A Guide to Predicting Fire Behaviour and to Patch-burning in Hummock Grasslands
Version 2.

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1. Background

- CALM manages in excess of 8 million ha of hummock grasslands, which are characterised by the dominance of spinifex species (*Triodia* sp.) occupying a diversity of landforms including sand plains, dune fields and rocky hills.

- Fire is a natural environmental factor in hummock grasslands. Fire regimes and their effects on the environment are variable in space and time.

- The primary fire management objectives for hummock grassland nature reserves and national parks are to maintain biodiversity and to safeguard human life, property and cultural values.

- While our knowledge of fire effects in hummock grasslands is incomplete, there is evidence that fire regimes having changed significantly in many areas since the decline of traditional Aboriginal burning practices. Generally, there has been a reduction in patchiness and diversity of fire regimes (frequency, season, intensity), and an increase in the intensity and scale of wildfires.

- Altered fire regime, together with predation by introduced predators, may have contributed to the decline in native fauna, particularly medium sized mammals and some ground-nesting birds. There is also evidence that large and intense wildfires are adversely impacting on fire sensitive communities embedded in hummock grasslands, such as mulga and Callitris stands.

- Management intervention by the prescribed use of fire in hummock grasslands to create a diversity of interlocking successional states and to break up major wildfires is now accepted as a desirable strategy in many areas. Fire management is constrained by limited resources, the vastness and remoteness of many national parks and nature reserves, poor accessibility and imperfect knowledge of fire behaviour and fire effects.

- In many areas, traditional owners have maintained continuous association with country, have profound knowledge of fire and must be supported to engage effectively in fire management on CALM administered lands.

- Techniques for using aircraft to implement unbounded and self extinguishing fires have been developed for some fuel types. Where this has been applied operationally, success has been mixed due to difficulties associated with remoteness (i.e., limited ability to measure/monitor and forecast fuel and weather conditions) and because of the limitations with the existing fire spread models (Burrows *et al*. 1991).

- In an effort to improve the predictability of fire behaviour, particularly threshold conditions for fire start and spread, further research has been conducted in a wider range of hummock grassland fuel types since the production of the Version 1 fire behaviour prediction guides (Burrows *et al*. 1991).

- Version 2 is the culmination of field experiments carried out in both the Gibson Desert (Gibson Desert Nature Reserve) and the Great Sandy Desert (Rudall River National Park). Being empirically derived, the guides will be most reliable when applied under the same or similar conditions as the original field experiments (see Table 1 below). Because of the complex nature of fire behaviour, there will be some variation in fire behaviour that cannot be adequately explained by the models. Thus, the models presented here should be used in conjunction with local experience and wisdom to guide management decisions.

Table 1: The mean and range of fuel, weather and fire behaviour conditions under which the version 2 spinifex fire behaviour prediction models were developed.

Variable	Mean	Range
Wind speed (km h^{-1})	15	4 - 36
Temperature (^oC)	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

2. Summary of Version 2 Model Development

A detailed description of methodologies and analysis is currently being prepared for scientific journal publication. Rather than delay the transfer of information to operations, we have decided to produce this guide before publishing the work. The methods employed to develop the models presented here are similar to those published by Burrows *et al*. 1991. In essence, about 100 experimental fires were set in a range of fuel and weather conditions in hummock grasslands (plains) in the Gibson Desert Nature Reserve and in the Rudall River National Park. For various reasons, not all of these fires were used in analysis. Experimental fires were lit by a 100-200m line of fire and using a drip torch. Not all fires sustained spread and analysis focussed on a) attempting to determine threshold conditions of fuel and weather for fire spread and b) predicting fire rate of spread when these were met. Models were developed by applying various regression techniques to determine the best statistical relationships between dependent (fire behaviour) variables and independent (fuel and weather) variables.

Standard methods for measuring the variables used in the models are described in Table 3 below. A description of common spinifex fuel types is contained in Table 4 below.

