Buttongrass moorland fire-behaviour prediction and management

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Abstract

This paper summarises the outcomes of the buttongrass moorland fire behaviour and management research conducted over the past decade in Tasmania by the Parks and Wildlife Service, Forestry Tasmania, the University of Tasmania, the Tasmania Fire Service and the Bureau of Meteorology. The major influences on buttongrass fuel characteristics are time since the last fire and site productivity. The major influences on buttongrass moorland fire behaviour are wind speed, time since the last fire, dead-fuel moisture content and site productivity. This paper presents prediction tables and equations for estimating buttongrass moorland fuel characteristics, rates of fire spread, flame heights and fire danger ratings. These predictions are also discussed in the context of operational fire management, prescriptions for conducting prescribed burning and options for wildfire control.

Introduction

The purpose of this paper is to summarise the major outcomes of the buttongrass moorland fire behaviour and management research performed in Tasmania by the Parks and Wildlife Service, the University of Tasmania, Forestry Tasmania, the Tasmania Fire Service and the Bureau of Meteorology over the past decade. The paper is an operational fire-management guide for buttongrass moorlands in north-western, western and south-western Tasmania and supersedes the previous guides published in 1993 and 1996. A shortened version designed for field use is included in Appendix 1, and the equations used in this guide are in Appendix 2.

In the 1980s, there was a series of buttongrass moorland fires which exhibited markedly different behaviour from that predicted by the fire-behaviour prediction systems available at that time. These fires included hazard-reduction burns, habitat-management burns and wildfires. In total, they burnt more than 77 000 ha. At the time, the main fire-behaviour prediction tools utilised in Tasmania were the McArthur Forest Fire Danger Meter (McArthur 1973) and the *Guidelines for Prescribed Burning* (Forestry Commission 1977; Gellie 1980). As a result of these failings, a decision was made in the early 1990s to research buttongrass moorland fuel and fire dynamics. The aim of the research was initially to test a range of pre-existing fire-behaviour prediction systems which had been developed elsewhere in the world. They included the Rothermel fire-behaviour model (Rothermel 1972), gorse and

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Photo 1. Buttongrass moorland near Melaleuca in south-western Tasmania.

heather fire-behaviour models (Thomas 1963, 1970, 1971) and McArthur grassland fire danger meters (McArthur 1966, 1977). Since none of these fire-behaviour models provided adequate predictions of fire behaviour, a fire-behaviour prediction system specific to buttongrass moorland was developed. The outcomes are presented in this paper.

The buttongrass moorland fire-behaviour prediction system predicts fuel characteristics, dead-fuel moistures, spread rates and flame heights of head-fires, flank-fires and back-fires, fire danger ratings, options for fire control at different levels of fire behaviour and prescriptions for performing prescribed burning. Detailed descriptions of different aspects of the buttongrass moorland fuel characteristics and fire-behaviour modelling have been published in a series of technical reports and scientific papers. These publications detail how the research was performed, the sites utilised, the data collected and the prediction equations developed. Thus, an account of fuel characteristics is given in Marsden-Smedley (1993) and Marsden-Smedley and Catchpole (1995a), fuel moisture is discussed in Marsden-Smedley *et al.* (1998) and Marsden-Smedley and Catchpole (in press), fire rate-of-spread and intensity is dealt with in Marsden-Smedley (1993) and Marsden-Smedley and Catchpole (1995b), and fire extinguishment is treated in Marsden-Smedley *et al.* (1998) and Marsden-Smedley *et al.* (in press).

The vegetation: buttongrass moorland

Buttongrass (*Gymnoschoenus sphaerocephalus*) is a component of wet heathlands, swamps, sedgelands and moorlands in south-eastern Australia. In Tasmania, vegetation dominated by this species is normally referred to as buttongrass moorland. Jarman *et al.* (1988) defined buttongrass moorland to be:

(a) Any treeless or near treeless vegetation containing buttongrass (*Gymnoschoenus sphaerocephalus*), except communities where only a few isolated obviously adventive buttongrass plants are present;

(b) Vegetation in which buttongrass is common but which contains widely spaced emergent trees;

(c) Small recurring islands (mostly less than 50 m x 50 m) of non-alpine treeless vegetation which do not contain buttongrass but which are surrounded by communities of the type described in (a) or (b) above. Small strips of similar vegetation (about 20–30 m wide) along creeks or in gullies are also included as buttongrass vegetation providing that communities of type (a) or (b) border them on either side.

Other major plant species in Tasmanian buttongrass moorlands are *Lepidosperma filiforme*, *Empodisma minus*, *Leptocarpus tenax*, *Lepyrodia tasmanica*, *Restio complanatus*, *Restio hookeri*, *Sprengelia incarnata* (sprengelia), *Leptospermum nitidum (*shiny tea-tree), *L. scoparium (*manuka), *Melaleuca squamea (*swamp paper-bark), *M. squarrosa (*scented paper-bark), *Agastachys odorata (*white waratah) and *Banksia marginata (*banksia, also known as honey-suckle).

In north-western, western and south-western Tasmania, buttongrass moorlands (Photo 1) are the most extensive vegetation type present, occurring from sea level up to about 600 m in the far south-west and up to about 1100 m near Cradle Mountain. They occur on a wide range of substrates, but their greatest extent is on low fertility substrates such as quartzite, conglomerate, granite and/or gravels derived from these geological types (Jarman *et al.* 1988; Pemberton 1989). In total, buttongrass moorlands cover more than one seventh of Tasmania's land area, or about 1.1 million hectares.

Aims of buttongrass moorland fire management

Operational fire management in buttongrass moorlands can be divided into three main categories: hazard-reduction burning, ecosystem-management burning and wildfire control (Photo 2A, 2B).

The aim of hazard-reduction burning is to broaden the weather conditions within which effective fire suppression can be performed and/or within which fires will not be sustained. If the management objective for a given area is to maintain the area in a permanent state of low fire hazard, then an implicit assumption is that wildfire control is the most important factor being managed for and ecological considerations are of secondary importance. Hazard-reduction burning acts to change the fuel characteristics present at a site so that the ratio of dead to live fuel, bulk density, fuel continuity, fuel height and the total fuel load are all reduced. The normal aim of hazard-reduction burning is to reduce 70% of the fuels over 70% of the area of the site being burnt (Forestry Tasmania *et al.* 1998).

The aim of ecosystem-management burning is to maintain species and/or community diversity and can be performed for either broad-scale community values or for single-species management (e.g. to maintain suitable habitat for orange-bellied parrots).

The aim of wildfire control is to minimise adverse impacts to assets such as human lives, buildings, commercial forests and/or fire-sensitive vegetation.

Predicting buttongrass moorland fuel characteristics

The major influences on buttongrass moorland fuel characteristics are the site age and site productivity (Marsden-Smedley and Catchpole 1995a).

Determining site age in buttongrass moorlands

In Tasmanian buttongrass moorlands, there tends to be a pulse of regeneration following fire, resulting in the above-ground parts of the vegetation being even-aged. Therefore, the age of most sites can be quickly determined from fire records (e.g. fire management plans) or, in the field, from counting banksia nodes (Brown and Podger 1982) and/or annual growth rings of tea-trees.

