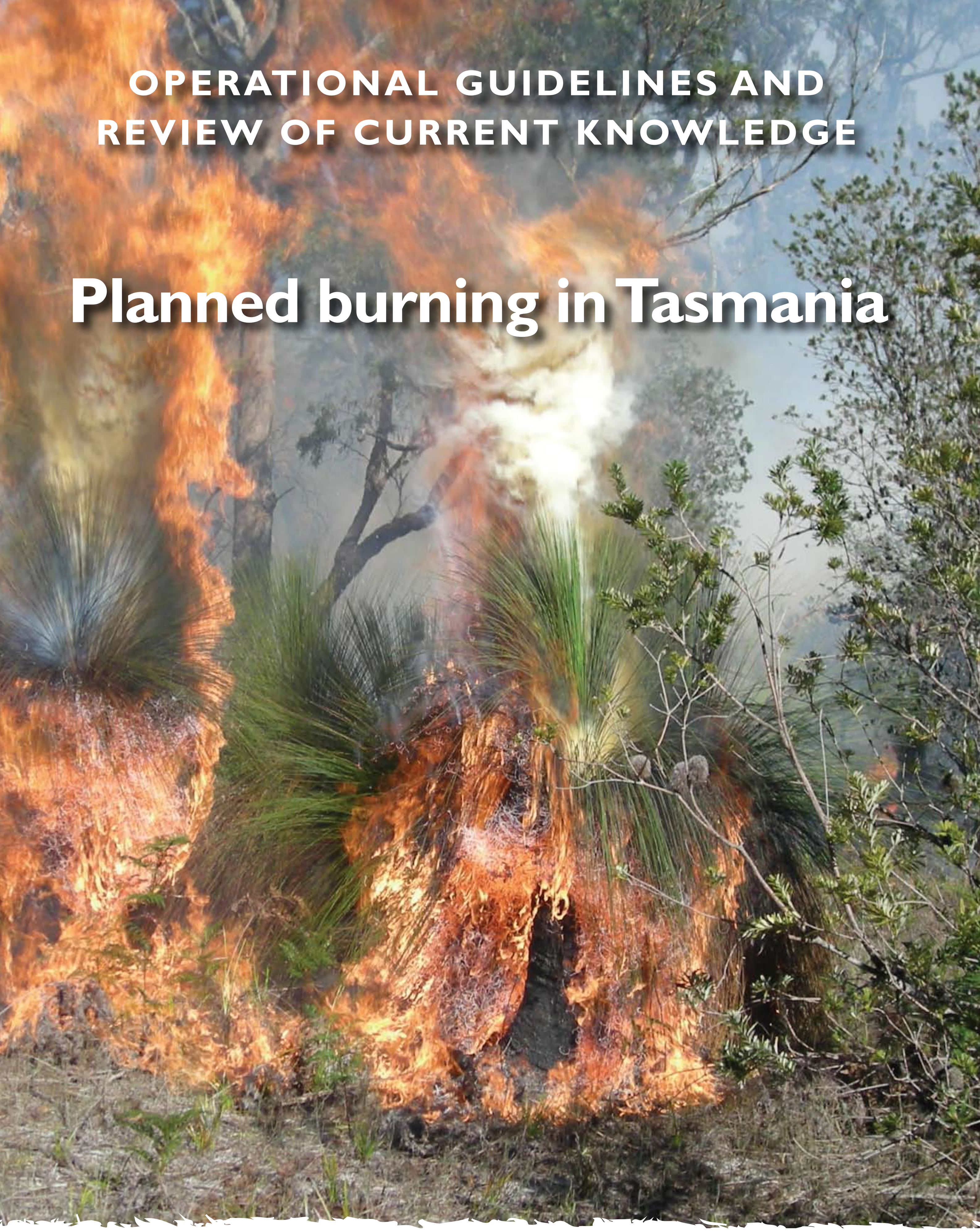
OPERATIONAL GUIDELINES AND
REVIEW OF CURRENT KNOWLEDGE

Planned burning in Tasmania



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PLANNED BURNING IN TASMANIA

Operational Guidelines and Review of Current Knowledge

September 2009

Jon Marsden-Smedley
for the
Tasmanian Fire Research Fund

Forestry Tasmania

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Front cover photograph: eastern Tasmanian dry eucalypt forest planned burning by John Duggan.

Executive Summary

The Tasmanian fire management agencies, the Tasmania Fire Service, Forestry Tasmania and the Parks and Wildlife Service, through the Tasmanian Fire Research Fund, have conducted a review of planned burning guidelines and methodologies. These revised guidelines aim to minimise the risk of adverse outcomes from planned burning whilst also ensuring that the burning is performed safely and meets fire management objectives.

Planned burning is the deliberate use of fire under specified conditions for the purposes of fuel management, ecological management, promoting agricultural green pick and weed management. This review does not cover silvicultural regeneration burning.

Fire is a fundamental aspect of the Australian environment, with many vegetation types requiring periodic fire to maintain ecological values. However, not all fires are desirable. Fires may occur under conditions that threaten human life and property, may be too frequent, too intense, cause temporary reductions to air quality and/or disruptions to the public.

Planned burning has an important role in reducing adverse impacts, but is not a panacea for all fire management problems. Planned burning can decrease wildfire risk by reducing fuel hazards, and enhance ecological management by increasing fire regime variability. However, it needs to be performed in conjunction with a wide range of risk management strategies, including public education, effective training of personnel and resourcing of wildfire suppression, along with appropriate management of ecological values.

This review addresses these issues by providing an assessment of the available literature and summarising the outcomes of meetings with experienced planned burning practitioners. Updated guidelines for planned burning in dry eucalypt forests, heathlands, dry scrub, wet scrub, buttongrass moorland, native grasslands and for weed management have been developed. A critical aspect of these revised guidelines is the linking of clearly defined objectives with measurable outcomes. The review includes the following main sections:

- review scope and background information
- revised guidelines for conducting planned burning
- background information for performing planned burning
- review of the literature, existing practices, expert opinion, knowledge gaps and further information required
- references
- appendices:
    - glossary of relevant fire management terms
    - fire behaviour prediction equations for use in Tasmania.

The planned burning guidelines and methodologies covered by this review should be reassessed in 10 years time, or earlier if required by Tasmanian fire management agencies.

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1. Fire and the Tasmanian Environment

Fire is a fundamental aspect of the Australian environment, with many vegetation types requiring periodic fire to maintain ecological values. However, not all fires are desirable. Fires may occur under conditions that threaten human life and property, may be too frequent, too intense, cause temporary reductions to air quality and/or disruptions to the public.

The last decade has seen several major wildfires in southern Australia. These include the 2003 Canberra and alpine fires in NSW, ACT and Victoria, the 2005 Wangary fire on the Eyre Peninsula in South Australia, the 2006/07 Great Divide fires in Victoria and the February 2009 fires in Victoria. In addition, projections from climate change models suggest that in the next few decades across much of southeastern Australia there will be major increases in the level of fire threat through increases in the incidence of high fire danger conditions (although smaller increases in fire threat are predicted in southern Tasmania; Lucas et al. 2007).

Planned burning has the potential to address some of these issues. A stated aim of planned burning is to minimise the area burnt by wildfires, and in particular large scale, high intensity wildfires. These high intensity wildfires are responsible for the majority of the threats to public health and safety; extremely expensive to suppress; and frequently result in threats to ecological values through their lack of fire regime variability and the small proportion of the landscape left unburnt. Planned burning can assist with the maintenance of ecological values by providing a range of fire types, seasons, frequencies, ages, sizes and intensities.

In the past, major wildfires have occurred in Tasmania with the most recent occurring 32 years ago in February 1967, when over a five hour period 62 people died, and approximately 1400 buildings destroyed and 265 000 ha burnt (Luke and McArthur 1978). However, the area burnt in the February 1967 fires is dwarfed by that burnt in the 1933/34 and 1897/98 fires when at least 5 and 10 times respectively were burnt (Marsden-Smedley 1998a; Johnson and Marsden-Smedley 2001). The 1933/34 fires burnt over 1 000 000 ha (mostly in western and southwestern Tasmania) and the 1897/98 state-wide fires burnt over 2 000 000 ha (Marsden-Smedley 1998a). This means that although Tasmania has avoided catastrophic wildfires for several decades, it is not immune to the threat. It is worth noting that many of the areas burnt in the 1933/34 and 1897/98 fires consisted of “bush”, however, by February 1967 these areas had been built up with houses, farms and forest plantations, and since February 1967 many additional areas of “bush” have been developed resulting in the potential for increased levels of damage should fires occur.

Over the past few decades there have been marked reductions in the area of planned fires on both private and crown land in Tasmania (Robson 1993; Kirkpatrick and Bridle 2007; von Platen 2008). This has resulted in increases in the average fire age (ie the time since the last fire), with resultant increases in the level of fuel-hazard. In addition, over the past decade there have been marked increases in the incidence of lightning caused fires, particularly in southwestern, western and northwestern Tasmania (Marsden-Smedley 2007).

The cause of these increases in lightning fires are uncertain, but are consistent with what is expected from climate change.

Enhanced application and implementation of fire management practices is required if land management agencies and fire authorities are to address these issues. This enhanced fire management will require high level inter-agency cooperation, along with an improved understanding of the interactions between asset protection, community aspirations regarding fire, fire management planning, fire risk assessment, fire behaviour and suppression, and the ecological management of fire prone areas.

In vegetation adapted to periodic fire (which includes the majority of Australian vegetation types) the interactions between vegetation, fuel and fire occurrence can not be ignored. The fuel characteristics in these vegetation types are such that with increasing time since fire the levels of fuel hazard, fuel continuity and fuel load all increase, resulting in increased levels of flammability. This increased flammability means that when ignitions occur, the fires are typically high intensity, fast moving wildfires which burn large areas, threaten assets, cause death and leave few areas unburnt.

Therefore, the community, in consultation with fire managers, needs to make informed decisions as to the type of fire regime desired: a mixed regime of planned burning and periodic wildfires, versus a regime dominated by infrequent mostly high to extreme intensity wildfires. The costs associated with the results of making such decisions will be significant and recurring if they are to be effective. These costs will include smoke impacts, reductions in visual amenity, compromised ecological values in some areas along with the requirement for significant monetary and resource inputs.