Alternative models for predicting fire behaviour (thresholds for spread and rate of spread) are presented so that managers can choose the most practical model for their circumstances. For example, in some cases it may be easier to measure fuel cover 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 to use.

2.1 Model limitations

- Combustion and bush fire behaviour are complex phenomena that are poorly understood at the fundamental level. The empirically derived 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 70% - 80% of the variation in observed fire behaviour in spinifex fuels.
- 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 hummock 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 or found in hummock grasslands throughout WA. For example, an obvious range/variable omission is the influence of slope and slope-wind interactions, which are likely to be important in parks such as Karijini. 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 operational 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 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. While we measured this, we were unable to identify or isolate its contribution to fire behaviour, thus were unable to incorporate it into the models.

- These models do not take account of spotting. Except in the presence of mallees, other eucalypts or other myrtaceous scrub, we observed short distance spotting (up to 200 m) and spot fires were usually quickly overrun by the main headfire.

3. Predicting Fire Behaviour

3.1 Step 1: Predicting whether fire will spread.

The first step in predicting fire behaviour is to determine the probability that, following ignition, fire will actually spread for a given set of conditions. Hummock grasslands form a simplex, discontinuous or patchy fuel, unlike forest fuels, which are generally complex and continuous. Fuel moisture content is the main factor limiting sustained fire spread in continuous fuels. 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 or fuel patch.

Factors that determine fire energy and flame size, therefore the capacity for sustained spread, include wind speed (and slope), fuel quantity and fuel moisture content. Fuel structural characteristics such as cover/patchiness and height will also affect spread potential. There may be other fuel and weather factors involved, but these were either not recognised, not measured or had such a minor effect in the field experiments that they did not meet statistical criteria for model entry.

Of the variables measured, wind speed, fuel quantity and fuel moisture content were found to be the most important variables influencing the initiation of fire spread. Fuel quantity is important in its own right, but is also a surrogate for cover and height. Using these factors, the probability of sustained fire spread was estimated by:

SI_{FQ} = 0.57(W) + 0.96(FQ) – 0.42(PMC) – 7.42……………….(Equation1)

OR;

SI_{FF} = 0.37(W) + 0.78(FF) – 0.31(PMC) – 5.23………………….(Equation 2)

Where:

SI_{FQ} = Spread Index using fuel quantity. A positive value means fire will probably spread.
SI_{FF} = Spread Index using fuel factor.
W = average wind speed (km h^{-1}) over a 5 minute period at 2 m above ground.
FQ = fuel quantity (spinifex and other fine ground cover) (oven dry weight in t ha^{-1}).
PMC = the profile moisture content of the spinifex hummock (% oven dry weight).
FF = fuel factor (see below).

FF = 0.25(CV) + 0.04(HT) - 3.2…………………………………(Equation 3)

Where:

FF = fuel factor (a surrogate for fuel quantity)
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……………………………………………(Equation 4)

FF is almost equal to FQ so can be substituted for FQ if fuel quantity cannot be measured in the field (see Figure 1).

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 sight (eg, soil type and termite activity) and seasons (rainfall), so fuel quantity is the preferred variable, hence Equation 1 the preferred equation.

3.1.2 Interpreting the 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	Likelihood of fire spread and potential ROS (m h^{-1})
SI < -2	Very low - fire highly unlikely to spread (ROS = 0)
-2 < SI < 0	Low – fire could spread (ROS < 500)
0 < SI < 2	Moderate – fire should spread (ROS: 500 –1,000)
2 < SI < 4	High – fire will spread (ROS: 1000 – 1,500)
4 < SI < 6	Very High – fire will spread (ROS: 1,500 – 2,000)
6 < SI < 10	Extreme – fire will spread (ROS: 2,000 – 3,000)
SI > 10	Very Extreme – fire will spread (ROS > 3,000)