Photo 2. Buttongrass moorland fires. (A, Research burn at McPartlan Pass, November 1992; B, hazard-reduction burn near the Lyell Highway, September 1992.)

When estimating site age in the field, banksia node counts are the quickest, simplest, most reliable and least destructive method of determining site age and so should be used whenever possible. Banksia nodes are the swellings at branch junctions. In most seasons, each branch will form one new junction (Photo 3), so it is possible to estimate the individual's age by counting the number of branch junctions. Care must be taken to ensure that all the nodes on the plant's trunk have been counted, since these are often hard to differentiate. The situation where the banksia nodes on the lower trunk are hard to count typically only occurs in older individuals (e.g. greater than 20 years of age) and is therefore of only minor importance since an adequate estimate of site age for fire-management purposes in these sites is 20 years.

Where it is not possible to age a site from banksias, then counts of growth rings should be made from tea-trees (i.e. *Leptospermum* spp.). Tea-trees occur in most moorland sites and have reliable, easily counted rings. Paper-bark species (i.e. *Melaleuca* spp.) should not be used because of their poor ring structure.

Ring counts should be made by taking cross-sections from just above the ground surface, drying the stem, polishing it with up to 1200-grade sandpaper and counting the growth rings (Photo 4) using a dissecting microscope. In some older sites (e.g. greater than 20 years of age), poor ring differentiation can result in problems when counting tea-tree rings. In common with the situation with banksia nodes, an adequate estimate of site age for fire management purposes is 20 years.

Where node or ring counts are made, a minimum of six individuals should be sampled at each site. At most sites, the age will be equal to the modal count plus one. For example, if the following node and/or ring counts were made at a site: 12, 11, 12, 31, 10, 12, 5, 12, and 6, then the most common count is 12 and it would be assumed that the site was last burnt 13 years ago.

If the fire history of a site is unknown and it is not possible to sample for node and/or ring counts, then for the purposes of predicting fire behaviour the assumption should be made that the site is 20 years of age.

Site productivity in buttongrass moorlands

In western, north-western and south-western Tasmania, site productivity is based on the geological type. The reason for the restriction to these regions is that buttongrass moorlands in eastern and north-eastern Tasmania tend to have significantly higher fuel accumulation rates, resulting in this guide under-predicting fuel loads. Sites underlain by quartzite, conglomerate, granite, and/or gravel derived from these geological types are classified as low productivity. These low productivity

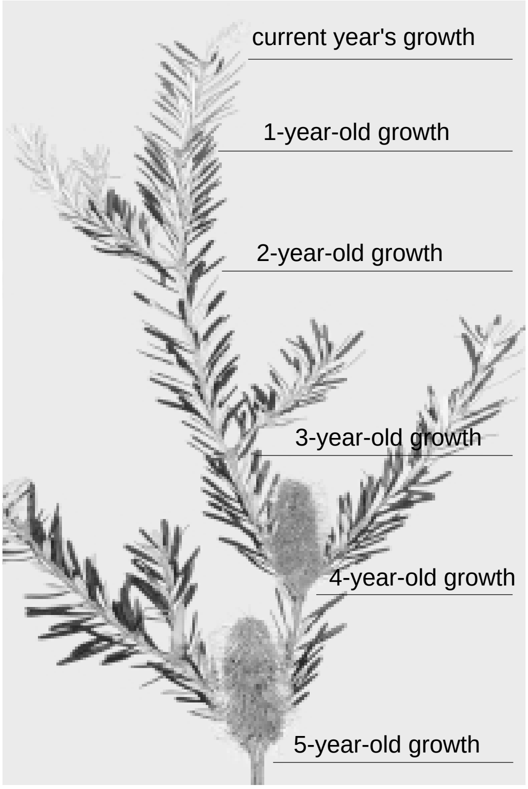

Photo 3. Banksia stem showing the last five year's growth.

Photo 4. Leptospermum scoparium *stem from the Dempster Plains, showing annual growth rings. (Age = 25 years)*

Table 1. Prediction of the total fuel load and the dead-fuel load in buttongrass moorlands.

	low productivity		medium productivity	
Age (years)	total load (t/ha)	dead load (t/ha)	total load (t/ha)	dead load (t/ha)
3	3.2	0.3	5.2	0.7
5	4.8	0.7	8.3	1.9
10	7.7	2.0	15.0	5.9
20	10.3	4.6	25.0	15.7
40	11.6	7.7	36.0	30.2

sites comprise the majority of the area of buttongrass moorland in Tasmania. All other geological types in these regions are classified as medium productivity. Compared to low productivity moorlands, those of medium productivity tend to have higher fuel covers, fuel loads, dead-fuel loads and fuel continuities, and fewer bare patches in the fuel array. If the geological type is unknown, then it should be assumed that the moorland is of medium productivity.

Total fuel load and dead-fuel load in buttongrass moorlands

The total fuel load and the dead-fuel load are predicted from the site age (i.e. time since the last fire) and the site productivity (low or medium), as shown in Table 1.

Predicting buttongrass moorland fire behaviour

The major influence on fire behaviour is the wind speed, but dead-fuel moisture and fuel characteristics also have significant effects (Marsden-Smedley 1993; Marsden-Smedley and Catchpole 1995b, in press; Marsden-Smedley *et al.* 1998, in press). This means that if conditions are windy, buttongrass moorland fires can spread with high head-fire rates of spread, even in relatively recently burnt sites and/or with high fuel moistures. The major influences on buttongrass moorland fuel moisture are the rain and/or dewfall in the preceding 48 hours, along with the current temperature and relative humidity.

Within buttongrass moorlands, the soil dryness index (SDI) has only minor influences on buttongrass moorland fuel moisture and, as a result, only very minor influences on fire behaviour. However, the SDI has major influences on the flammability of other vegetation types such as wet scrub, wet eucalypt forest and rainforest. Therefore, the SDI has a major influence on the difficulties associated with wildfire suppression and the suitability of different conditions for prescribed burning. The issue of interactions between the SDI and the potential of different vegetation types to burn is discussed further below.

The fire behaviour factors predicted are the fuel moisture, spread rates and flame heights of head-fires, flank-fires and back-fires, as well as a Moorland Fire Danger Rating. The Moorland Fire Danger Rating is a dimensionless index which indicates the degree of fire suppression difficulty. It ranges from 0 (fires will not be sustained), through 1 to 5 (low fire danger), 6 to 12 (moderate fire danger), 13 to 24 (high fire danger), 25 to 50 (very high fire danger), up to 51 to 100 (extreme fire danger), as shown in Table 9.

Measuring weather parameters for predicting fire behaviour

The weather parameters used for predicting buttongrass moorland fire behaviour are the current wind speed, temperature and relative humidity, along with any rainfall in the previous 48 hours.