The revised and updated guidelines for planned burning developed by this review are one aspect of this improved fire management. These revised guidelines also assist with the identification of knowledge gaps, with new information and systems being identified, addressed and incorporated into management practices. The review contains the following sections:

- review scope and background information
- revised guidelines for conducting planned burning
- background information for performing planned burning
- review of the literature, existing practices, expert opinion, knowledge gaps and further information required
- references
- appendices
    - glossary of relevant fire management terms
    - fire behaviour prediction equations for use in Tasmania.

The planned burning guidelines and methodologies covered by this review should be reassessed in 10 years time, or earlier if required by Tasmanian fire management agencies.

2. Guidelines for Planned Burning in Tasmania

2.1 Introduction

Planned burning in Tasmania is conducted for fuel management, ecological management, agricultural green pick and/or weed management. The suitable vegetation associations for burning are:

- dry eucalypt forests
- heathlands, dry scrub and wet scrub
- buttongrass moorlands
- native grasslands
- weed management (mainly for gorse removal).

The supporting information for planned burning operations is in Section 3 of this document. Section 4 contains a review of the fuel characteristics, fuel moisture, fire behaviour and fire ecology literature that has not previously been applied to planned burning in Tasmania. Appendix 1 contains a glossary of relevant fire management terms while Appendix 2 contains the equations for predicting fire behaviour in Tasmanian vegetation associations.

Planned burn objectives must be linked to measurable post-burn outcomes and where practical, target multiple objectives. Ecological management burning requires the identification of targeted outcomes and effective pre and post-fire monitoring.

Examples of planned burn objectives are in Table 2.1.

Table 2.1 Potential planned burning objectives and their corresponding outcomes.

Objective	Target outcome
All burns	
- burn performed safely	- no reportable safety incidents;
- no escapes	- fire contained to planned area;
- fire outcomes and effects recorded	- fire data collected and recorded on databases; - post-fire monitoring performed;
- minimise adverse community impacts	- effective community consultation and notification at planning, implementation and post-burn stages; - smoke impacts minimised;
- fire management targets achieved	- ≥90% of burns in asset protection zones and ≥75% of other burns conducted within 2 years of target date.
Fuel management burning: asset protection	
- reduce fuel-hazards	- reduce elevated and bark fuel-hazard to low and burn >70% of fuel across >70% of block within 250 m of the boundary; - reduce overall fuel-hazard rating to low across entire block;
Fuel management burning: strategic management	
- reduce fuel-hazards	- reduce overall fuel-hazard rating to low or moderate; - minimise impacts to community and ecological values;
Ecological management burning: broad-scale	
- manage for the full range of values	- ecological requirements of target associations recorded; - area of target associations stable or increasing; - 40 to 70% of block burnt, dependent on management aims; - unburnt patches scattered throughout the block; - burns conducted with a variable fire regime; - effective pre and post-burn monitoring and documentation.
Ecological management burning: species management	
- maintain target species	- ecological requirements of target species documented; - target species numbers stable or increasing; - effective pre and post-burn monitoring and documentation.

2.2 Planned burning guidelines

The standardised fire behaviour prediction spreadsheet and the Burn Risk Assessment Tool (BRAT; Sections 3.5 and 3.13.7) should be used to identify burning parameters, likely fire behaviour and fire control options. The standardised fire behaviour prediction spreadsheet predicts fire spread rates and intensity. The BRAT predicts the risk of fires escaping (ie likelihood of impact), the potential of escapes to do damage (ie consequence), the effects of mitigation strategies in reducing the probability of adverse outcomes, and the potential for the burn to meet fire management objectives (ie benefit).

Planned burning in asset protection zones aims to minimise wildfire risk and maximise wildfire suppression potential. This requires fuel-hazard ratings to be reduced to low levels.

In strategic management zones the aim is to reduce the level of wildfire threat and minimise wildfire spread rates and intensities.

In ecological management zones the aims and objectives will be dependent on the species and/or association being managed, and will be specified in appropriate management plans. A critical aspect of ecological management burning is effective pre and post-fire monitoring.

During dry eucalypt forest planned burns the wind speed is measured at 10 metres above the ground, while all other planned burns use the surface wind speed measured at 1.7 to 2 metres above the ground surface.

The characteristics of the boundaries utilised during planned burning will depend on the type of planned burn and anticipated level of fire behaviour. Where buttongrass moorland planned burns are undertaken, requiring fires to self-extinguish without burning to boundaries, the guidelines detailed in Table 2.5 should be used. If planned burns are performed with fire intensities below about 500 kW/m, or flame heights below two metres, then handlines and/or vehicle tracks one to four metres wide may be used. Where planned burns are performed with fire intensities of up to 2000 kW/m, or flame heights of up to three metres, fire breaks four to six metres wide will be required. However, if planned burns are performed in dry eucalypt forests which have very high or extreme bark hazards (see Table 2.2), then burns should be resourced to a higher level, wider boundaries used and/or the burn undertaken at lower levels of fire danger (eg higher relative humidity, higher fuel moisture, lower Soil Dryness Index and/or lower wind speed).

The integration of the burning parameters is a critical component of planned burning. If burning is conducted with all of the parameters at their maximum values (eg highest wind speed, lowest relative humidity, highest Soil Dryness Index and longest time since fire) then fires will burn with fast rates of spread, high intensities and a high risk of escapes. Conversely, if burning is conducted with all of the parameters at their lowest values, then fires may fail to sustain or the fire may burn with insufficient intensity to meet objectives.

The recommended process for selecting appropriate burning parameters is:

1 specify the burn’s objectives

2 determine the minimum and maximum fire intensity to achieve objectives, including the level of fuel modification required

3 use the fire prediction spreadsheet and the BRAT to determine appropriate weather and site parameters and the burn's risk profile

4 if necessary, modify the weather and site parameters to reduce the level of fire risk whilst maintaining acceptable levels of fire intensity

5 undertake the burn

6 undertake post-burn assessments to determine if burn objectives have been met (and develop strategies to address the issue if they haven't), and record the burn outcomes on appropriate databases.

2.2.1 Dry eucalypt forest planned burning guidelines

Planned burning in dry eucalypt forest is conducted for fuel and ecological management.

In asset protection zones, surface, near-surface, elevated and bark fuel-hazard ratings must be reduced to low, requiring fires to be conducted with flame heights of two to four meters. In strategic management zones the aim will be to reduce overall fuel-hazards to low or moderate.

Fuel-hazard rating (Table 2.2) is used in the standardised fire prediction spreadsheet and for performing pre and post-burn assessments.

The guidelines for dry eucalypt forest planned burning are in Table 2.3.

Table 2.2 Dry eucalypt forest fuel-hazard guide.

Hazard rating and description	
Surface fuel-hazard	
Low	litter depth including duff: <15 mm, <4 t/ha.
Mod	litter depth including duff: 15 - 25 mm, 4 - 8 t/ha.
High	litter depth including duff: 25 - 35 mm, 8 - 12 t/ha.
Very high	litter depth including duff: 35 - 50 mm, 12 - 20 t/ha.
Extreme	litter depth including duff: >50 mm >20 t/ha.
Near-surface fuel-hazard	
Low	fuel cover <10%, little or no influence on fire behaviour.
Mod	fuel cover 10 - 20% of tussock grasses, low sedges and rushes, hummock grasses and low shrubs with little or no suspended bark and leaves.
High	fuel cover 20 - 40%, 5 - 20% dead of tussock grasses, low sedges, rushes, ± suspended bark and twigs; fuel cover 20 - 35% cover of hummock grasses; fuel cover 20 - 40% of low shrubs, ± suspended bark and twigs.
Very high	fuel cover 40 - 70% cover with 20 - 30% dead of tussock grasses, low sedges, rushes; fuel cover 40 - 70% cover of hummock grasses; fuel cover 35 - 60% of low shrubs.
Extreme	>70% fuel cover of tussock grasses, low sedges, rushes with >30% dead grass, leaves and bark; >60% fuel cover of hummock grasses or low shrubs.
Elevated fuel	
Low	very little elevated fuel.
Mod	<20% fuel cover or no fine fuel within 1 m of the ground, little or no dead material.
High	fuel cover 20 - 50% cover or little fine fuel within 0.5 m of the ground, <20% dead material or, if the vegetation is 5+ m tall then it has little fine fuel within 2 - 4 of the ground.
Very high	20 - 50% cover of dead material, high vertical and horizontal density and continuity, fuel particles mostly <1 - 2 mm thick, average height >0.5 m and usually >1 m high, 50 - 80% of fuel >0.5 m and usually >1 m high.
Extreme	>20% cover of dead material, high vertical and horizontal density and continuity and at least 2 - 3 m tall, >10 t/ha, large amounts of suspended leaves, twigs and bark, >70% of fuel cover >1 m (and usually >2 m) tall.

Table 2.2 Dry eucalypt forest fuel-hazard guide, continued.

Bark fuel	
Low	stringybarks: 100% of trunk charred; platy/subfibrous barks: >90% of trunk charred; smooth/gum barks: no bark ribbons.
Mod	stringybarks: bark tightly held, >90% of trunk charred; platy/subfibrous barks: bark very tightly held onto trunk; smooth/gum barks: no long bark ribbons.
High	stringybarks: few pieces of loosely held bark, bark tightly held, 50 - 90% of trunk charred; platy/subfibrous barks: bark tightly held onto trunk, long unburnt; smooth/gum barks: long ribbons of bark but smooth trunk.
Very high	stringybarks: significant amounts of loosely held bark, 10 - 50% of trunk charred; platy/subfibrous barks: bark loosely held onto trunk; smooth/gum barks: long ribbons of bark hanging to ground level.
Extreme	stringybarks: outer bark weakly attached and easily dislodged, <10% of trunk charred; platy/subfibrous barks and smooth/gum barks: does not occur.

Table 2.3 Dry eucalypt forest planned burning guidelines.

Parameter		Units	Range
Weather	wind speed at 10 m	km/h	<30
	relative humidity	%	40 to 80
	Soil Dryness Index	dimensionless	<125
	temperature	° C	10 to 25
Hazard-stick moisture	within the burning block	%	14 to 17
	adjacent to burning block	%	>24
Fuel moisture	within the burning block	%	10 to 15
	adjacent to burning block	%	>20
Fire frequency	fuel management	years	4 to 10
	ecological management: as specified in management plans		
Forest Fire Danger Rating	fuel management	dimensionless	5 to 10
	ecological management	dimensionless	≤10
Fire intensity: flame height required	asset protection	m	2 to 4
	strategic management	m	1 to 4
	ecological management: as specified in management plans		

2.2.2 Heathland, dry scrub and wet scrub planned burning guidelines

Planned burning in heathlands, dry scrub and wet scrub is conducted for fuel management and ecological management. During heathland, dry scrub and wet scrub burning, the tight threshold between sustaining and non-sustaining fires can result in minor increases in wind speed and/or slope, along with decreases in fuel moisture rapidly transforming low intensity fires, requiring intensive lighting, into high intensity fires.