3.2 Step 2: Predicting rate of spread, flame height and intensity.

Having determined whether or not a fire will spread (SI), the next step is to predict its behaviour (rate of spread, flame height and intensity). Once conditions are suitable for fire spread, then fire behaviour is largely a function of wind speed, fuel quantity and fuel moisture content, with wind speed being the most influential variable. 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. Basically, rate of spread in patchy fuels depends on flame size 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 means larger flames. Two (linear) prediction models are presented; 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. *Note: these models do not apply when conditions are below thresholds for fire spread, i.e., SI must be greater than 0.*

Forward Rate of Spread (ROS):

ROS_{FQ} = 154.9(W) + 140.6(FQ) – 228.0(PMC) + 1581…………………..Equation 4

OR;

ROS_{FF} = 142.8(W) + 120.1(FF) – 229.1(PMC) + 1969……………………Equation 5

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 ground cover) (oven dry weight in ha^{-1}).
PMC = the profile moisture content of the spinifex hummock (% oven dry weight).
FF = fuel factor (see above).

The relationship between actual rate of spread (of experimental fires) and that predicted using Equation 4 is shown in Figure 2 below. Examples of the relationship between predicted rate of spread and wind speed by fuel moisture content classes and controlling for fuel quantity (7.2 t ha^{-1}) are graphed in Figure 3 below.

Flame height (FH):

Flame height is probably of minor interest to hummock grassland fire managers but it is a crude indicator of fire intensity, hence suppression difficulty and damage potential. Flame length is a better indicator, but is difficult to measure reliably in the field.

FH = 0.0006(ROS) + 0.08(FQ) + 1.1……………………………………Equation 6

Where;

FH = flame height (m)
ROS = rate of spread (m h^{-1})
FQ = dry fuel quantity (t ha^{-1})

Fire intensity (I);

A generic equation can be used to calculate fire intensity. This assumes a calorific value (heat yield) of 18,600 kJ kg^{-1} for spinifex and is not corrected for fuel moisture content. While often fast spreading, the relatively low quantity of available fuel in hummock grasslands means that fire intensities are unlikely to exceed 50,000 kW m^{-1} and are more commonly in the range 4,000 – 10,000 kW m^{-1}.

I = ROS x FQ x 0.56……………………………………Equation 7.

Where;

I = fire intensity (kW m^{-1})
ROS = headfire rate of spread (m h^{-1})
FQ = fuel quantity consumed (t ha^{-1})

4. 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. Table 3 below contains a brief description of how these variables were measured.

Appended are photographs illustrating a) variation in profile moisture content of spinifex hummocks and b) some of the fuel types described in Table 4 below.

Table 3: Spinifex fire spread model inputs

Input variable	Units	Rules/tips for measurement
WIND SPEED (W)	Km h-1	• Measure mean wind speed at 2 m above ground and for at least 5 minutes. • Portable hand held sensitive cup-type anemometers are adequate, providing they are reasonably accurate and have a low threshold. • Spot forecasts from BoM are useful. While not highly accurate, they can be helpful for planning burns or forecasting wildfire behaviour. • Obtain historical wind speed and direction information to determine the best season (from a wind point of view) to burn. Ideal conditions are when diurnal wind speed patterns exist i.e., moderate winds during the day and calm at night. The best prescribed burning conditions in the Gibson Desert are likely to occur in September to November.
FUEL QUANTITY (FQ)	T ha^{-1}	• Spinifex is the dominant fuel • Stratify vegetation/fuels if more than one 'type' or age is apparent within the burn. Assess this either visually (on the ground), or from Landsat imagery. • For each type, remove all fine fuel from 20-30 randomly located $1m^2$ quadrats. This can be simply done with a rakeho. Bag the sample being careful not to contaminate it with sand. Some quadrats will fall on bare patches –they must be counted. Samples should then be oven-dried for 24 hours at 85^o C, and then weighed. Calculate mean fuel quantity. • An alternative is to estimate fuel quantity from cover (%) and height (cm). For each fuel/veg. type, run out at least 2 x 100 m line transects. One hundred meter tapes are best for this. Move along the tape measuring the continuous distance of bare ground, spinifex or other vegetation in the surface fuels. Using a height stick, measure the height of each spinifex clump intersected by the tape. Calculate the mean cover of spinifex (%) and the mean height (cm). Use this to calculate the fuel factor (Equation 3), hence fuel quantity.
FUEL PROFILE MOISTURE CONTENT (PMC)	% moisture of oven dry weight	• This is the moisture content of the entire above ground portion of the spinifex clump and includes live and dead material. Profile moisture content ranges from about 12% (very dry) - 32%+ (green), but will vary depending on the proportion of dead material in the clump. It is common for dead material to dry down to 3-4% under hot, dry desert conditions where the RH is commonly <25%. • For each fuel/veg. type, take a profile sample from at least 10 'typical' spinifex clumps. The sample size should be enough to fit into the crown of a hat or cap. Samples must be immediately sealed in an air-tight container. Moisture content is determined by weighing before and after drying in an oven at 85^o C for 24 hours. Avoid contamination. • An alternative is to use one of a variety of electronic moisture content meters. These may or may not be suitable and will require calibration for spinifex fuels. Consult CALMfire. • A rough guide is to use the colour charts shown in

