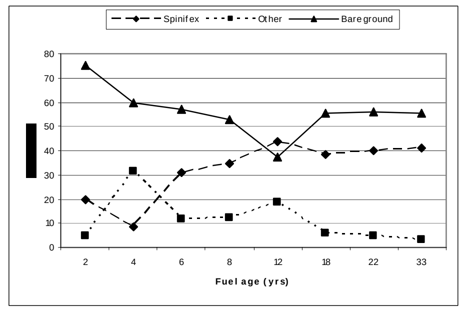


Figure 3: Change in the height of hummocks with time since fire.

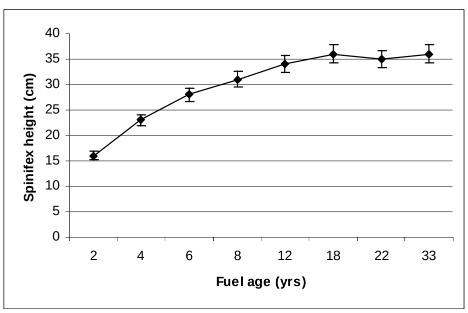


Figure 4: Hummock profile moisture content with hummock age (time since fire).

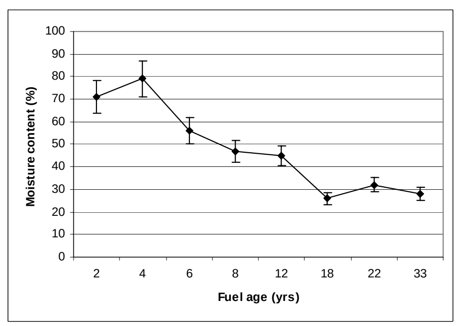
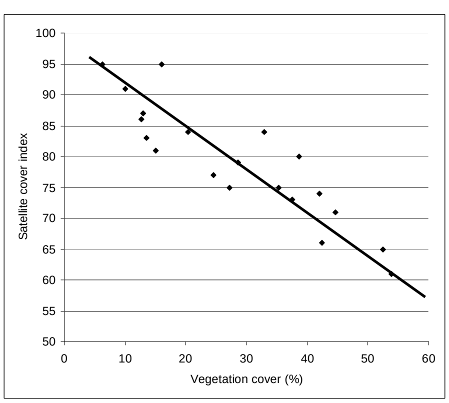


Figure 5: Relationship between satellite vegetation cover index and actual spinifex cover ($y = 136.7-1.37(x)$ $R^2 = 0.79$)



The range of fuel, weather and fire behaviour conditions experienced during the fire behaviour experiments is shown in Table 1.

Table 1: The mean and range of fuel, weather and fire behaviour conditions under which the spinifex fire behaviour prediction model was developed (n = 83).

Variable	Mean	Range
Wind speed (km h^{-1})	15	4 - 36
Temperature (°C)	31	19 - 50
RH (%)	14	5 - 48
Fuel quantity (t ha^{-}1)	7	2 - 14
Fuel cover (%)	38	9 - 65
Fuel height (cm)	25	18 - 37
Fuel profile moisture (%)	18	12 - 31
Rate of spread (m h^{-1})	842	0 – 5,520
Flame height (m)	1.4	0 – 5
Fire intensity (kW m^{-1})	3,515	0 – 19,111

Gill *et al.* (1995) suggested three stages in the formulation and application of fire spread models; (i) a domain analysis for the applicability of inputs to a fire spread model, (ii) a 'likelihood of fire spread' analysis and (iii) application of a spread model to predict rate of spread. In discontinuous or patchy fuels such as spinifex grasslands, there are multiple thresholds to fire spread (Burrows *et al*. 1991, Gill *et al*. 1995). Conditions of fuel and weather need to be such that the flame dimensions are sufficient to breach gaps in the fuel. Therefore, an important step in predicting fire behaviour is to determine the probability that, following ignition, fire will actually spread for a given set of conditions. Fuel moisture content is the main factor limiting ignition and sustained fire spread in continuous fuels but in patchy fuels, such as hummock grasslands, fire spread can only be sustained if conditions are such that the flames from burning hummocks can breach the inter-hummock gaps and ignite the adjacent hummock (Gill *et al.* 1995). Factors that determine fire energy, flame size and flame tilt, therefore the capacity for sustained spread, include wind speed (and slope), fuel quantity, fuel moisture content and fuel structural characteristics such as height, cover and patchiness (or separation of fuel pieces).