The heathland, dry scrub and wet scrub planned burning guidelines are in Table 2.4.

Table 2.4 Heathland, dry scrub and wet scrub planned burning guidelines.

Parameter			Units	Range
Weather	wind speed at 1.7 to 2 m		km/h	5 to 20
	relative humidity		%	40 to 80
	temperature		° C	10 to 25
Wet scrub only	Soil Dryness Index		dimensionless	15 to 25
	Hazard-stick moisture:	within burning block	%	14 to 20
		adjacent to block	%	>24
Fire frequency	fuel management		years	5 to 10
	ecological management: as specified in management plans			
Scrub Fire Danger Rating	all planned burns		dimensionless	≤20

2.2.3 Buttongrass moorland planned burning guidelines

Buttongrass moorland planned burning is conducted for fuel management and ecological management. The most important issue influencing buttongrass moorland burning is the balance between boundary security versus fuel removal. When the Soil Dryness Index (SDI) is below 10, natural boundaries (typically wet scrub) will have high moistures and a low potential to burn. Under these conditions, soil moistures will also be high and fuel in the lower parts of the fuel array may be left unburnt as thatch. Where burns are conducted with boundaries wider than 250 metres and a SDI below 10, burns may be conducted as high intensity fast moving fires with surface wind speeds of up to 20 km/h. Where burns aim to minimise thatch and maximise fuel removal, fires may be conducted with the SDI between 10 and 20 and wind speeds below 10 km/h. However, under these conditions scrub boundaries will be ineffective at containing fires resulting in mineral earth boundaries, roads, tracks and/or watercourses being required. Unbounded burning may be performed in low productivity areas where the aim is to have fires self-extinguish without burning to boundaries, leaving part of the site unburnt.

Low productivity buttongrass moorlands occur in western and southwestern Tasmania and are underlain by quartzite and/or quartzite derived geologies. Buttongrass moorlands underlain by other geologies and/or in other parts of Tasmania are classified as medium productivity.

The buttongrass moorland planned burning guidelines are in Table 2.5.

Table 2.5 Buttongrass moorland planned burning guidelines.

Parameter	Units	Range
Fuel management burning: secure natural boundaries		
Surface wind speed at 1.7 to 2 m	km/h	≤20
Relative humidity	%	40 to 90
Temperature	° C	10 to 25
Days since rain (>2 mm)	days	2 to 10
Soil Dryness Index	dimensionless	≤10
Fire frequency	years	5 to 10
Moorland Fire Danger Rating	dimensionless	≤10
Fuel management burning: mineral earth boundaries		
Surface wind speed at 1.7 to 2 m	km/h	≤10
Relative humidity	%	40 to 90
Temperature	° C	10 to 25
Days since rain (>2 mm)	days	4 to 10
Soil Dryness Index	dimensionless	≤20
Fire frequency	years	5 to 10
Moorland Fire Danger Rating	dimensionless	≤ low 5
Ecological management burning		
Surface wind speed at 1.7 to 2 m	km/h	≤20
Relative humidity	%	40 to 90
Temperature	° C	10 to 25
Days since rain (>2 mm)	days	2 to 10
Soil Dryness Index	dimensionless	≤10
Fire frequency will be specified in management plans		
Moorland Fire Danger Rating	dimensionless	≤10
Unbounded burning: overnight conditions required for fires to self-extinguish		
Surface wind speed at 1.7 to 2 m	km/h	≤5
Relative humidity	%	>60
Temperature	° C	<10
Rain and/or dewfall to 09:00 on the following day	mm	≥0.1
Site productivity	dimensionless	low

2.2.4 Native grassland planned burning guidelines

Native grassland burns in Tasmania are mainly conducted for agricultural green pick and for ecological management to maintain species and structural diversity. The critical factors controlling fire behaviour are fuel moisture, fuel load and continuity, curing (ie percentage of dead fuel) and wind speed.

The guidelines for native grassland planned burning are in Table 2.6.

Table 2.6 Native grassland planned burning guidelines.

Parameter	Units	Range
Surface wind speed at 1.7 to 2 m	km/h	≤20
Relative humidity	%	40 to 80
Temperature	º C	10 to 25
Days since rain (>2 mm)	days	2 to 10
Curing (percentage dead fuel)	%	>60
Grassland Fire Danger Index	dimensionless	≤ low 5

2.2.5 Guidelines for gorse management using planned burning

The main weed species where fire is used for management are gorse (*Ulex europaeus*) and to a lesser extent broom (*Cytisus* spp. and *Genista* sp.), Spanish heath (*Erica lusitanica*) and blackberry (*Rubus fruticosus*).

The guidelines in Table 2.7 are mainly intended for gorse fire management, with other weed species (except marram grass) being less flammable than gorse. If planned burning is performed in areas dominated by marram grass, the grassland planned burning guidelines in Table 2.7 should be used.

Fire is a major issue in areas dominated by gorse due to its ability to sustain burning over a wide range of conditions, and its rapid post-fire regeneration. Therefore, integrated pre and post-fire treatments are essential. Treatment effectiveness can be enhanced by pre-burning herbicide spraying, scrub rolling and/or slashing to maximise burn intensity, and biomass consumption (to kill shallowly buried seeds and/or enhance seedling germination of deeper buried seeds) and improve post-fire access for follow-up treatments. Pre-burn treatment can also be used to broaden the burning window by increasing the weed's flammability and allowing the fire to be performed under higher fuel moisture conditions, reducing the risk of fires spreading to other vegetation types.

The guidelines for gorse management using fire are in Table 2.7.

Table 2.7 Guidelines for gorse management using fire.

Parameter	Units	Range
Surface wind speed at 1.7 to 2 m	km/h	≤20
Relative humidity	%	50 to 85
Temperature	º C	10 to 25
Days since rain (>2 mm)	days	<2
Soil Dryness Index	dimensionless	≤20
Hazard-stick moisture	%	14 to 20
Scrub Fire Danger Index	dimensionless	≤ mod 10

Integrated post-burning follow-up is a critical aspect of the management regime

3. Planned Burning Operations in Tasmania

3.1 Introduction

This section of the review of planned burning in Tasmania covers the background information required to undertake planned burning. The main topics covered are:

- fire management zones
- planned burn objectives
- effectiveness of planned burning
- fire risk assessment
- burn block design
- vegetation type
- fire regime
- fuel characteristics
- weather
- fuel moisture
- slope
- fire behaviour
- planned burning techniques.

This section on planned burning operations provides the supporting information for Section 2 of this report. Section 4 contains the review of the fuel characteristics, fuel moisture, fire behaviour and fire ecology literature along with expert opinion on performing planned burning. Appendix 1 contains a glossary of relevant fire management terms and Appendix 2 contains equations for predicting fire behaviour in Tasmanian vegetation associations.

Planned burning is a balancing act and is not a panacea for all fire management problems, with many fire management issues being more closely aligned with social rather than operational factors, particularly on the urban interface (Kanowski et al. 2005). In this area, the overriding factor is ensuring that appropriate fuel management is conducted immediately adjacent (ie within about 5 to 50 metres) to assets (mostly houses, but also critical infrastructure such as urban services, electricity and telecommunications infrastructure), with planned burning being of lower importance. Planned burning can, however, reduce the impact of wildfires and assist with the maintenance of fire-dependent species and vegetation associations.

In the past, planned burning was normally referred to as fuel-reduction burning. This term could, however, be misleading due to the low correlation between fuel load and fire spread rate, and as fuel-reduction burning only refers to one burning objective. Hence, it is more appropriate to specify the burn's objectives, target outcomes and degree of fuel and ecological management required.

Backburning and area burn-outs during wildfire suppression operations has not been included in this review. However, many of the topics reviewed are relevant, including the objectives summarised in Table 2.1, fire control methods, control lines and ignition strategies.

This review also does not cover silvicultural regeneration burning or the policies utilised by the different fire management agencies.

The other terminology issue that needs to be addressed relates to whether the systems used to guide planned burning are *prescriptions* or *guidelines*. In the previously published reports and papers (eg Marsden-Smedley et al. 1999; FT 2005b) the weather, site and burning patterns were clearly detailed as prescriptions, meaning that burning must be performed within the specified range of the published parameters. However, as will be detailed below, several of these parameters have either very low influence on fire behaviour, or are rarely within the range of the previously specified prescriptions. This has resulted in field practitioners regularly undertaking planned burning operations outside the published prescriptions. Thus, the term *guidelines* is recommended and is used throughout this review.

However, when planned burning is undertaken, the level of fire behaviour must be kept within acceptable bounds. In most situations, ensuring that the fire danger rating is kept below the maximum levels specified in the guidelines will be the operationally practical approach to achieve this.

3.2 Fire management zoning

Fire management zone types and their names will be determined by legal requirements and the management aims of the land manager. Some general zone types can however, be defined, including asset zones, asset-protection zones, strategic management zones, general land management zones and planned burning exclusion zones (DSE 2006).

The asset zone covers the geographic location of defined high value assets, such as urban areas, buildings, ecological assets and/or communication infrastructure with zone size being dependent on the asset's characteristics. Planned burning for fuel management would not normally be conducted within the asset zone, although ecological management burning for the maintenance of rare and/or threatened fire-dependent species may. In most situations, fire risk in asset zones will be managed by the manual removal of fuel-hazards and by requiring appropriate building designs.

Asset-protection zones are located immediately adjacent to assets and/or ignition sources, with the primary objective being intensive fuel management to minimise wildfire risk. In this zone ecological values, viewfields and/or recreational opportunities are of secondary importance and may be adversely impacted. As such, the area of the asset-protection zone needs to be kept as small as practical.

The strategic management zone aims to provide broad-scale fuel management to increase wildfire suppression potential and reduce wildfire size whilst minimising adverse impacts on other values. This means that the strategic-fuel management zone needs to be of sufficient size and continuity to act as a barrier to fire spread by reducing rate of spread, intensity and spotting under a broad range of fire weather conditions and/or allow for effective fire suppression operations.