When measuring wind speed for predicting buttongrass moorland fire behaviour, the wind-speed sensor should be held at between 1.7 m and 2 m above the ground surface. In Bureau of Meteorology forecasts, the predicted wind speed is assumed to be the wind speed that would occur at 10 m above the ground surface. Therefore, if information on wind speed is being obtained from Bureau of Meteorology forecasts, then the wind speed will need to be corrected from the speed at 10 m height to the speed at 1.7 m by reducing it by one third (e.g. a 15 km/hr 10-metre wind speed equals a 10 km/hr 1.7-metre wind speed). The temperature and relative humidity should be measured in an area shaded from direct sunlight but exposed to the prevailing wind (e.g. under an isolated tree or in a Stephenson screen). Rainfall in the preceding 48 hours should be measured in the open using a graduated rain gauge. Both the wind speed and the rainfall should be measured in sites where the distance from the measurement site to the nearest up-wind obstacles (e.g. trees) is at least ten times the height of these up-wind obstacles and at least three times the height of any down-wind obstacles. This means that if the wind speed and/or rainfall is being measured in a clearing surrounded by ten-metre tall trees, then they must be measured at least 100 m from any trees in the up-wind direction and 30 m from any trees in the down-wind direction.

Predicting fuel moisture

The dead-fuel moisture is the amount of water in the dead fuel as a percentage of the oven-dry weight. It is predicted by adding together the Rainfall and Humidity Factors using Table 2. The Rainfall Factor is calculated in Table 2a using the time since the last precipitation (i.e. rainfall and/or dewfall) event and the amount of precipitation that fell in that event. Precipitation readings should be made at 09:00 hours daily. In addition, if rain falls in the six hours between 09:00 and 15:00 hours, then this precipitation should be recorded as soon as practical after the rain stops falling. If no precipitation has fallen in the last 48 hours, the Rainfall Factor is assumed to be zero and is ignored. If more than 1 mm of precipitation fell in the last event, then the dead fuels are assumed to be saturated, and all of the precipitation in excess of 1 mm is ignored. Alternatively, if the amount of precipitation is being predicted by the Bureau of Meteorology Fire Weather Forecast, then the 24-hour rainfall is assumed to have stopped falling at 09:00 hours, and the time since 09:00 hours can be used to estimate the hours since last rain. If the Fire Weather Forecast predicts rainfall in the six-hour period, then the hours since the rain stopped are assumed to be zero. The Humidity Factor is calculated using current temperature and relative humidity in Table 2b.

Table 2. Predicting the Rainfall and Humidity Factors.

(a) Rainfall Factor

Hours since rain stopped	Rain and/or dewfall (mm) 0.05	0.1	0.2	0.5	1+
0	10	18	31	53	64
3	8	14	24	41	50
6	6	11	19	32	38
9	4	8	14	25	30
12	3	6	11	19	23
24	1	2	4	7	8
48	0	0	1	1	1

(b) Humidity Factor

Temp (°C)	Relative humidity (%) 20	40	60	80	100
8	12	14	19	25	35
12	11	13	17	23	32
15	10	12	15	21	29
18	9	11	14	19	27
25	8	9	12	16	22
30	7	8	10	14	19
35	6	7	9	12	16

Note: the dead-fuel moisture is the amount of water in the fuel as a percentage of the oven-dry weight and is calculated by adding together the Rainfall Factor (Table 2a) and the Humidity Factor (Table 2b).

Predicting fire-spread rates, flame heights and Moorland Fire Danger Rating

The rate of head-fire spread is predicted using Table 3 using the dead-fuel moisture (addition of the outputs from Tables 2a and 2b), the wind speed at 1.7 m and the site age. The Moorland Fire Danger Rating is predicted from the head-fire spread rate, using Table 4, and the flame height is predicted from the head-fire spread rate, site productivity and site age using Table 5.

Table 3. Buttongrass moorland head-fire spread rate (m/min) predictions.

Dead-fuel moisture (% dry weight)	Wind speed (km/hr)					
	1	5	10	20	40	60
Age = 5 years						
>100	fires probably will not be sustained					
100	0.0	0.0	0.0	1.3	3.3	5.7
80	0.0	0.0	0.9	2.2	5.4	9.2
60	0.0	0.6	1.4	3.5	8.8	14.9
30	0.1	1.2	3.0	7.3	18.2	31.0
20	0.2	1.5	3.8	9.3	23.2	39.5
15	0.2	1.7	4.3	10.6	26.2	44.6
10	0.2	1.9	4.8	11.9	29.6	50.4
5	0.3	2.2	5.4	13.5	33.4	56.9
Age = 10 years						
>100	fires probably will not be sustained					
100	0.0	0.0	0.0	2.1	5.2	8.9
80	0.0	0.0	1.4	3.4	8.5	14.4
60	0.1	0.9	2.2	5.5	13.7	23.3
30	0.2	1.9	4.6	11.4	28.4	48.3
20	0.3	2.4	5.9	14.6	36.2	61.6
15	0.3	2.7	6.6	16.5	40.9	69.6
10	0.4	3.0	7.5	18.6	46.2	78.6
5	0.4	3.4	8.5	21.0	52.1	88.7
Age = 20+ years						
>100	fires probably will not be sustained					
100	0.0	0.0	0.0	2.8	6.8	11.6
80	0.0	0.0	1.8	4.5	11.1	18.9
60	0.1	1.2	2.9	7.2	18.0	30.6
30	0.3	2.4	6.0	15.0	37.3	63.5
20	0.4	3.1	7.7	19.2	47.5	80.9
15	0.4	3.5	8.7	21.6	53.7	91.4
10	0.5	4.0	9.8	24.4	60.6	103.2
5	0.5	4.5	11.1	27.6	68.5	116.5

Note: the dead-fuel moisture is predicted by adding together the outputs of Table 2a and 2b.

Table 4. Moorland Fire Danger Rating predicted from the head-fire spread rate.

Head-fire spread rate (m/min)	Moorland Fire Danger Rating (dimensionless)
0	0
5	low – 3
7.5	low – 5
10	moderate – 7
15	moderate – 10
17	moderate – 12
20	high – 14
30	high – 20
34	high – 24
50	very high – 35
70	very high – 50
140	extreme – 100

Flank- and back-fire predictions

Flank-fires normally have about 40% of the fire spread rate and about 60% of flame height that would be expected on head-fires. Back-fires normally have about 10% of the fire spread rate and about 50% of flame height that would be expected on head-fires. However, in many situations, if the head-fire spread rate is below about 0.5 m/min, flank- and/or back-fires will not be sustained unless the dead-fuel moistures are low (e.g. below about 10–15 %) and/or the site is old (e.g. more than about 20 years since the last fire).

The fire spread rates and flame heights of flank- and back-fires are predicted from the fire spread rates and flame heights that would be expected on head-fires using Table 6.

Buttongrass moorland prescribed burning

The principles for performing prescribed burning are detailed in the *Fuel Reduction Burning Course Notes* (see Forestry Tasmania *et al.* 1998). These notes detail the aims, types and standards of prescribed burning, planning issues, safety concerns, resources required, use of test fires and the methodologies utilised for fire ignition.