Of the independent variables measured, wind speed, fuel quantity and fuel moisture content were found to be the most important variables influencing whether fires would spread. Fuel quantity is important in its own right, but is also a surrogate for, and correlated with, cover and height. Using these factors, the probability of fire spreading was best estimated by an applied logistic function (SAS 2002) of the form:

SI_{FQ} = 0.57(W) + 0.96(FQ) – 0.42(PMC) – 7.42...(Eq.1), **or**, SI_{FF} = 0.37(W) + 0.78(FF) – 0.31(PMC) – 5.23…(Eq. 2)

Where:
SI_{FQ} = Fire Spread Index using fuel quantity. A positive value means fire will probably spread.
SI_{FF} = Fire Spread Index using fuel factor (see below).
W = average wind speed (km h^{-1}) over a 5 minute period at 2 m above ground.
FQ = fuel quantity (spinifex and other fine fuels) (oven dry weight in t ha^{-1}).
PMC = the profile moisture content of the spinifex hummock (% oven dry weight).
FF = fuel factor = 0.25(CV) + 0.04(HT) - 3.2…(Eq. 3) (R^2=0.71)
Where:
FF = fuel factor (a surrogate for fuel quantity incorporating fuel cover and height)
CV = fuel (spinifex) cover (%)
HT = mean hummock height (cm)
Fuel quantity (FQ) and fuel factor (FF) are related by the equation:
FQ = 0.98(FF) - 0.08..(Eq. 4) (R^2=0.71).

FF is almost equal to FQ so can be substituted for FQ if fuel quantity cannot be measured in the field. Equation 3 assumes a more-or-less constant hummock bulk density of about 17 kg m^3. This can vary within and between species depending on site (e.g., soil type and termite activity) and seasons (rainfall), so fuel quantity is the preferred variable, hence Equation 1 the preferred equation for predicting the likelihood of fire spread.

Interpreting the fire Spread Index (SI)

SI (Equations 1&2) is an applied logistic regression function, which means that the outcome is binary, or dichotomous. That is, it determines whether or not fire will spread. If the SI is negative, then fire should not spread; if it is positive, then fire should spread. The more negative the value, the less likely is spread and vice versa (see Table 2).

Table 2: The likelihood of sustained fire spread (SI) determined from Equations 1 or 2 above, and potential rates of spread

SI	Fire Danger Rating (FDR), likelihood of fire spread and potential ROS (m h-1)
SI < -2	FDR Very low - fire highly unlikely to spread (ROS = 0)
-2 < SI < 0	FDR Low – fire could spread (ROS < 500)
0 < SI < 2	FDR Moderate – fire should spread (ROS: 500 –1,000)
2 < SI < 4	FDR High – fire will spread (ROS: 1000 – 1,500)
4 < SI < 6	FDR Very High – fire will spread (ROS: 1,500 – 2,000)
6 < SI < 10	FDR Extreme – fire will spread (ROS: 2,000 – 3,000)
SI > 10	FDR Very Extreme – fire will spread (ROS > 3,000)

Predicting rate of spread, flame height and intensity

Having determined whether or not a fire will spread (SI), the next step involved developing a model to predict rate of spread. Once conditions are suitable for fire spread, then rate of spread was found to be best explained by a linear function of wind speed, fuel quantity and fuel moisture content, with wind speed being the most influential variable (Figure 6). Other variables such as fuel cover and height were also found to be important, but these are related to, and are best represented, by fuel quantity. In essence, rate of spread in discrete fuel arrays depends on flame dimensions which in turn depends on wind speed, fuel quantity and fuel moisture content. Clearly, a feed back mechanism exists, as more fuel becomes involved at higher rates of spread, which in turn results in larger flames. Two (linear) prediction models were developed; one requires measurement of fuel quantity (dry weight), the other requires the more easily obtained measures of fuel cover and height. Temperature and relative humidity were found not to be highly significant, so were not included in the model. It is important to note that these models do not apply when conditions are below thresholds for fire spread, i.e., SI < 0. The relationship between actual rate of spread (of experimental fires) and that predicted using Equation 4 is shown in Figure 7.

Figure 6: Headfire rate of spread with wind speed @ 2m above ground.

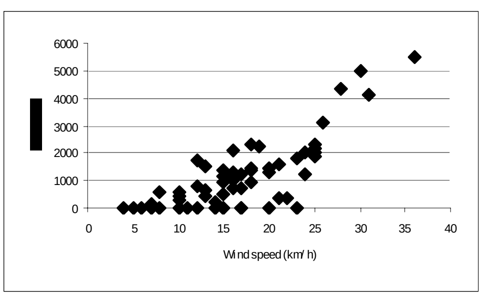
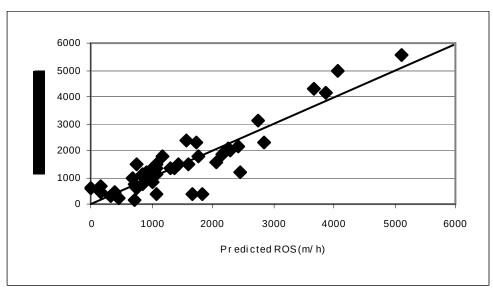


Figure 7: Relationship between actual spread and that predicted using Equation 4.