The land management zone aims to allow for land management in keeping with the land manager's requirements. This zoning will aim to maintain fire regimes for vegetation management (eg species and structural diversity), cultural heritage, catchment management, weed management and/or fire exclusion. This fire management should provide for a range of ecological objectives and requirements for both flora and fauna including, where appropriate fire management for single species (eg Orange-bellied parrots). Planned burning exclusion zones may be located within land management zones where planned burning is inappropriate. These areas may have vegetation types that are unsuitable for planned burning (eg rainforest, wet eucalypt forest), have fire-sensitive geology and/or vegetation types (eg karst, rainforest, alpine areas), may have unsuitable site characteristics (eg too steep) and/or planned burning may result in inacceptable visual impacts (eg sites adjacent to scenic lookouts).

3.3 Planned burning objectives

A fundamental aspect of planned burning is the identification of the burn's objectives prior to ignition. The overarching planned burning objectives are for fuel, ecological, agricultural green-pick and weed management. The vegetation types suitable for planned burning include dry eucalypt forests, heathlands, dry scrub, wet scrub, buttongrass moorlands, native grasslands and weeds.

3.3.1 Fuel management burning

Fuel management burning is undertaken in asset-protection and strategic fuel management zones, and requires fires of sufficient intensity to meet objectives whilst ensuring safety standards are not compromised and escapes are minimised. The objectives of fuel management burning are to increase the potential for wildfire suppression and/or the likelihood that fires will self-extinguish.

The primary aim in asset-protection zones is to minimise wildfire risk. Management in asset-protection zones requires the use of intensive fuel management (typically 5 to 10 years between fires) to minimise risk levels. Other values (eg ecological values, viewfields and/or recreational opportunities) are of secondary importance. The primary aim in strategic fuel management zones is to reduce the level of wildfire risk whilst minimising adverse impacts to other values. In strategic management zones the normal situation is to burn 70% of fuels over 70% of the site (FT 2005b).

As the name implies, fuel management burning aims to reduce fuel-hazards so that the potential for wildfire suppression and/or the likelihood that wildfires will self-extinguish is increased. Thus, it is critical that the fuel-hazards immediately adjacent to assets and/or sources of ignition are prioritised (Luke and McArthur 1978). Typical fuel management burning objectives are:

- conduct the burn safely
- minimise escapes
- reduce the level of fuel-hazard (and in particular bark fuel-hazard) to low or moderate
- keep scorch within acceptable limits
- burn a specified amount of the available fuel over a specified proportion of the site.

3.3.2 Ecological management burning

The characteristics of planned burning in ecological management zones will be dependent on the requirements of the species and/or vegetation associations being managed, and includes species regeneration, habitat manipulation and development of mosaics of burnt and unburnt areas. Ecological management burning will aim to either increase and/or promote fire-dependent species or associations (eg Orange-bellied parrots), or reduce and/or remove unwanted species or associations (eg weeds). These objectives typically include:

- species regeneration (frequency used will very between different species)
- habitat manipulation to increase native animal food availability
- development of mosaics of burnt and unburnt areas.

3.3.3 Green pick agricultural planned burning

Green-pick burns are used to a limited extent in bushruns on agricultural land to regenerate native grasses, herbs and forbs for stock food (Kirkpatrick and Bridle 2007). This is mainly due to recently regenerated plants normally having a much increased palatability in their first one to three years (JB Kirkpatrick and JB Marsden-Smedley unpublished data). Green-pick burning can also act to reduce the cover and dominance of woody species, which are normally unpalatable to stock.

3.3.4 Weed management using fire

In Tasmania weed management burning is commonly targeted to removing gorse (*Ulex europaeus*) and to a lesser extent broom (*Cytisus* spp. and *Genista* sp.), Spanish heath (*Erica lusitanica*) and blackberries (*Rubus fruticosus*). A critical factor with the use of fire for weed management is that it should not be used unless follow-up treatment is undertaken, due to the potential for fire to promote and expand weed populations (Swezy and Odion 1997; Baeza et al. 2003, 2006; De Luis et al. 2004, 2005). The aim of burning during weed management is to remove adult plants to improve access for subsequent treatments, and to promote seedling germination to deplete seed banks reducing subsequent seedling germination. The follow-up weed treatments performed will need to be completed prior to the weeds reaching maturity and replenishing seed banks. Pre-burn spraying during follow-up treatments may also be used to increase the weed flammability by increasing the proportion of dead fuel (DiTomaso et al. 2006).

3.4 Effectiveness of planned burning

The potential for fuel management burning to reduce wildfire spread and intensity has been documented in several Australian studies (eg McArthur 1962; Peet and Williamson 1968; Billing 1981; Grant and Wouters 1993; Robson 1993; Cheney 1996; McCarthy and Tolhurst 2001; McCaw et al. 2008b). However, there have also been several cases where planned burning appears to have had only limited effectiveness (see Meredith 1996).

The reasons for the success or failure of planned burning to reduce wildfire potential are many and varied, and include:

- the amount of the fuel-hazard actually reduced
- the location, size and shape of the planned burning
- weather conditions so extreme that even sparse fuels carry wildfires.

These issues have been examined in Victorian dry eucalypt forests by McCarthy and Tolhurst (2001), who found strong relationships between the level of fuel-hazard and fire danger rating versus fire suppression potential. McCarthy and Tolhurst (2001) also found strong correlations between the time since burning and the fire suppression potential, due to the influence of fire age on the level of fuel-hazard. In general, the relationship between time since fire and the effectiveness of planned burning can be summarised as follows:

- highly effective at reducing wildfire potential – burning intervals of no more that 3 years;
- moderate to high level reductions in wildfire potential – burning intervals of between 3 and 6 years; and
- minimal reductions in wildfire potential – burning intervals of 10 years or more (due to the recovery of near-surface, elevated and bark fuel-hazard).

In addition, in order to minimise the risk of planned burns escaping, burns are often conducted at low to very low levels of fire danger. However, these low intensity fires frequently result in inadequate levels of fuel modification. For example, although the majority of burns conducted in southeast Tasmania over the past 15 years have resulted in effective reductions to the level of surface and near-surface fuel-hazard (and moderate reductions to elevated fuel-hazards), these planned burns have failed to significantly reduce the level of bark hazard (Davis in prep.). This suggests that in order to be effective, dry eucalypt forest fuel management burning needs to be conducted at higher intensities, with drier fuels and/or with higher levels of fire danger than is the current situation. Leading on from this requirement, an increase the level of fire behaviour during dry eucalypt forest fuel management burns will also require a higher level of resourcing where burns are conducted in sites adjacent to high value assets (eg on the urban interface).

3.5 Fire risk assessment

Fire risk assessment can be used to identify areas with a high likelihood of being burnt along with fire consequence. It can also be used to predict the impacts (positive and negative) of different fire management strategies (eg changes in the amount and location of planned burns and/or changes in resource level and location).

The major advantages and disadvantages of fire risk assessment are:

Advantages

- clarification and summarisation of wildfire risks
- display of the level of wildfire risk in a easily understood manner
- comparison of the effects of different strategies, including
    - location and/or type of fuel management
    - resource allocation
    - visitor management
    - communication of risk levels to other personnel and the public

Disadvantages

- base information may be unclear and/or hidden
- parameter relationships in the system may be inappropriate.

Fire risk assessment has an important role during planned burning. The Burn Risk Assessment Tool (BRAT, Slijepcevic et al. 2007) provides a standardised framework for assessing planned burn risks versus benefits. The BRAT is based on the Standards Australia risk management standard (Standards Australia 2004) and was developed from the Forestry Tasmania burn risk assessment system (Marsden-Smedley and Chuter 1999). The BRAT assesses the risk of escapes (ie likelihood of impact), potential for damage (ie consequence), effect of mitigation strategies in reducing escape probability, and the burn's potential to meet fire management objectives (ie benefits).

The major benefit of the BRAT system is its ability to provide an objective, consistent, standardised and repeatable process for assessing planned burning risks. The system allows the practitioner to identify the criteria having the greatest influence on risk level and hence, which parameters could be modified to reduce the level of risk. For example, if a burn has excessive risks associated with spotting, the burn's risk profile could be reduced by burning with higher fuel moistures (eg higher Soil Dryness Index, higher relative humidity and/or in a cooler season), increased resources could be used where spotting is predicted to be an issue, additional boundary works could be completed and/or the burn's boundaries could be moved to a lower risk location.

The BRAT system also provides a record of the risk assessment process which can be used to assess operational performance and quantify improvements to risk management.

3.6 Planned burn block design

The selection of suitable burning block locations and boundaries (including any additional boundary preparation required) must be performed at an early stage in the planning process. The planned burning block shape should avoid as much as practical convoluted and/or steep boundaries. The type of boundaries used will depend on the vegetation type, terrain, presence or absence of tracks, roads, water courses and/or other low fuel zones (eg scree slopes). Where practical and safe, the use of non-flammable vegetation (eg scrub boundaries which are too wet to burn, green paddocks) as fire boundaries will be the most effective strategy. Where tracks or roads are used, all boundary preparation and/or reinforcement must be completed prior to ignition. In general, larger burns may provide for more effective burning conditions due to their having less boundary relative to their area (FT 2005a, 2005b). Some of the major factors that need to be taken into consideration when designing planned burning blocks include:

- relative location of the assets versus hazards
- location of potential ignition sources
- burning block size and shape
- location of suitable boundaries
- fuels within and adjacent to the burning block
- special values within and/or adjacent to the burning block.

When proposals for planned burns are made, a large amount of the background information required is available from map databases, reports and published sources. However, ground surveys are still required to ensure that this information is up-to-date, correct and representative of what actually occurs within the area planned for burning.

3.7 Fire-attributes vegetation associations in Tasmania

The main vegetation associations in Tasmania have been mapped by the TasVeg mapping program (Harris and Kitchener 2005). Due to the complexity of TasVeg classification and since it was not designed for fire management purposes, Pyrke and Marsden-Smedley (2005) used TasVeg1 to develop a fire-attributes vegetation map. The TasVeg map has recently been updated to TasVeg2. The TasVeg2 map has been simplified into 21 vegetation types fire-attributes types using the system in Pyrke and Marsden-Smedley (2005, Tables 3.1 to 3.3).

Table 3.1 Area, sensitivity and flammability of fire-attributes vegetation associations.