Burning prescriptions

The choice of prescriptions for prescribed burning in buttongrass moorlands depends on two main factors: the objective of the burn (hazard-reduction and/or ecosystem-management burning) and whether or not secure boundaries are available to control the fire. Secure boundaries include vegetation which is too wet to burn, roads, rivers and/or

Table 5. Buttongrass moorland head-fire flame height predictions.

Head-fire spread rate (m/min)	Age = 5 years Productivity class		Age = 10 years Productivity class		Age = 20+ years Productivity class	
	low	medium	low	medium	low	medium
0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	1.6	2.0	1.9	2.5	2.2	3.1
5	2.1	2.6	2.6	3.4	2.9	4.1
10	2.8	3.5	3.4	4.5	3.8	5.5
20	3.7	4.6	4.5	5.9	5.1	7.2
40	4.9	6.1	5.9	7.8	6.7	9.6

Table 6. Flank- and back-fire rates of fire spread (m/min) and flame heights (m), predicted from head-fire rates of fire spread and flame height.

Rate of fire spread (m/min)			Flame height (m)		
Head-fire	Flank-fire	Back-fire	Head-fire	Flank-fire	Back-fire
0.5	0.2	< 0.1	0.5	0.3	0.3
1.0	0.4	0.1	1.0	0.6	0.5
5.0	2.0	0.5	2.0	1.2	1.0
10.0	4.0	1.0	3.0	1.8	1.5
20.0	8.0	2.0	5.0	3.0	2.5
40.0	16.0	4.0	7.5	4.5	3.8
60.0	24.0	6.0	10.0	6.0	5.0

the coast. Where secure boundaries are not available and therefore the risk of fires escaping is much higher, burning must be conducted under a more restrictive range of conditions than is the case when secure boundaries are available. The burning technique which does not rely on secure boundaries is normally referred to as unbounded patch burning.

Since hazard-reduction burning is undertaken to reduce the risk to fire-sensitive assets, these burns aim to substantially remove the majority of the fuel array. With ecosystem-management burning, where the aim is to regenerate the community and/or promote suitable habitat for selected species, burning may be conducted over a broader range of conditions. The prescriptions for performing prescribed burning using secure boundaries are shown in Table 7 and those for performing unbounded patch burning are shown in Table 8.

The prescriptions in Tables 7 and 8 also indicate the optimum conditions for burning, along with the maximum and minimum conditions. It should be noted that if a burn is performed with some or all of the parameters at the maximum allowable level in Table 7 (i.e. the strongest wind speed, highest temperature, lowest relative humidity and longest time since fire), the resulting fire behaviour will almost certainly be outside the acceptable limits indicated in Table 7. Conversely, if all of the parameters are at the minimum allowable level in Table 7, the resulting burn may not sustain itself or, if it can be sustained, it may fail to adequately burn the site and hence be ineffective for hazard-reduction purposes.

However, conducting burning at or near the minimum allowable conditions in Table 7 may be acceptable during unbounded patch burning. Such a burning strategy may be employed if a site has poor boundaries and/

Table 7. Burning prescriptions for hazard-reduction and ecosystem-management burning in buttongrass moorlands with secure boundaries.

	Hazard-reduction burning			Ecosystem-management burning		
Season						
Autumn	April – early May			April – June		
Spring	September – early October			August – early October		
	Optimum	Min	Max	Optimum	Min	Max
Fire frequency (yrs)						
Low productivity sites	7–10	5	15	variable, dependent on the species and/or community type being managed		
Medium productivity sites	5–8	5	10			
Weather conditions						
Days since rain	2	1	-	2	1	-
Temperature (°C)	14–16	10	20	8–16	5	20
Relative humidity (%)	50–60	45	75	50–75	45	95
1.7 m wind speed (km/hr)	6	3	10	4–6	0	10
Soil dryness index (mm)	5	0	10	5	0	10
Acceptable fire behaviour						
Rate of fire spread (m/min)		≤ 8			≤ 8	
Flame height (m)		≤ 5			≤ 5	
Moorland Fire Danger Rating (dimensionless)		≤ 5			≤ 5	

Table 8. Burning prescriptions for unbounded patch burning in low productivity buttongrass moorlands.

Season	April – mid September	
Synoptic situation and outlook	High pressure cell centred over Tasmania, with low wind speeds for the next 48 hours and, if possible, fog	
Days since rain	2 or 3 (must be less than 5)	
Minimum amount of rain in last fall (mm)	5	
Soil dryness index (mm)	< 5	
	During the day	Forecast overnight conditions
Temperature (°C)	10–16	< 10
Relative humidity (%)	45–80	> 60
Wind speed (km/hr)	< 10	< 5
Dewfall (mm)	-	≥ 0.1

or the aim is to burn only part of the site. Unbounded patch burning should only be attempted in low productivity moorlands. In these moorlands, the fuel array is normally relatively open and sparse. As a result, fuel moistures rapidly increase overnight due to decreases in temperature, increases in relative humidity and dewfall. This rapid wetting-up of the fuel array in association with fuel discontinuities results in fires self-extinguishing over a relatively broad range of conditions. In medium productivity

Table 9. Moorland Fire Danger Rating and the options for fire control. (MFDR = Buttongrass Moorland Fire Danger Rating; ROS = rate of head-fire spread (m/min); F_H = head-fire flame height (m))

MFDR	ROS	F_H	Fire characteristics
1–3 low	0–4.5	0–4.5	• Suitable fire behaviour for hazard-reduction and ecosystem-management burns. • Hand tools (knapsacks and beaters) effective on head-, flank- and back-fires. • 2 m wide control lines should hold if supported by hand tools.
4–5 low	4.5–8	2–6	• Suitable fire behaviour for hazard-reduction and ecosystem-management burns. • Hand tools (knapsacks and beaters) effective on flank- and back-fires. • 5 m wide control lines should hold if supported by hand tools. • Short distance (up to about 5 m) spotting expected.
6–12 moderate	8–17	2–9	• Fire hard to control. • Fire behaviour too intense for prescribed burning. • Control lines 10–25 m wide supported by pumps required to control head-fires; control lines 5 m wide supported by pumps required to hold flank- and back-fires. • Spot fires > 30 m ahead of the head-fire expected.
13–24 high	18–34	3–12	• Head-fire control very difficult, with 25–50 m wide fire-breaks required. • 10 m wide control lines may hold flank- and back-fires if supported by pumps. • High risk of fire spotting across fire-breaks. • Personnel positioned down-wind and to the flanks of the fire should be made aware of the high risk of the fire jumping fire-breaks.
25–50 very high	35–70	4–16	• Direct attack on fire not possible. • > 100 m wide fire-breaks supported by pumps required to control head-fires, and > 10 m wide fire-breaks supported by pumps required to control flank- and back-fires; very high risk of fire spotting across fire-breaks. • Essential no personnel be positioned down-wind or to the flank of the fire unless they have safe fuel-free zones to retreat into.
51–100 extreme	> 70	> 8	• Fire control not possible until the level of fire behaviour is reduced. • Essential no personnel be positioned down-wind or to the flank of the fire.

moorlands, the typically highly continuous and dense nature of the fuel array results in much slower overnight wetting-up of the fuels and hence a much lower probability of fires self-extinguishing.