Forward Rate of Spread (ROS):

ROS_{FQ} = 154.9(W) + 140.6(FQ) – 228.0(PMC) + 1581…(Eq. 4) (R^2=0.79)

or;

ROS_{FF} = 142.8(W) + 120.1(FF) – 229.1(PMC) + 1969…(Eq. 5) (R^2=0.79)

Where;

ROS_{FQ} = forward rate of spread calculated using fuel quantity ($m\ h^{-1}$)
ROS_{FF} = forward rate of spread calculated using fuel factor ($m\ h^{-1}$)
W = average wind speed ($km\ h^{-1}$) over 5 minutes @ 2 m above ground.
FQ = fuel quantity (spinifex and other fine fuel) (oven dry weight in ha^{-1}).
PMC = the profile moisture content of the spinifex hummock (% oven dry weight).

FF = fuel factor (see above).

Measuring model input variables

The models described above will perform best if the input (independent) variables are measured the same way as they were measured for the experimental fires, on which the models are based. Alternative models for predicting fire behaviour (thresholds for spread and rate of spread) are presented above so that fire managers can choose the most practical model for their circumstances. For example, in some cases it may be easier to measure fuel cover (in the field or from satellite imagery – see Figure 5) and height (surrogates) than to measure fuel quantity. Using surrogate variables will, in most cases, reduce the reliability of the models, but may be more practical.

Model limitations

Combustion and bush fire behaviour are complex phenomena that are poorly understood at the fundamental level. The empirically-derived spread models presented here do not include all of the potential variables likely to influence fire behaviour, but include key integrator variables that are relatively straight forward to measure in the field. The models explain between 70% and 80% of the variation in observed fire behaviour. The models are constrained by the parameter bounds described in Table 1, which represent a wide range, but not all, of potential burning conditions likely to be encountered in spinifex grasslands. The experimental fires on which the models are based did not capture the entire range of fuel structure, fuel moisture, weather and terrain conditions likely to be experienced in spinifex grasslands throughout Western Australia. For example, an obvious range/variable omission is the influence of slope and slope-wind interactions, which are likely to be important in some regions. Where slope is an important terrain variable, then we recommend adopting the formula developed by Burrows (1994) for forest fuels as a guide. Roughly, rate of spread (upslope) doubles for every 10^o of slope. That is;

$$ROS_{SC} = ROS*e^{(0.0687S)}$$

Where;
ROS_{SC} = rate of spread corrected for slope (m h^{-1})
ROS = rate of spread on flat terrain (m h^{-1})
S = slope (degrees)

The models were developed using line ignitions, which may not be the preferred ignition technique in prescribed burns. It is more likely that aerial incendiaries (point ignition) will be used in prescribed burn operations. This is more likely to affect the probability of ignition and sustained spread, and the time to reach potential spread rate, rather than fire behaviour once spread thresholds are exceeded. Spinifex hummocks consist mostly of live vegetation and have the capacity to persist at very low moisture contents. The proportions of live and dead material in the hummocks varies and depends on species, age (time since last fire), seasonal conditions and termite activity. Variation in the live-to-dead fuel ratio is not accounted for by the models. These models do not take account of fire propagation by spotting. Except in the presence of mallees, other eucalypts or other myrtaceous scrub, we observed only short distance spotting (up to 200 m) and spot fires were usually quickly overrun by the main headfire.

Conclusions

The fire regime has changed significantly and recently in parts of the Western Desert following the departure of Aboriginal people and the cessation of traditional burning. Today, and in the absence of regular burning by Aborigines, fuels have accumulated over vast areas and when lightning (or people) ignites these fuels and under hot, dry, windy summer conditions, large and intense wildfires occur. It is imperative that anthropogenic fire is reintroduced into these landscapes to prevent further declines in ecosystem health. The spinifex grassland fire behaviour models presented here provide land managers with a guide to planning and implementing prescribed burns to achieve a variety of management objectives. There are many Aboriginal communities located in the Western Desert and given the knowledge and skills possessed by older people particularly, and the overwhelming desire by many Aboriginal people to care for country, an opportunity exists for co-management of fire on these lands. The challenge for conservation and land management agencies is to develop processes that enable Aboriginal people to participate in land management in a meaningful and mutually beneficial manner.

Acknowledgements

We thank Canning Resources Pty Ltd. based at Kintyre (Rudall River) and especially Bruce Harvey (CRA exploration geologist) for their support for this work. We also thank Malcolm Gill and Peter Moore who assisted with components

of the field work, and Pilbara and Goldfields Regional staff of the Department of Conservation and Land Management (CALM) who provided logistic support and assistance with fire control. One of the authors (A.D. Robinson) is now deceased and this paper is dedicated to his memory.

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