		Appendix 2.
FUEL FACTOR (FF)	No units	• A surrogate for fuel quantity and calculated from cover and height. See Equation 3.
FUEL COVER (CV)	%	• This is the projected ground cover, primarily of spinifex, but also other ground covers likely to be involved as fuel during a fire. See Table 3. • For each fuel/veg. type, run out at least 2 x 100 m line transects. One hundred meter tapes are best for this. Move along the tape measuring the continuous length of bare ground, spinifex or other vegetation beneath the tape. Tally up these distances and express as a % of total distance.
FUEL HEIGHT (FH)	cm	• Using a height stick, measure the height (cm) of each spinifex clump intersected by the (above) tape. Use mean height (cm) to calculate the fuel factor (Equation 3), hence fuel quantity.

Table 4: Characteristics of some mature (> 20 years since last fire) spinifex fuels in typical habitats found in the Gibson Desert (GD) and Great Sandy Desert (GSD).

Fuel variable	**Plateau (GSD)**	**Ravine (GSD)**	**Scree slope (GSD)**	**Sand plain/ valley (GSD)**	**Creek/ valley floor (GSD)**	**Sand plain/ dune-field (GD)**	**Light buck-shot plain (GD)**	**Heavy buck-shot plain (GD)**	**Ironstone and quartz over loamy sands (GD)**
Spinifex cover (%)	21	65	31	43	42	43	39	37	15
Spinifex clump ht (cm)	24	37	23	28	29	28	26	19	25
Spinifex clump length (m)	0.6	1.3	0.5	0.7	0.9	0.7	0.6	0.5	0.6
Bare patch length (m)	2.2	0.8	1.1	0.9	1.5	1.0	1.1	1.2	6.8
Dry fuel quantity (t ha^{-1})	2.4	12.1	4.2	7.9	7.2	9.8	5.6	5.3	2.8
Bare patch ratio	2.3	0.7	0.6	0.7	1.4	1.5	1.1	1.25	14.9
Spinifex patch ratio	0.2	1.1	0.2	0.3	0.4	0.4	0.4	0.6	0.3
Spinifex clump bulk density (kg m^3)	-	-	-	15.6	17.8	18.5	16.1	16.4	17.8

5. A Guide to Patch-burning Hummock Grasslands Using Aircraft

Aerial ignition is well suited to patch-burning large, remote and poorly accessible desert reserves. As described above, the management objective in most cases is to restrict the size and intensity of wildfires and to re-introduce an interlocking mosaic of vegetation of different post-fire successional states, ranging from recently burnt patches to long unburnt patches.

We cannot be definitive about the ideal size of burnt patches and the temporal and spatial variability of the mosaic. However, information gleaned from early black and white aerial photographs of a remote desert area known to have been influenced by traditional Aboriginal (Pintubi) burning practices at the time of the photography provides a useful starting point (Burrows and Christensen 1991 and Burrows and Van Didden 1991). This is summarised in Table 5.