Of the different factors shown in Table 8 for unbounded patch burning, the most important are the season, synoptic situation and soil dryness index. Between April and mid September when there is a high pressure cell centred over Tasmania, the normal situation is that overnight wind speeds and temperatures tend to be low, relative humidities high and heavy falls of dew occur. Under these conditions, when the SDI is below five, the probability of fires being sustained overnight is very low.

Buttongrass moorland wildfire control

During wildfires, the level of fire behaviour is often much higher than that observed during prescribed burning and, if fires occur under dry conditions, natural boundaries often cannot be relied upon to stop them. The fire behaviour expected under different conditions can be predicted using Tables 2 to 6 and the options for fire control are shown in Table 9.

As can be seen in Table 9, the rate of fire spread and flame height are major factors influencing whether a fire suppression effort will have the potential to be successful. Other factors influencing the success of fire suppression include the terrain, remoteness and resources available. If the head-fire behaviour predicted by Tables 2 to 5 is too severe for fire suppression operations to be feasible and safe, then it may still be possible to attack the flank- and/or back-fire (see Table 5).

As discussed above, although the SDI has only very minor influences on buttongrass moorland fire behaviour, it can provide a good indication of the potential for wet scrub, wet eucalypt forest and rainforest to burn. If buttongrass moorlands are surrounded by wet scrub, wet eucalypt forest and/or rainforest which are dry enough to burn, then fires may dramatically increase in intensity when they burn into these vegetation types. A good indication of the likely result of a fire burning up to such vegetation boundaries can be obtained from the SDI. When the SDI is below about 10, fires are unlikely to burn vegetation other than buttongrass moorland; when it is between about 10 and 25, wet scrub may burn and cannot be relied on to stop fires; when it is between about 25 and 50, wet eucalypt forest will burn, and when it is above about 50, rainforest (and all other vegetation types) has the potential to burn. In addition, if wet scrub, wet eucalypt forest and/or rainforest are dry enough to burn, then there is a very high probability that peat fires will also occur. Such fires are very hard to extinguish and may smoulder underground for several months after the initial fire occurred. They may then act as ignition sources if high fire danger conditions subsequently occur.

Conclusion

This paper has summarised the major outcomes of the buttongrass moorland fire behaviour and management research conducted over the past decade and has reviewed buttongrass moorland fuel characteristics and fire behaviour. The paper replaces previously published guides and predicts buttongrass moorland fire behaviour over a wide range of conditions, the prescriptions for conducting prescribed burning and the options for wildfire control. As can be seen in the tables presented in this paper, buttongrass moorland fires will burn over a very wide range of conditions. If conditions are windy, fires may spread with high head-fire rates of spread even in relatively recently burnt sites and/or at high fuel moistures. The tables provide a reliable guide for predicting these variables and, in doing so, will allow for improved management of fires in buttongrass moorlands.

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References

Brown, M.J. and Podger, F.D. (1982). Floristics and fire regimes of a vegetation sequence from sedgeland-heath to rainforest at Bathurst Harbour, Tasmania. *Australian Journal of Botany* 30: 659–676.

Forestry Commission (1977). *Guidelines for Prescribed Burning*. Forestry Commission, Tasmania.

Forestry Tasmania, Parks and Wildlife Service and Tasmania Fire Service (1998). *Fuel Reduction Burning Course Notes*. Forestry Tasmania, Parks and Wildlife Service and Tasmania Fire Service, Hobart, Tasmania.

Gellie, N.J.H. (1980). *Fire Ecology of Buttongrass Moorlands*. Bulletin 6. Forestry Commission, Tasmania.

Jarman, S.J., Kantvilas, G. and Brown, M.J. (1988). *Buttongrass Moorland in Tasmania*. Research Report 2, Tasmanian Forest Research Council Inc., Hobart, Tasmania.

Marsden-Smedley, J.B. (1993). *Fuel Characteristics and Fire Behaviour in Tasmanian Buttongrass Moorlands*. Parks and Wildlife Service, Department of Environment and Land Management, Hobart, Tasmania.

Marsden-Smedley, J.B. and Catchpole, W.R. (1995a). Fire behaviour modelling in Tasmanian buttongrass moorlands. I. Fuel modelling. *International Journal of Wildland Fire* 5: 203–214.

Marsden-Smedley, J.B. and Catchpole, W.R. (1995b). Fire behaviour modelling in Tasmanian buttongrass moorlands. II. Fire behaviour. *International Journal of Wildland Fire* 5: 215–228.

Marsden-Smedley, J.B. and Catchpole, W.R. (in press). Fire behaviour modelling in Tasmanian buttongrass moorlands. III. Fuel moisture. *International Journal of Wildland Fire*.

Marsden-Smedley, J.B., Catchpole, W.R. and Pyrke, A. (in press). Fire behaviour modelling in Tasmanian buttongrass moorlands. IV. Fire extinguishment. *International Journal of Wildland Fire*.

Marsden-Smedley, J.B., Catchpole, W.R. and Pyrke, A. (1998). Unbounded burning in Tasmanian buttongrass moorlands. Unpublished report prepared for the Tasmanian Fire Research Fund. Parks and Wildlife Service, Forestry Tasmania and Tasmania Fire Service.

McArthur, A.G. (1966). *Weather and Grassland Fire Behaviour*. Leaflet 100. Department of National Development, Commonwealth of Australia, Forestry and Timber Research Bureau, Canberra.

McArthur, A.G. (1973). *Forest Fire Danger Meter, Mark 5*. Forest Research Institute, Forestry and Timber Bureau, Canberra, Australia.

McArthur, A.G. (1977). *Grassland Fire Danger Meter, Mark 5*. Country Fire Authority of Victoria, Melbourne.

Pemberton, M. (1989). *Land Systems of Tasmania Region 7—Southwest*. Department of Agriculture, Hobart, Tasmania.

Rothermel, R.C. (1972). *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*. USDA Forest Service Research Paper INT-115. Intermountain Forest and Range Experimental Station, Ogden, Utah, USA.

Thomas, P.H. (1963). The size of flames from natural fires. *Nineth Symposium on Combustion*. The Combustion Institute, Pittsburgh, PA, USA.

Thomas, P.H. (1970). The rates of spread of head-fires in gorse and heather. *Forest Research Note No. 796*. Joint Fire Research Organisation, Ministry of Technical and Fire Office’s Commission, England.

Thomas, P.H. (1971). Rates of spread of some wind-driven fires. *Forestry* 44: 155–175.

Appendix 1. A field guide for operational fire management in buttongrass moorlands in Tasmania.

Buttongrass moorland fire-behaviour prediction and management

1999

Parks and Wildlife Service
Tasmania

Forestry Tasmania
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Introduction

This guide is intended to be used for the operational fire management of buttongrass moorland fires in north-western, western and south-western Tasmania. It has been developed from fire-behaviour research performed in Tasmania by the Parks and Wildlife Service, Forestry Tasmania, University of Tasmania, Tasmania Fire Service and Bureau of Meteorology. The guides published in 1993 and 1996 are superseded by this guide. Additional information to that provided in this guide is available in the article: *Buttongrass moorland fire-behaviour prediction and management* published in *Tasforests* 11, pages 87–99 (1999).