Fire-attributes vegetation		Fire sensitivity	Flammability	Area ha	Area %
Ac	Alpine/subalpine coniferous heathland	E	L - M	34 477	0.5
As	Alpine/subalpine heathland	M, VH	L - M	81 494	1.2
Ag	Alpine/subalpine sedgy and grassy	M	H	82 752	1.2
Sp	Sphagnum	H	L	3134	0.1
Bs	Buttongrass moorland	L	VH	576 306	8.5
Df	Dry forest	L - E	M - H	1 403 535	20.7
Dd	Dry woodland	L - E	M - H	27 480	0.4
Dp	Damp sclerophyll forest	M	M	95 671	1.4
Hh	Heathland	L - VH	H - VH	77 121	1.1
Ds	Dry scrub	L - VH	H - VH	150 181	2.2
Ws	Wet scrub	L - M	H	366 979	5.4
Wf	Wet sclerophyll forest and woodland	H	M	1 104 633	16.3
Mf	Mixed forest	VH	L - M	187 904	2.8
Rf	Rainforest	H - E	L	663 870	9.8
Rc	Coniferous rainforest	H - E	L	49 164	0.7
Gr	Native grassland	L	H	132 429	1.9
Pt	Agricultural land	L	M	1 186 855	17.5
Sr	Plantation	E	M	284 626	4.2
Ub	Urban	-	-	32 140	0.5
We	Flammable weeds and bracken	L	VH	26 191	0.4
Wl	Swamp and wetland	L	L - H	21 465	0.3
Wt	Lakes and rivers	-	-	14 132	2.2
Zz	Unvegetated	-	-	58 323	0.9
Total area				6 795 862	100.0

Note: L=low, M=moderate, H=high, VH=very high, E=extreme.
Table adapted from the TasVeg2 map using the system in Pyrke and Marsden-Smedley (2005).

In the vegetation mapping, the majority of the area covered by flammable weeds consists of: gorse in the Midlands, Derwent Valley, Fingal Valley and on the West Coast of Tasmania; or marram grass in coastal areas. The majority of the area mapped as agricultural land consists of cropland and/or improved pasture. Where agricultural land consists of bush runs used for stock grazing, the vegetation mapping has been based on the characteristics of the remaining native vegetation.

The fire-attributes vegetation associations suitable for planned burning are in Table 3.2, while the vegetation associations not suitable for planned burning are in Table 3.3 (see also FT 2005b). Nearly half of the area of Tasmania is covered by vegetation types suitable for planned burning (ie 2 760 222 ha or about 41%; see Tables 3.1 and 3.2). Issues related to the fire ecology of the Tasmanian fire-attributes vegetation associations are discussed further in Section 4.3.1.

Table 3.2 Tasmanian vegetation associations suitable for planned burning.

Fire-attributes code and vegetation association	
Dd, Df	dry forest and woodland
Bs	buttongrass moorland
Ds, Hh, Ws	heathland, dry scrub and wet scrub
Gr	lowland, highland and subalpine native grassland
We	flammable weeds

Table adapted from the TasVeg2 map using the system in Pyrke and Marsden-Smedley (2005).

Table 3.3 Tasmanian vegetation associations not suitable for planned burning.

Fire-attributes code and vegetation association	
Ac, As	alpine and subalpine heathland, with or without conifers and/or deciduous beech
Ag	alpine native grassland
Rf, Rc	rainforest, with or without conifers and/or deciduous beech
Dp	damp eucalypt forest
Mf	mixed forest
Wf	wet forest
Pt	agricultural land
Sp	sphagnum
Wl	swamp and wetland

Table adapted from the TasVeg2 map using the system in Pyrke and Marsden-Smedley (2005).

3.8 Fire regime

A site's fire regime comprises a wide range of factors including: age (ie time since fire); frequency (ie the time between fires); season; patchiness and intensity. The management aims for that site will determine which factors are the most important. When performing fuel management burns, the critical issues are ensuring adequate burn coverage and fire intensity. In contrast, when managing for ecological values (eg species diversity), the variability in fire frequency, season, patchiness and intensity may be the most important. The effects of variation in fire regime has been reviewed in detail by Gill (2008).

Bradstock et al. (2005; see also Gill et al. 2003) use the concept of the visible versus invisible mosaic. The visible mosaic consists of the current variation in fire age, season, patchiness and intensity. The invisible mosaic, which may be just as important for ecological management, is the temporal variation in previous fires' frequency, season, patchiness and intensity.

Site fire age is normally the main fire regime factor used in fire planning and operations. This is due to the ease with which age can be assessed, mapped and incorporated into planning along with its influence on vegetation structure, fuel-hazard, fuel continuity and fuel load. Fire frequency is typically much harder to assess than fire age, due to combining the effects of a large number of fire events over a larger number of years.

Information on fire history is normally obtained from fire crew records, fire history maps and/or ageing of the vegetation present at the site. A major issue with the collation of fire history information is recognising the potential for variation in fire behaviour across the site. Factors to be considered include:

- extent area burnt in the last fire
- variation in fire intensity
- variation in the fire history, prior to the last fire.

A major assumption in site ageing is that fire is the principle disturbance factor. For many vegetation types, and especially those suitable for planned burning (Table 3.2), this is not an unreasonable assumption due to many vegetation types undergoing pulse regeneration following fire. This results in the majority of the vegetation's understorey dating from the time of the last fire (see Marsden-Smedley et al. 1999). However, in some vegetation types, such as coastal heath and riverine scrub, fire may not be the only disturbance agent and vegetation regeneration may be more closely tied to storms and/or floods. In other vegetation types, especially those not suited to planned burning (Table 3.3), continuous regeneration may occur which is unrelated to fire (Jarman and Brown 1993).

When site ageing is conducted in Tasmania the normal system is either counts of banksia nodes or basal annual rings (Marsden-Smedley et al. 1999). Provided these counts are done correctly, both techniques are robust and accurate. However, the banksia node count system has the major advantage of providing data rapidly and non-destructively in the field, while the basal ring count system is slower and much more labour intensive.

Banksia node counts involve counting swellings on *Banksia marginata* branch junctions (Figure 3.1a). Banksias normally form one new branch node per season (although occasionally they will miss a season, or less frequently form multiple nodes in one season). The nodes on banksias up to about 25 years of age are normally quick and easy to count. With care, banksias up to about 100 years old can be reliably aged although the nodes on the lower trunk are normally hard to count in individuals older than about 50 years.

Where it is not possible to age a site from banksias, basal ring counts should be made from tea-tree species (ie *Leptospermum* spp.) due to their reliable, easily counted rings (see Figure 3.1b). Ring counts should be made by taking cross sections from just above the ground, drying the stem, polishing it with up to 1200 grade sand paper and counting the rings, normally using a dissecting microscope. Where banksia node or tea-tree ring counts are made a minimum of six individuals should be sampled. If other species are used, such as eucalypts (ie *Eucalyptus* spp.) or paper-barks (ie *Melaleuca* spp.) a minimum of 10 individuals should be sampled due to their poorer ring structure.

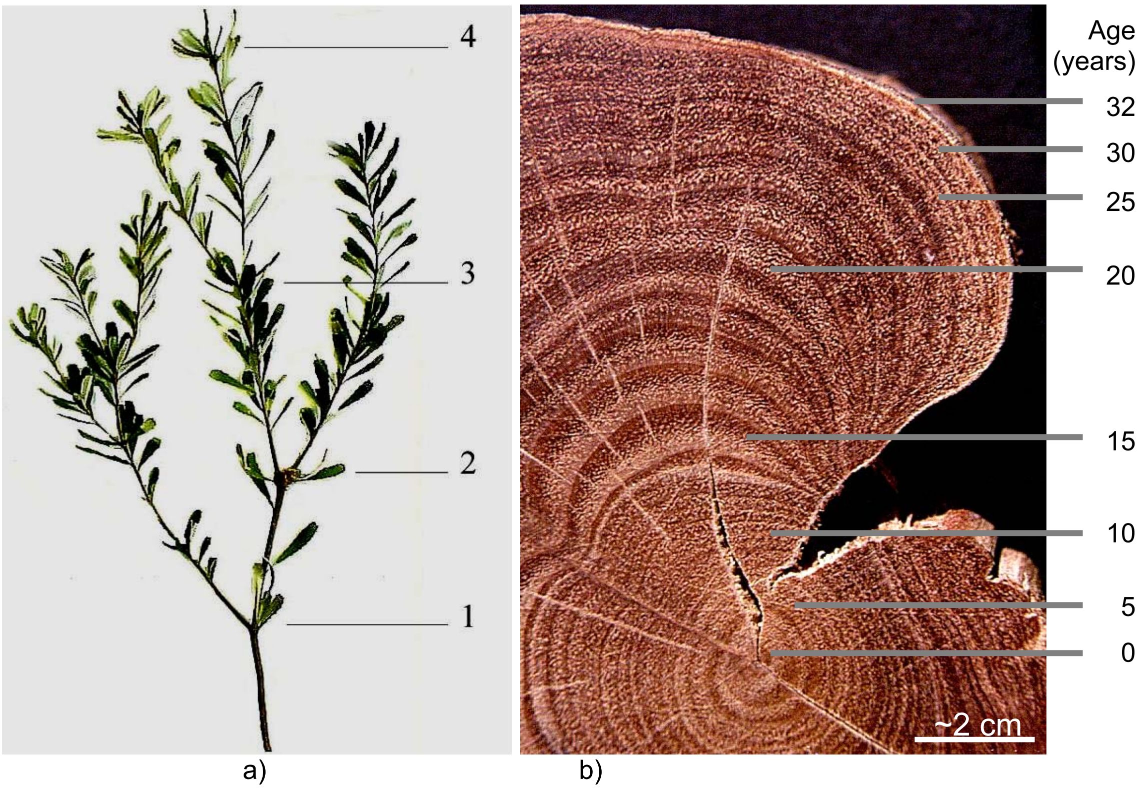


Figure 3.1 a) Banksia node and b) tea-tree ring counts.
Marsden-Smedley et al. (1999).

For fire management purposes, accurate age data is required for ages up to about 25 years post-fire, after which fuel characteristics normally reach equilibrium. At most sites, the age will be equal to the median count plus one.

3.9 Fuel characteristics

Prior to about 15 years ago the term *fuel characteristics* typically meant the total litter fuel load (Luke and McArthur 1978). Since this time there has been a growing realisation that fire spread rate is poorly correlated with fuel load, but well correlated with fuel structure and composition (Gould 1993; Marsden-Smedley and Catchpole 1995b; Gould et al. 2007a). As a result fuel-hazard rating systems have been developed, primarily for use in dry eucalypt forests (McCarthy et al. 1999; DEH 2008; Gould et al. 2007a, 2007b).