Table 5: Summary of the size and number of burnt patches clearly visible on early (1953) aerial photography of a 54,000 ha area of the Great Sandy Desert known to have been influenced by traditional Pintubi Aboriginal burning practices at the time of the photography.

Number of recently burnt patches	Mean size of burnt patch (ha)	Median size of burnt patch (ha)	Maximum size of burnt patch (ha)	Total area recently burnt (< 4yrs) (ha)	Total burnt perimeter (km)
372	34	6	1,744	12,23.4 (23.4%)	1,198

As a first approximation, the data in Table 5 should be used to guide patch-burning in hummock grasslands. The prescription in Table 6 below is a guide to conditions that are likely to result in a patchy burn using aerial ignition techniques. Wind speed is the most influential variable, but is the most difficult to forecast. Ideally, the wind speed conditions described in Table 6 should persist for 2-3 hours after ignition, then subside to speeds below the threshold for spread so that fires self extinguish (i.e., SI < 0). Where fuels are heavy and more-or-less continuous, rather than patchy, fire may continue to spread even when wind speed drops.

Table 6: A preliminary prescription guide for achieving a patch-burn mosaic in mature spinifex fuels (30-40% cover) using aerial ignition. Fire size and patchiness relies on wind speed dropping to below spread thresholds (~< 10 km/hr) about 2-3 hours after ignition. Best times for diurnal wind patters that suit this prescription is August-September, when daylight winds are often above threshold, but evenings are often calm (not always). Note: the Temp and RH range is not as critical as the wind speed and profile fuel moisture content, which can be determined by working backwards from the SI and wind inputs for a given cover value (see Equations above).

Mean burn patch size (ha)	Total area burnt (%)	Wind speed (km h^{-1})	Temp. (^{o}C)	Rel. Hum. (%)	Spread Index (SI)	Rate of spread (m h^{-1})	Ignition pattern (m)
2-10	15-20	12-15	20-25	25-35	1-2	500-1,000	300m x 1,000m
10-50	20-35	15-20	25-30	10-25	2-4	1,000-1,500	200m x 1,000m

Landsat MSS/TM imagery is useful for both planning flight lines and for mapping and monitoring fire histories.