The major influences on buttongrass moorland fire behaviour are the wind speed, time since the last fire, recent rain and/or dewfall, temperature, relative humidity and site productivity.

Buttongrass moorland

Buttongrass moorlands are a diverse range of low open sedge- and heath-dominated community types which cover very extensive areas in north-western, western and south-western Tasmania. The main plant species in buttongrass moorlands are buttongrass (*Gymnoschoenus sphaerocephalus*), *Lepidosperma filiforme*, *Empodisma minus*, *Leptocarpus tenax*, *Lepyrodia tasmanica*, *Restio complanatus*, *Restio hookeri*, sprengelia (*Sprengelia incarnata*), shiny tea-tree (*Leptospermum nitidum*), manuka (*Leptospermum scoparium*), swamp paper-bark (*Melaleuca squamea*), scented paper-bark (*Melaleuca squarrosa*), white waratah (*Agastachys odorata*) and banksia (*Banksia marginata*, also known as honey-suckle). In total, buttongrass moorlands cover more than 1.1 million hectares in Tasmania.

Aims of buttongrass moorland fire management

Fire-management operations in buttongrass moorlands aim to:

- Reduce the fire hazard and, in doing so, protect life, property and fire-sensitive assets;
- Maintain ecosystem values; and/or
- Suppress wildfires.

Hazard-reduction burning acts to change the fuel characteristics present at a site so that the ratio of dead to live fuel, bulk density, fuel continuity, fuel height and the total fuel load are all reduced. The normal aim of hazard-reduction burning is to reduce 70% of the fuels over 70% of the area of the site being burnt. *Ecosystem-management burning* aims to maintain species and/or community diversity and can be performed either on the broad scale for maintaining vegetation and animal communities or at the local scale for maintaining habitat management of rare and/or threatened species (e.g. orange-bellied parrots).

Predicting buttongrass moorland fire behaviour

To predict buttongrass moorland fire behaviour, the following are required: site age (years) (i.e. time since the last fire); site productivity (i.e. low or medium, dependent on the geological type); rain and/or dewfall in the past 48 hours (mm); current temperature (°C); current relative humidity (%) and current wind speed at 1.7 m above the ground (km/hr).

The steps for predicting buttongrass moorland fire behaviour are as follows:

1. Determine the site age and site productivity;
2. Predict the dead-fuel moisture from the rain and/or dewfall in the previous 48 hours, current temperature and relative humidity (Tables 1a, 1b);
3. Predict the head-fire rate of spread from the dead-fuel moisture, site age and wind speed (Table 2);
4. Predict the head-fire flame height from the head-fire spread rate, site age and site productivity (Table 3);
5. Predict the flank- and back-fire spread rates and flame heights from head-fire spread rates and flame heights (Table 4), and;
6. Predict the Moorland Fire Danger Rating from the head-fire rate of spread (Table 5).

Site age

If the site age is unknown, banksia nodes (branch junctions) can be counted. In most seasons, banksias form one new branch junction, which can be used to estimate the age. If banksias are not available, then growth ring counts can be made from tea-trees (i.e. *Leptospermum* spp.). Other species such as paper-barks (*Melaleuca* spp.) or eucalypts should not used due to their poor growth-ring structure. A minimum of six individuals should be sampled at each site.

Ring counts should be made by:

1. Cutting the stem just above the ground surface;
2. Drying and polishing it with fine sandpaper; and
3. Counting the rings using a dissecting microscope.

Site age equals the most common count (i.e. mode) plus one. For example, in the following node and/or ring counts: 12, 11, 12, 31, 10, 12, 5, 12, the most common count is 12 and so it is assumed that the site was last burnt 13 years ago. If it is not possible to measure the age at a site, assume the age is 20 years.

Site productivity

In north-western, western and south-western Tasmania, all sites underlain by quartzite, conglomerate, granite and/or gravel derived from these substrates are low productivity, with all other geological types being medium productivity. If the geological type is unknown, assume it is medium productivity.

Dead-fuel moisture content

The dead-fuel moisture content is predicted by adding together the Rainfall Factor and the Humidity Factor. The Rainfall Factor is derived from the rain and/or dewfall in the previous 48 hours, along with the number of hours since the rain stopped falling, using Table 1a. The Humidity Factor is derived from the current temperature and current relative humidity using Table 1b. The methodology for predicting dead-fuel moistures is as follows:

1. Only count the rain and/or dewfall in the last 48 hours and only count the first 1 mm of rain and/or dewfall. If more than 1 mm of rain and/or dew fell, then the dead fuels are saturated and all subsequent rain and/or dewfall is ignored.
2. Estimate the time (hours) since the rain and/or dewfall stopped. Alternatively, if the rain is being predicted by the Fire Weather Forecast, then the 24-hour rainfall is assumed to have stopped falling at 09:00 hours, and the time since then is used to estimate the fuel drying time. If the Fire Weather Forecast predicts rain in the 6-hour period, then the hours since the rain stopped are assumed to be zero.

3. Predict the Rainfall Factor from the rain and/or dewfall along with the time since it stopped, using Table 1a.
4. Predict the Humidity Factor from the current temperature and relative humidity in Table 1b.
5. The dead-fuel moisture is calculated by adding together the Rainfall Factor and the Humidity Factor.

Measuring wind speed

The wind speed should be measured with the wind-speed sensor held at between 1.7 and 2 m above the ground surface. If information on the wind speed is being obtained from Bureau of Meteorology forecasts, then the wind speed will need to be corrected from the 10 m wind speed to the 1.7 m wind speed by reducing its value by one third. For example, a 15 km/hr wind speed at a height of 10 m is equivalent to a 10 km/hr wind speed at a height of 1.7 m.

Head-fire rate of spread

Buttongrass moorland head-fire rates of spread are predicted from the dead-fuel moisture, wind speed at 1.7 m and site age using Table 2. The units used for rate of fire spread are metres per minute.

Predicting head-fire flame heights

Buttongrass moorland head-fire flame heights are predicted from the head-fire rate of fire spread, site age and site productivity using Table 3. The units used for flame height are metres.

Flank- and back-fire behaviour

Flank- and back-fire rates of spread and flame heights are predicted from head-fire rates of spread and flame heights using Table 4.

Moorland Fire Danger Rating

The Moorland Fire Danger Rating is a dimensionless index similar in concept to the McArthur Forest Fire Danger Rating. These indices indicate the degree of fire suppression difficulty and range from 0 (fires will not be sustained), through 1 to 5 (low fire danger), 6 to 12 (moderate fire danger), 13 to 24 (high fire danger), 25 to 50 (very high fire danger), up to 51 to 100 (extreme fire danger). The Moorland Fire Danger Rating is predicted from the head-fire spread rate using Table 5.