When fuels are assessed, except for bark fuels, dead fuel up to six millimetres in diameter and live fuel up to two millimetres in diameter is included. With bark, all dead bark likely to be burnt in a fire is included (ie including bark more than six millimetres in diameter). Fine fuels are also known as *short residence-time fuels* (in contrast to *long residence-time fuels* which are thicker than six millimetres in diameter). In the fire front, short residence-time fuels only remain alight for a short period of time (eg less than 5 to 30 minutes) and as a result have a low potential to result in re-ignitions at a later date. In contrast, long residence-time fuels may continue to sustain combustion for extended periods, and have the potential to cause fire re-ignitions.

3.9.1 Fuel cover and height

Intuitively, it should be possible to predict fuel characteristics from vegetation height and cover. However, it is rarely possible to do this accurately due to the difficulty of estimating the projective cover (ie the percentage cover of leaves, twigs and small branches) and height of multiple overlapping stratums.

Information on fuel height is required for heathland, scrub and dry eucalypt forest where it is used as an input in the fire prediction models (Marsden-Smedley 2002; Gould et al. 2007a, 2007b). In sites with a tree canopy, the height is also of concern due to interactions with scorch height, and the potential for fires to pulse and/or form crown fires. Pulsing and/or crown fires can result in increases in intensity, rate of spread and/or spotting.

The methodology used to estimate height is important given the potential for wide variation to result when different systems are used. When sampling heathland vegetation in southeast Queensland, McFarland (1988) determined the vegetation height by using transect point intercepts. When sampling dry eucalypt forest for the Project Vesta fire behaviour study, Gould et al. (2007a, 2007b) used a combination of line intercept transects and point quadrats.

In contrast, Marsden-Smedley (1993) estimated fuel height in buttongrass moorlands by looking across the top of the fuel array and recording the height below which the majority of the fuel occurred (ie ignoring the height of emergent shrubs). This system is less susceptible to bias due to its wide sampling area, is very quick to perform and works well in buttongrass moorlands, as height stratification and emergent shrubs typically consist of less than 12% of the fuel load (Marsden-Smedley 1993). However, looking across the top of the fuel array is not practical in taller vegetation and/or where clear lines of sight are not available. McCaw (1997) addressed the issue of variability in vegetation height by developing two systems, based on the heights of the 50^{th} and 70^{th} percentiles.

3.9.2 Fuel load

Most fuel load prediction models have been based on an asymptotic relationship developed by Olson (1963; see also Walker 1981). These models assume that fuel loads will steadily increase following fire until they reach a quasi-equilibrium state where fuel production equals fuel decomposition. The time taken to reach quasi-equilibrium fuel loads in Tasmanian vegetation types varies between about two years in some native grasslands (JB Kirkpatrick and JB Marsden-Smedley unpublished data) and up to about 20 to 40 years in many dry eucalypt forests (Fensham 1992; Neyland and Askey-Doran 1994; Bresnehan 1998; Bresnehan and Pyrke 1998) and buttongrass moorlands (Marsden-Smedley and Catchpole 1995a).

Information on Tasmanian fuel loads is available for dry eucalypt forest in southeast Tasmania (Fensham 1992; Bresnehan 1998; Bresnehan and Pyrke 1998) northeast Tasmania (Neyland and Askey-Doran 1994; PWS unpublished data), buttongrass moorland (Marsden-Smedley and Catchpole 1995a) and native grasslands (Leonard 2009). This means that fuel load accumulation in most Tasmanian vegetation types has been reasonably well researched. The relationships between time since fire and fuel load in some Tasmanian vegetation types are shown in Figure 3.2.

In Tasmanian buttongrass moorlands site productivity has a major influence on the fuel accumulation rate. In western and southwestern Tasmania, sites underlain by quartzite and/or quartzite derived substrates are classified as low productivity while sites in other parts of Tasmania and/or those underlain by dolerite, clay rich glacial till or limestone are classified as medium productivity (Marsden-Smedley 1993; Marsden-Smedley and Catchpole 1995a).

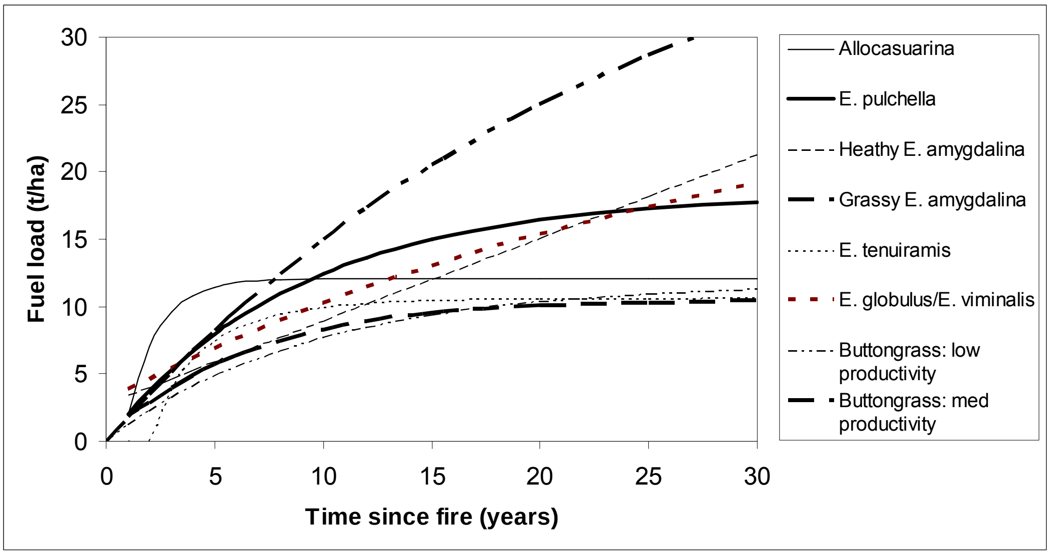


Figure 3.2 Fuel load versus time since fire in some Tasmanian native vegetation types. Predictions for *Allocasuarina*, *E. pulchella*, heathy *E. amygdalina*, grassy *E. amygdalina*, *E. tenuiramis*, *E. globulus/E. viminalis* from Bresnehan (1998); buttongrass low and medium productivity from Marsden-Smedley and Catchpole (1995a).

The fuel loads in Tasmanian native grasslands have been researched by Leonard (2009) who found that good fuel load estimates can be made using a function based on the combined sum of individual species height times cover. Leonard (2009) also found that highly consistent visual estimates of grassland curing (ie percentage dead fuel) can be made by different observers using a grassland curing guide, with the proviso that these estimates consistently under estimate curing by about 10%.

3.9.3 Fuel structure

In native vegetation the main fuel strata are: surface fuels; near-surface fuels; elevated fuels and bark fuels, along with canopy height and density (McCarthy et al. 1999; DEH 2008; Gould et al. 2007a, 2007b). The main fuel factor influencing the rate of fire spread is the near-surface stratum, while the main fuel factor influencing fire intensity is the total fuel load (Gould 1993; Marsden-Smedley and Catchpole 1995b; Gould et al. 2007a, 2007b).

3.9.3.1 Surface fuels

The surface fuel stratum is comprised of: dead grass; leaves; bark; and twigs; predominantly in a horizontal orientation and in contact or close to contact with the soil surface. Surface fuels typically contain the majority of the fuel load and often have elevated fuel moistures and relatively low aeration. This results in these fuels having minor influences on rates of spread, but major influences on fire intensity.

3.9.3.2 Near-surface fuels

The near-surface fuel stratum consists of live and dead fuels above the surface fuel stratum, and comprises both vertical and horizontal material. In some sites, the surface and near-surface fuel stratums intergrade with no clear break between them. Near-surface fuels are typically about 10 to 30 centimetres deep, but may be as high as one metre in some situations. Due to their proximity to the surface fuels, near-surface fuels will always be burnt in a fire. Near-surface fuels consist of fine fuel including: suspended bark; leaf litter; low shrubs; bracken; tussock grasses; and sedges and rushes.

3.9.3.3 Elevated fuels

The elevated fuel stratum consists of shrubs and tall bracken, which have a largely vertical orientation. They are typically about one to two metres tall, but may be 8 to 10 metres tall in wet eucalypt forests. This stratum has a major influence on flame height and the development of crown fires.

3.9.3.4 Bark fuels

The main bark types affecting fire behaviour are: smooth or gum barks; platy bark; and stringybark. Gum bark (also known as candle bark) consist of long, coiled bark strips which may burn for extended periods and be lofted in the fire's convection column, resulting in the potential to cause long distance spotting (ie >two kilometres). Platy bark (ie the bark tends to form small “plates”) from peppermints, ironbarks and pines is characterised by layers of dead bark which can flake off and cause short to medium range spotting (ie up to about two kilometres). Stringybarks form fibrous wads which can be removed by fire and can result in extensive short to medium range spotting.

Some bark types, notably stringybarks, may contribute up to seven tonnes per hectare to the fuel load (McCarthy et al. 1999; DEH 2008; Gould et al. 2007a, 2007b), contributing to fire intensity and providing massive amounts of potential firebrand material. Bark fuels are assessed for both overstorey and intermediate canopy strata.

3.9.3.5 Canopy height and density

Forest canopies mainly affect fire behaviour through influences on wind speed, and during high intensity crown fires, spot fire number and distance.

3.9.4 Fuel-hazard rating

In dry eucalypt forests the height (or depth as appropriate) and cover of the surface, near-surface, elevated and bark fuels are used to predict the fuel-hazard rating (McCarthy et al. 1999; DEH 2008; Gould et al. 2007a, 2007b). In buttongrass moorlands, fuel age is used as a surrogate for fuel-hazard (Marsden-Smedley and Catchpole 1995b). In native grasslands the percentage curing is used to estimate fuel-hazard (Cheney and Sullivan 1997). In heathlands and dry scrub, the fuel height is used to estimate fuel hazard (Anon 1998; Catchpole et al. 1998, 1999). In wet scrub, fuel height and age are used to estimate fuel-hazard (Marsden-Smedley 2002).

The Victorian and South Australian dry eucalypt forest fuel-hazard rating systems are intended to be a guide to fire suppression operations. These systems use different cover, height and continuity thresholds to the Project Vesta fuel-hazard rating system, which is intended to provide information for fire behaviour prediction (McCarthy et al. 1999; DEH 2008; Gould et al. 2007a, 2007b). In order to address these issues the Victorian Department of Sustainability and Environment has developed a fuel-hazard assessment system for southeastern Australia (see Table 2.2). The revised fuel-hazard assessment system will be used for:

- predicting fire suppression difficulty during planned burning and wildfire control operations;
- land managers planning fire management works
- property owners planning for wildfire protection (DSE unpublished).