References

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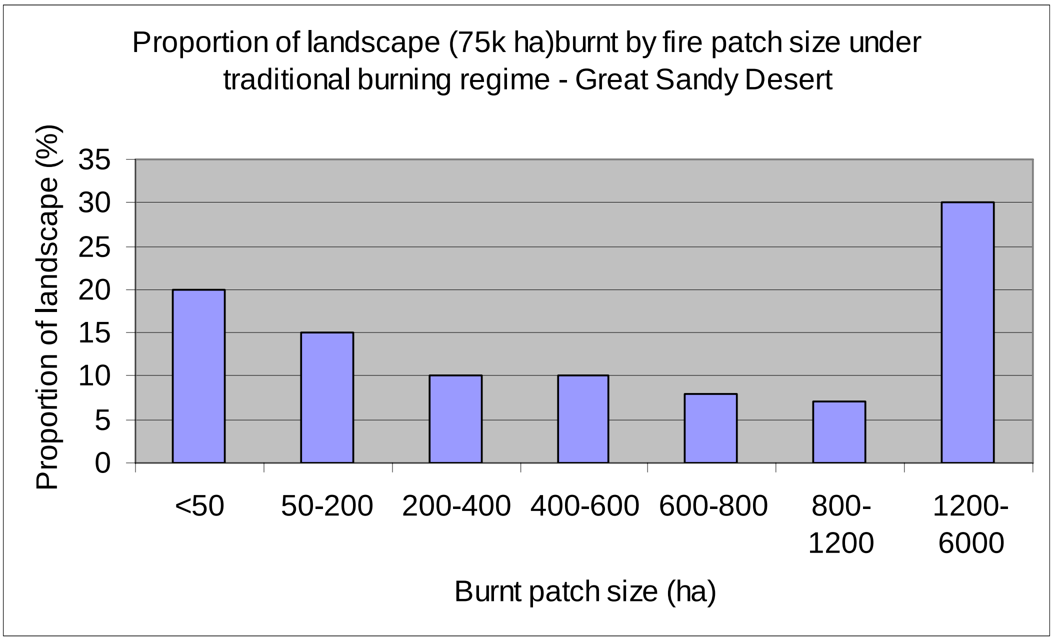
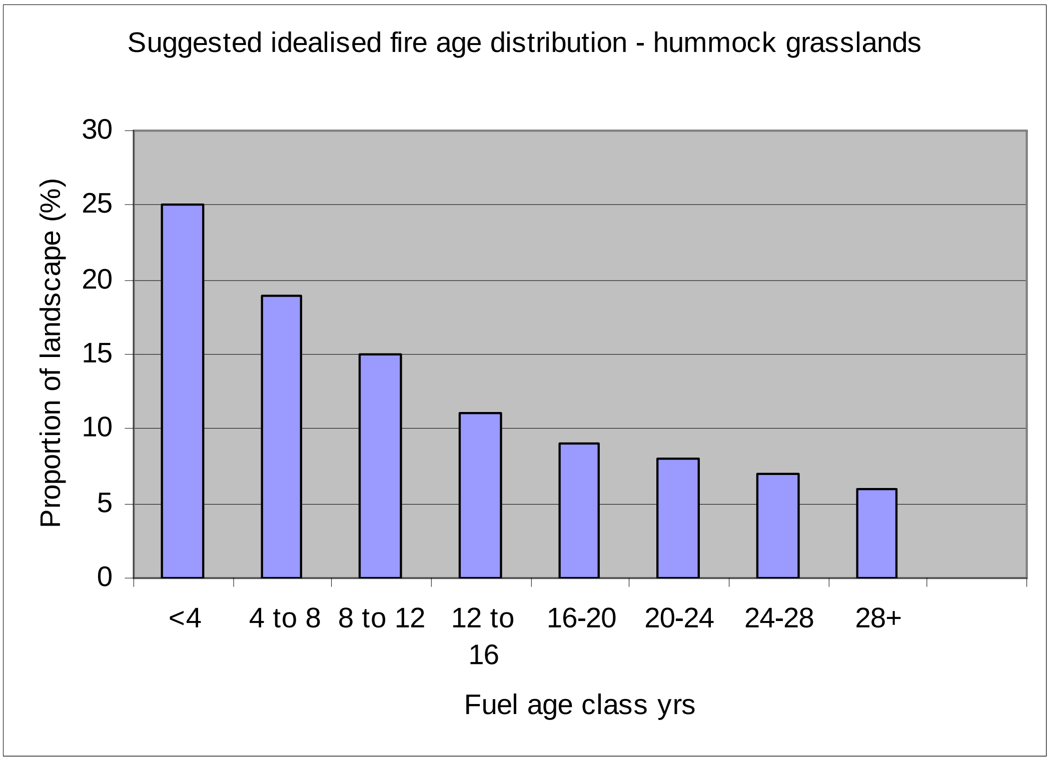

Proportion of landscape (75k ha)burnt by fire patch size under traditional burning regime - Great Sandy Desert
Proportion of landscape (%)
35
30
25
20
15
10
5
0
<50
50-200
200-400
400-600
600-800
800-1200
1200-6000
Burnt patch size (ha)


Suggested idealised fire age distribution - hummock grasslands
Proportion of landscape (%)
30
25
20
15
10
5
0
<4
4 to 8
8 to 12
12 to 16
16-20
20-24
24-28
28+
Fuel age class yrs

Appendix 1: Profile moisture content (PMC) ranges in spinifex fuels (rough guide only)

PMC = 20-30%

PMC = 15-20%

PMC - 10-15%

Appendix 2: Some common fuel types in hummock grasslands

Heavy buckshot plains

Light buckshot plains

Buckshot plain

Sand plain

Sand plain

Sand plain and sand dune