Peat fires and the soil dryness index

In north-western, western and south-western Tasmania most vegetation types are underlain by organic peat soils. The soil dryness index (SDI) is a useful predictor of the potential for different vegetation and peat types to burn, as shown in Table 6. However, the SDI should only be used as a guide since the site that is being burnt may have a different SDI from the site where the SDI is predicted for.

Buttongrass moorland prescribed burning and wildfire control

The principles for performing prescribed burning are shown in the *Fuel Reduction Burning Course Notes* published by Forestry Tasmania. These notes detail the aims, types and standards of prescribed burning, planning issues, safety concerns, resources required, use of test fires and fire-ignition methodologies.

The prescriptions shown in Table 7 indicate the optimum conditions for performing prescribed burning, along with the maximum and minimum conditions acceptable. If a burn is performed with all of the parameters at the highest allowable levels (i.e. highest temperature, wind speed and site age, along with the lowest relative humidity), then the resulting fire behaviour may be uncontrollable. If all of the parameters are at the lowest allowable levels, the burn may fail to sustain itself and/or inadequately reduce the fuels and will be ineffective as a hazard-reduction burn.

The options for buttongrass moorland fire control at different rates of fire spread, flame height and Moorland Fire Danger Rating are in Table 8.

Table 1. Predicting the Rainfall and Humidity Factors.

(a) Rainfall Factor

Hours since rain stopped	Rain and/or dewfall (mm) 0.05	0.1	0.2	0.5	1+
0	10	18	31	53	64
3	8	14	24	41	50
6	6	11	19	32	38
9	4	8	14	25	30
12	3	6	11	19	23
24	1	2	4	7	8
48	0	0	1	1	1

(b) Humidity Factor

Temp (°C)	Relative humidity (%) 20	40	60	80	100
8	12	14	19	25	35
12	11	13	17	23	32
15	10	12	15	21	29
18	9	11	14	19	27
25	8	9	12	16	22
30	7	8	10	14	19
35	6	7	9	12	16

The dead-fuel moisture is calculated by adding together the Rainfall and Humidity Factors.

Table 2. Predicting head-fire spread rate (m/min).

Dead-fuel moisture	Wind speed (km/hr) 1	5	10	20	40	60
Age = 5 years						
>100	fires probably will not be sustained					
100	0.0	0.0	0.0	1.3	3.3	5.7
80	0.0	0.0	0.9	2.2	5.4	9.2
60	0.0	0.6	1.4	3.5	8.8	14.9
30	0.1	1.2	3.0	7.3	18.2	31.0
20	0.2	1.5	3.8	9.3	23.2	39.5
15	0.2	1.7	4.3	10.6	26.2	44.6
10	0.2	1.9	4.8	11.9	29.6	50.4
5	0.3	2.2	5.4	13.5	33.4	56.9
Age = 10 years						
>100	fires probably will not be sustained					
100	0.0	0.0	0.0	2.1	5.2	8.9
80	0.0	0.0	1.4	3.4	8.5	11.4
60	0.1	0.9	2.2	5.5	13.7	23.3
30	0.2	1.9	4.6	11.4	28.4	48.3
20	0.3	2.4	5.9	14.6	36.2	61.6
15	0.3	2.7	6.6	16.5	40.9	69.6
10	0.4	3.0	7.5	18.6	46.2	78.6
5	0.4	3.4	8.5	21.0	52.1	88.7

Table 2. Continued.

Dead-fuel moisture	Wind speed (km/hr) 1	5	10	20	40	60
Age = 20+ years						
>100	fires probably will not be sustained					
100	0.0	0.0	0.0	2.8	6.8	11.6
80	0.0	0.0	1.8	4.5	11.1	18.9
60	0.1	1.2	2.9	7.2	18.0	30.6
30	0.3	2.4	6.0	15.0	37.3	63.5
20	0.4	3.1	7.7	19.2	47.5	80.9
15	0.4	3.5	8.7	21.6	53.7	91.4
10	0.5	4.0	9.8	24.4	60.6	103.2
5	0.5	4.5	11.1	27.6	68.5	116.5

Table 3. Predicting head-fire flame heights (m).

	Age = 5 years		Age = 10 years		Age = 20+years	
Head-fire	Productivity		Productivity		Productivity	
spread rate	low	med	low	med	low	med
0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	1.6	2.0	1.9	2.5	2.2	3.1
5	2.1	2.6	2.6	3.4	2.9	4.1
10	2.8	3.5	3.4	4.5	3.8	5.5
20	3.7	4.6	4.5	5.9	5.1	7.2
40	4.9	6.1	5.9	7.8	6.7	9.6

Table 4. Flank- and back-fire spread rates (m/min) and flame heights (m).

Head-fire	Flank-fire	Back-fire
(a) Rate of fire spread (m/min)		
1.0	0.4	0.1
5.0	2.0	0.5
10.0	4.0	1.0
20.0	8.0	2.0
40.0	16.0	4.0
(b) Flame height (m)		
1.0	0.6	0.5
2.5	1.5	1.3
5.0	3.0	2.5
7.5	4.5	3.8
10.0	6.0	5.0

Table 5. Moorland Fire Danger Rating.

Head fire spread rate (m/min)	Moorland Fire Danger Rating (dimensionless)
0	0
5	low – 3
7.5	low – 5
10	moderate – 7
15	moderate – 10
17	moderate – 12
20	high – 14
30	high – 20
34	high – 24
50	very high – 35
70	very high – 50
140	extreme – 100

Table 6. Soil dryness index (SDI) and the potential for different vegetation and peat types to burn.

		Probability of burning	
SDI	Community type	Vegetation	Peat
< 10	buttongrass moorland	high	low
	all other vegetation types	low	low
10–15	buttongrass moorland	high	low
	wet scrub	mod	low
	wet eucalypt forest	low	low
	rainforest	low	low
15–25	buttongrass moorland	high	low
	wet scrub	high	high
	wet eucalypt forest	low	low
	rainforest	low	low
25–50	buttongrass moorland	high	mod
	wet scrub	high	high
	wet eucalypt forest	high	high
	rainforest	low	low
> 50	all community types	high	high

Table 7. Prescribed burning prescriptions.

(a) Hazard-reduction burning

Season			
Autumn	April – early May		
Spring	September – mid October		
	Optimum	Min	Max
Fire frequency (yrs)			
Low productivity sites	7–10	5	15
Medium productivity sites	5–8	5	10
Weather conditions			
Days since rain	2	1	-
Temperature (°C)	14–16	10	20
Relative humidity (%)	50–60	45	75
Wind speed at 1.7 m (km/hr)	6	3	10
Soil dryness index (mm)	5	0	10

Table 7. Continued.

(b) Ecosystem-management burning

Season			
Autumn	April – June		
Spring	August – October		
	Optimum	Min	Max
Fire frequency (yrs)	dependent on the species and/or community type being burnt for		
Weather conditions			
Days since rain	2	1	-
Temperature (°C)	8–16	5	20
Relative humidity, %	50–75	45	95
Wind speed at 1.7 m (km/hr)	4–6	< 1	10
Soil dryness index (mm)	5	0	10

Table 8. Moorland Fire Danger Rating and the options for fire control.