The overall fuel-hazard rating has been defined as the sum of the surface, near-surface, elevated and bark fuel-hazard scores (McCarthy et al. 1999; DEH 2008; DSE unpublished). Gould et al. (2007a) have derived a similar factor called the fuel combustibility score which is defined as the sum of the product of the fuel-hazard and fuel cover scores.

3.10 Weather

Weather has major influences on fire behaviour through both direct and indirect influences. The major weather factors directly influencing fire behaviour are wind speed, fuel moisture and atmospheric stability. The major weather factors indirectly affecting fire behaviour through their influences on fuel moisture are: RH; Drought Factor (DF); SDI; wind speed; cloud type and cover; and temperature. The major factors affecting the Drought Factor and SDI are rainfall intensity and duration, the time since the rain fell, vegetation type and temperature.

The methodology for recording weather data is detailed in BoM (1997).

3.10.1 Wind speed

The major issues related to measuring wind speed are: its highly changeable nature (Gould et al. 2007a); and the difficulty of measuring wind speed in many sites. For wind speeds to be measured correctly large areas free of obstacles are required, with the width of the open area being at least 10 times the height of surrounding obstacles (BoM 1997). Alternatively, where clearings of sufficient size are not available, the 10 metre wind speed can be estimated using the Beaufort scale, as described in Table 3.4.

Table 3.4 Beaufort wind scale.

Category		km/h	Description
0	calm	<1	smoke rises vertically
1	light air	1 - 5	smoke drifts slowly, slight leaf movements
2	light breeze	6 - 10	wind felt on face, leaves rustle
3	light wind	11 - 20	leaves and small twigs move
4	moderate wind	21 - 30	dust raised, small branches moved
5	fresh wind	31 - 40	small trees sway
6	strong wind	41 - 50	large branches moved, wires whistle
7	near gale	51 - 60	large trees sway
8	gale	61 - 75	twigs and small branches broken off
9	full gale	75 - 90	large branches broken off
10	storm	91 - 115	trees uprooted, severe building structural damage

Wind speed is strongly affected by friction from the ground surface (BoM 1997), which means it is also necessary to record the wind measurement height. Where possible, wind speed should be measured at a height of 10 metres above the ground surface, although the surface wind speed (ie the wind speed at 1.7 or 2 metres above the ground surface) may also be recorded. In open sites, the wind speed at 10 metres above the ground averages about 1.5 times the surface wind speed (Marsden-Smedley 1993; Tran 1999). In forested sites, Tran (1999) and Gould (2007a) found that wind speed at 10 metres above the ground averaged about 2.5 times the surface wind speed. Tran (1999) also found an approximately 50% reduction in the 10 metre wind speed between open versus forested sites (canopy densities of about 20 to 55%).

Wind speed measurements and predictions, from the Bureau of Meteorology forecasts and automatic weather stations, are 10 minute averages. This means that there will be gusts with considerably faster wind speeds (typically by about 30%) and lulls with lower wind speeds, along with periods when the wind direction will vary. These periods of higher wind speed can temporally increase the potential for spotting, especially if they result in fires pulsing into the canopy. Changes in wind direction can also greatly increase spot fire build up by causing the fire to switch between head to flank, effectively increasing the effective fireline length (Cheney and Sullivan 1997; Section 3.13.3).

Diurnal changes in wind direction can often be effectively utilised during planned burning. Many of these wind direction changes are predictable, especially under stable atmospheric conditions. For example, the time and strength of sea breezes and/or katabatic/anabatic winds can be used during planned burning to burn off firelines during the day and then have the fire burn back onto recently burnt areas in the evening and overnight. Conversely, if these wind directions are not accounted for they can cause major problems.

3.10.2 Humidity and temperature

The moisture content of the atmosphere is normally described using the relative humidity (RH) and the dew point temperature.

A major characteristic of RH is its dependence on temperature with warm air being able to hold a greater amount of water vapour than cold air. For example, air at 30º C can hold about six times as much water vapour as air at 0º C. The RH is calculated as a percentage of the actual water vapour pressure present in the air, to the saturation vapour pressure (Figure 3.3).

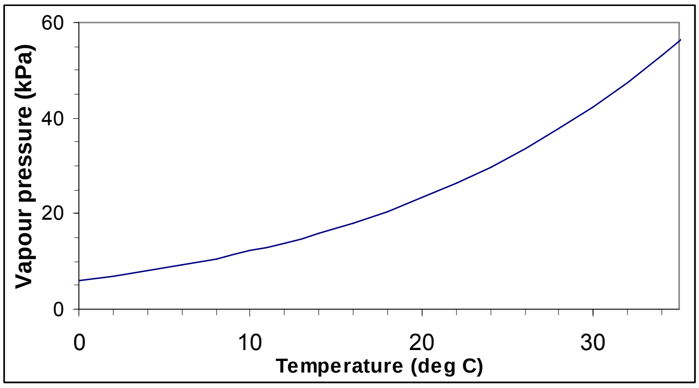


Figure 3.3 Saturation vapour pressure versus temperature.
Equation from Pendlebury (unpublished).

The dew point temperature is the temperature at which the vapour pressure of the moisture present in the atmosphere equals the maximum vapour pressure that the atmosphere can hold at that temperature (ie 100% RH).

Humidity influences fire behaviour through several aspects. RH is a major driver of fuel moisture, particularly when it falls below about 30%. At low fuel moistures embers tend to stay alight for extended periods resulting in increased potential for spot fires. In addition, low fuel moistures have a major influence on fire behaviour. When the dry bulb temperature falls to the dew point temperature and forms dew, there is typically a rapid increase in the fuel moisture content and a corresponding decrease in the level of fire behaviour.

Other than through its influence on the saturation vapour pressure, the dry bulb temperature has minor influences on fire behaviour. The dry bulb temperature does, however, have major influences on fire crew fatigue and the risk of dehydration, and as a result the ability of fire crews to manage fires and perform fire suppression operations.

3.10.3 Precipitation

Precipitation includes all moisture particles large enough to be deposited on the ground surface. It influences fuel moisture and hence fire dynamics through both short and long term effects.

Short term influences mostly occur to moisture content of fine dead fuel through the precipitation amount and time (typically hours) since the precipitation stopped. Long term influences mostly occur to heavier fuels through the precipitation amount, intensity and duration along with the time (typically days) since the precipitation stopped.

Precipitation may also be lost to the site through runoff and infiltration. Runoff occurs through two main sources, flash runoff and soil capacity runoff. Flash runoff occurs when the rainfall intensity exceeds the soil infiltration rate and can result in a significant proportion of the precipitation being directly removed from the system via drainage channels. This situation is a major issue in sites with organosols (ie as typically occur in buttongrass moorlands) which, due to their fine grain and high organic content, have low infiltration rates.

Aspect, topography and altitude have major influences on precipitation type, amount and duration, and as a result, the effect of precipitation on fuel moisture. In general, there is an increase in precipitation with altitude with a more marked increase in the number of days on which precipitation falls.

Precipitation is normally measured as the amount of rain in the 24 hours up to 09:00 (ie the 24 hour rainfall). In addition, in fire weather forecasts issued by the Bureau of Meteorology, the rain forecast to fall between 09:00 and 15:00 is specified as the 6 hour rainfall.

The amount and duration of precipitation along with the time since the precipitation fell is used to predict the SDI (Mount 1972) and the DF (McArthur 1967). The SDI provides an estimate of the longer term influences on coarse fuel moisture and the flammability of different vegetation types. The DF provides an estimate of short term influences on fuel moisture by predicting the proportion of the fine dead fuel available for burning. The SDI and DF will be discussed further below.

3.10.4 Atmospheric stability and inversions

The stability of the atmosphere, and the presence or absence of inversion layers, have major influences on fire weather and fire behaviour. This is mainly due to the likelihood that air from different altitudes will mix down to the ground surface and/or whether fires will form large convection columns.

The vertical structure of the atmosphere is normally described using the Bureau of Meteorology F160 aerological diagram (see also Appendix 5 of FPA 2009). A major issue with aerological soundings is the small number of sites where data is collected, with southeastern Australia soundings only being routinely made at Hobart, Melbourne, Mt Gambier, Adelaide, Wagga and Nowra, a distance between sites of up to 1000 km.

In the temperature profile on the F160 diagram, the environmental lapse rate (ie rate of temperature change with increasing altitude) is indicated by the slope of the line. When the temperature line on the F160 diagram is relatively straight a constant change in temperature with increasing altitude is indicated. Where the temperature line on the F160 diagram shows a kink to the right an inversion is indicated.

A stable atmosphere occurs when the rate of temperature decrease with increasing altitude is less than the adiabatic lapse rate. This means that if air is forced to rise it will be cooler than surrounding air, more dense and will tend to descend back down to a lower altitude. The effect of a stable atmosphere on fire behaviour will be to reduce the fire's ventilation rate, trap smoke close to the ground surface and reduce solar heating. This will tend to result in decreased wind speeds, higher humidities and lower temperatures.

A neutral atmosphere is where the environmental lapse rate equals the adiabatic lapse rate. This means that if air is forced to change altitude it will change temperature at the same rate as the surrounding atmosphere and hence, maintain the same density and not have a tendency to maintain further increases or decreases in altitude.

A unstable atmosphere occurs when the rate of temperature decrease with increasing altitude is greater than the adiabatic lapse rate. This means that if air is forced to rise it will be warmer than surrounding air and hence, less dense which means that it will tend to continue rising. The effect of an unstable atmosphere on fire behaviour will be to increase the fire's ventilation rate, allow smoke to dissipate and increase solar heating. This will tend to result in increased wind speeds, lower humidities and higher temperatures.

Inversions are layers of stable air where the temperature increases with increases in altitude and as a result act to decrease the tendency for air to change altitude.

Surface inversions are the main inversion type relevant to planned burning. They typically form overnight at the ground surface due to radiative cooling and result in a pool of cool to cold air beneath warmer air aloft. These inversions act to de-couple the atmosphere resulting in low wind speeds and high humidities at the ground surface. Surface inversions normally break down mid morning as a result of surface heating. Although, this breakdown may be delayed under cloudy conditions and/or when the atmosphere is smoky. Surface inversions are of major assistance during planned burning due to their influence on overnight fire behaviour, and their ability to increase the probability that fires will reduce to low fire behaviour levels and/or self-extinguish (Marsden-Smedley et al. 2001).