MFDR	ROS	F_H	Fire characteristics
1–3 low	0–4.5	0–4.5	• Suitable conditions for prescribed burns; • Fire easy to control using hand tools; • 2 m wide fire-breaks should hold if supported by hand tools.
4–5 low	4.5– 8	2–6	• Suitable conditions for prescribed burns if secure boundaries are available; • 5 m wide fire-breaks should hold if supported by hand tools; • Up to about 5 m spotting expected.
6–12 moderate	8–17	2–9	• Fire too intense for prescribed burning; • Control lines 10–25 m wide supported by pumps required to control head-fires, control lines 5 m wide required for flank- and back-fires; • > 30 m spot fires expected.

Table 8. Continued.

MFDR	ROS	F_H	Fire characteristics
13–24 high	18–34	3–12	• Head-fire control very difficult, with 25–50 m wide fire-breaks required; • 10 m wide fire-breaks may hold flank- or back-fires if supported by pumps; • High risk of fire spotting across fire-breaks; • Personnel positioned down-wind and to the flanks of the fire should be made aware of the high risk of the fire jumping fire-breaks.
25–50 very high	35–70	4–16	• Direct attack on fire not possible; • > 100 m wide fire-breaks supported by pumps required to control head-fires, and > 10 m wide fire-breaks supported by pumps required to control flank- and back-fires, very high risk of fire spotting across fire-breaks;

Table 8. Continued.

MFDR	ROS	F_H	Fire characteristics
			• Essential no personnel be positioned down-wind or to the flank of the fire unless they have safe fuel-free zones to retreat into.
51–100 extreme	> 70	> 8	• Fire control not possible until the level of fire behaviour is reduced; • Essential no personnel be positioned down-wind or to the flank of the fire.

MFDR = buttongrass moorland fire danger rating
ROS = rate of fire spread (m/min)
F_H = flame height (m)

Fuel-characteristics equations

Total fuel load in low productivity sites:

$$\text{Fuel}_{\text{low}} = 11.73*(1-\exp(-0.106*\text{age}))$$

Total fuel load in medium productivity sites:

$$\text{Fuel}_{\text{med}} = 44.61*(1-\exp(-0.041*\text{age}))$$

Dead-fuel load in low productivity sites:

$$\text{Dead}_{\text{low}} = (0.873*(1-\exp(-0.036*\text{age})))*\text{Fuel}_{\text{low}}$$

Dead-fuel load in medium productivity sites:

$$\text{Dead}_{\text{med}} = (0.950*(1-\exp(-0.054*\text{age})))*\text{Fuel}_{\text{med}}$$

Fuel-moisture equations

Rainfall Factor predicted using rain and/or dewfall and the hours since the rain stopped:

$$\text{Rf} = 67.128*(1-\exp(-3.132*\text{rain}))*\exp(-0.0858*\text{hours})$$

Humidity Factor predicted using RH and dew-point temperature:

$$\text{Hf} = \exp(1.660+0.0214*\text{RH}-0.0292*\text{dewpointtemperature})$$

An alternative form of the Humidity Factor in which the dew-point temperature has been replaced by a function using dry bulb temperature and relative humidity is shown below:

Humidity Factor predicted using RH and dry bulb temperature:

$$\text{Hf} = \exp(1.66+0.0214*\text{RH}-0.0292*(((1/273.16-0.000184*\ln(((0.611*\exp((17.2694*((\text{temp}+273.16)-273.16))/((\text{temp}+273.16)35.86)))*(\text{RH}/100))/0.611))^{-1})-273.16))$$

Fuel moisture:

$$\text{Mf} = \text{Rf} + \text{Hf}$$

Operational buttongrass moorland fire-behaviour equations

Buttongrass moorland rate of head-fire spread, all sites:

$$\text{ROS} = 0.678*\text{wind}^{1.312}*\exp(-0.0243*(\exp(1.66+0.0214*\text{RH}-0.0292*(((1/273.16-0.000184*\ln(((0.611*\exp((17.2694*((\text{temp}+273.16)-273.16))/((\text{temp}+273.16)-35.86)))*(\text{RH}/100))/0.611))^{-1})-273.16))+(67.128*(1-\exp(-3.132*\text{rain}))*\exp(-0.0858*\text{hours}))))*(1-\exp(-0.116*\text{age}))$$

Buttongrass moorland head fire-flame height, low productivity sites:

$$F_{\text{Hlow}} = 0.148*(((18637-(24*(\exp(1.66+0.0214*\text{RH}-0.0292*(((1/273.16-0.000184*\ln(((0.611*\exp((17.2694*((\text{temp}+273.16)-273.16))/((\text{temp}+273.16)-35.86)))*(\text{RH}/100))/0.611))^{-1})-273.16))+(67.128*(1-\exp(-3.132*\text{rain}))*\exp(-0.0858*\text{hours})))))*(11.73*(1-\exp(-0.106*\text{age})))*\text{ROS})/600)^{0.403}$$

Buttongrass moorland head-fire flame height, medium productivity sites:

$$\begin{aligned} F_{H_{med}} = {} & 0.148*(((18637-(24*(\exp(1.66+0.0214*RH-0.0292*(((1/273.16-0.000184*\\ & \ln(((0.611*\exp((17.2694*((temp+273.16)-273.16))/((temp+273.16)-35.86)))*\\ & (RH/100))/0.611))^{-1})-273.16))+(67.128*(1-\exp(-3.132*rain))*\exp(-0.0858*hours)))))*\\ & (44.61*(1-\exp(-0.041*age)))*ROS)/600)^{0.403} \end{aligned}$$

Moorland Fire Danger Rating:

$$MFDR = 0.65*ROS^{1.02}$$

Probability that buttongrass moorland fires will be sustained:

$$\text{Probability} = 1/(-1+\exp(-(-1+0.68*wind-0.07*Mf-0.0037*wind*Mf+2.1*productivity)))$$

Where:

$Fuel_{low}$ is the total fuel load in low productivity sites (t/ha); $Fuel_{med}$ is the total fuel load in medium productivity sites (t/ha); $dead_{low}$ is the dead-fuel load in low productivity sites (t/ha); $dead_{med}$ is the dead-fuel load in medium productivity sites (t/ha); age is the time since the last fire (yrs); Rf is the Rainfall Factor (%); rain is the rain and/or dewfall in the last 48 hours (mm); hours is the time since the rain and/or dewfall stopped; Hf is the Humidity Factor (%); RH is the relative humidity (%); dew-point temperature is in °C; temp is the dry bulb temperature (i.e. the air temperature) (°C); Mf is the total dead-fuel moisture (%); ROS is the head-fire rate of spread (m/min); wind is the surface wind speed, measured at 1.7 m above the ground surface (km/hr); F_{Hlow} is the flame height in low productivity sites (m); F_{Hmed} is the flame height in medium productivity sites (m); MFDR is the Moorland Fire Danger Rating; Probability is probability that fires will sustain themselves or self-extinguish; productivity is the site productivity, low productivity sites = 1, medium productivity = 2.