Predicting when inversions will form or break is a major issue during fire management operations, due to their influence on a wide range factors including: the degree of surface heating; which is in turn strongly influenced by the presence or absence of cloud cover and smoke. For example, on clear sunny and/or smoke free days the high level of solar radiation reaching the ground surface causes surface heating, updrafts and hence tends to erode inversions. In contrast, cloud cover and/or smoke in the atmosphere reduces surface heating and normally delays or prevents inversions breaking. This means that predictions of if and when inversions will form or break, have a higher degree of uncertainty.

Haines (1988) developed the Haines Index in order to incorporate information on atmospheric conditions into fire management operations by combining the effects of atmospheric stability and moisture content. The major advantages of the Haines Index are its simplicity, and its ability to provide information from higher altitudes above the ground surface. In doing so, the Haines Index overcomes a major short coming with the fire danger rating, which only considers weather information from the ground surface.

In Tasmania, Bally (1995) analysed the weather and fire data from seven fire seasons and found that about 84% of the area burnt occurred on the 25% of days when the Haines Index was five or six. In addition, Bally (1995) found that only about four percent of days had a Haines Index of six but these days accounted for about 44% of the area burnt. Bally (1995) also found that about 64% of the area burnt occurred on the nine percent of days when the Haines Index was five or six and the Forest Fire Danger Rating was ≥18.

However, a major issue with the Haines Index is that with 25% of days having an index of five or six, it provides poor discrimination between weather events which have high levels of atmospheric stability (although this issue is more of a problem in inland parts of the mainland of Australia, where about 50 to 75% of days have an index of five or six; Mills and McCaw 2009). In order to address this problem, Mills and McCaw (2009) developed the continuous Haines Index (C-HAINES) which varies between zero and a maximum of about 13. In Tasmania, about 95% of C-HAINES values are less than about 5.8 and 7.3 in the southeast and northeast respectively of the state. In their study of interactions between the C-HAINES and fire activity, Mills and McCaw (2009) found strong correlations between high values of the C-HAINES in the days leading up to and/or during days of high fire activity.

3.11 Fuel moisture

For fire management purposes, the term *fuel moisture* is the fuel moisture content of fine dead fuel, which has a diameter less than six milimetres, calculated as the percentage weight of water in the fuel to its oven dry weight. Fuel moisture influences ignition probability (Wilson 1985), fuel consumption rate (Rothermel 1972) and the transmission of radiant heat between fuel particles (Catchpole et al. 2001). Fuel moisture content is a critical factor in determining vegetation flammability and must be within a specific range for planned burning to be safely and effectively performed.

Under field conditions fuel moistures vary between a minimum of about two percent up to a maximum of about 200% with water occurring in two forms. When fuel moistures are less than the fibre saturation content of about 30 to 35%, water can occur within fibres and/or as vapour in intercellular spaces. At fuel moistures above about 30 to 35%, water can occur as liquid in intercellular spaces and/or on the surface of fuel particles (Cheney 1981).

The fuel moisture of extinction (ie the moisture content above which fires will not sustain) varies between about 8% in mallee, 16 to 20% in dry eucalypt forest, 20 and 24% (depending on the wind speed) in grassland, 30% in pine forest, 36 to 60% in gorse and heather and up to about 70 and 110% (depending on the wind speed) in buttongrass moorland (Luke and McArthur 1978, Hobbs and Gimingham 1984; McCaw 1997; Fernandes 2001; Marsden-Smedley et al. 2001; Baeza et al. 2002; De Luis et al. 2004; Cheney and Sullivan 1997; Leonard 2009; Anderson and Anderson in prep.).

In dry eucalypt forests, fires will fail to burn with adequate intensities and/or continuities when the dead-fuel moisture exceeds about 20 to 25%, but will typically burn with excessive intensities and with a high risk of spot fires when the dead-fuel moisture is less than about 11 to 13% (Tolhurst and Cheney 1999).

In buttongrass moorlands, fires will fail to burn with adequate intensities and/or continuities when the dead-fuel moisture exceeds about 35%, but will typically burn with excessive intensities and with a high risk of spot fires, when the dead-fuel moisture is less than about 15% (Marsden-Smedley and Catchpole 1995b, 2001).

Cheney and Bary (1969) found that when fuel moistures were above about 7% only large burning brands will start spot fires, but when the fuel moisture falls below about 4% most burning brands are capable of initiating new fires.

Live fuel moisture typically averages greater than 100% and acts as a damper on fire behaviour due to it exceeding the moisture of extinction. Live fuel moisture as a result has been found to be poorly correlated with the rate of fire spread in heathlands and moorlands (Marsden-Smedley and Catchpole 1995b; McCaw 1997; Catchpole et al. 1998, 1999).

3.11.1 Methods for determining fuel moisture

Dead fuel moistures are normally measured from field samples, estimated from secondary characteristics (eg the fuel's electrical resistance, or angle at which it will just support combustion or snap), predicted using surrogates (eg hazard sticks) and/or predicted using models based on the prevailing weather. A major issue with using secondary characteristics, surrogates and prediction models is ensuring that the system used is applicable to the fuel type being predicted. This means that systems should not be used outside the climatic, site, and fuel conditions for which they were developed without extensive checking and verification.

As with any system requiring the collection of field data, ensuring samples are representative of the prevailing conditions is of critical importance. Sampling fuel moisture is no different. When fuel moistures are measured, estimated from secondary characteristics and/or predicted from surrogates, it is critical that samples have been collected from the part of the fuel array carrying the fire (normally the near-surface fuels, see above). Samples also need to be collected from areas representative of the average conditions within the fuel array, and that are of sufficient size (ie about 10 to 30 grams) to average out minor variations in fuel moisture. For example, fuel moistures vary by about 2 or 3% depending on whether they are in the open or shaded (Luke and McArthur 1978; FT 2005a, 2005b).

In general, methods for predicting fuel moisture work poorly when the fuel moistures are above the fibre saturation point. This is due to the difficulty of predicting the effects of free water on fuel moisture (Pippen 2007).

3.11.1.1 Measurement of fuel moisture from field samples

The measurement of fuel moistures from field samples (ie gravimetric calculation) is the traditional and most accurate method of calculating fuel moisture. This method involves oven-drying fuel samples at between 80° and 105°C for 24 to 48 hours. Overall, 80°C for 48 hours is recommended given the risk of setting the drying oven on fire at higher temperatures, and since it gives the same result as higher temperatures (Leonard 2009). However, due to the time lag between sample collection and fuel moisture calculation, this method is impracticable under operational conditions, and there is a requirement to estimate fuel moisture by other techniques.

3.11.1.2 Estimation of fuel moisture from secondary characteristics

Fuel particle secondary characteristics can also be used to estimate fuel moisture. This normally involves determining: the fuel's electrical resistance; or the angle at which a fuel particle will just support flaming combustion; or the angle at which it snaps.

The Wiltronics fine fuel moisture meter (Chatto and Tolhurst 1997) uses pre-determined species specific relationships between fuel moisture and electrical resistance to estimate the fuel moisture.

The angle at which a fuel particle will just support combustion or at which it snaps can be used to estimate its fuel moisture using predetermined relationships (Burrows 1984, 1991). This system has the advantage of providing rapid estimates of fuel moisture in the field, but has the disadvantage that the relationship between the fuel moisture and the angle of combustion or snapping is species-specific and possibly site-specific (Burrows 1991).

The single leaf test can also be used to determine the *relative* moisture content of different parts of the fuel array. For example, if the burn objective is to only burn part of the fuel array (eg during ecological management burns), the single leaf test can be used to compare the relative differences in fuel moisture between upper and exposed versus the lower and shaded parts of the fuel array. This can indicate the conditions when fires will leave some fuel unburnt, resulting in potential reductions to erosion risk and possibly increasing the area suitable for seedling germination. Conversely, in burns conducted adjacent to high value assets (eg asset-protection burns on the urban interface) this system can be used to determine when the entire fuel array is dry enough to burn and hence, maximise fuel removal and minimise post-burn fuel-hazard.

3.11.1.3 Estimation of fuel moisture from surrogates

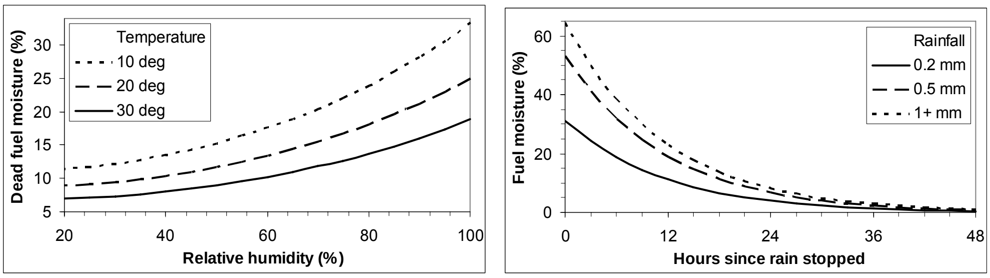
Fuel moisture can also be estimated using surrogates such as hazard-sticks. Hazard-sticks are arrays of wood (typically *Pinus radiata* in Tasmania) with a diameter of 12 millimetres and dry weight of 100 g. The advantage of hazard-sticks is that as well as being located within the fuel array (and subjected to the same conditions as the fuel array particles), they integrate the current and recent past conditions. This is particularly important in regard to precipitation, where the fuel moistures may lag considerably behind what would be expected based on the current weather. The main disadvantages of hazard-sticks are that the relationship between stick moisture and fuel moisture is vegetation-specific, sticks require standardisation time in the field prior to estimates of fuel moisture being made (typically 10 to 14 days) and stick life is typically less than about 12 weeks (Eron 1991).

Reliable systems for predicting vegetation flammability in wet and dry eucalypt forest can be made using 12 millimetres diameter hazard-sticks (Eron 1991; FT 2005a, 2005b). In wet scrub vegetation associations, good estimates of fuel moisture can be made from 12 millimetres diameter hazard-sticks (JB Marsden-Smedley unpublished). In buttongrass moorlands Marsden-Smedley and Catchpole (2001) found that 12 millimetres hazard-sticks gave poor predictions of fuel moisture due to their response time being too slow, and attempted to develop a hazard-stick system based on six millimetre diameter sticks. However, the relationship between fuel moisture and six millimetre hazard-stick weights was found to be highly seasonally dependent and better fuel moisture predictions could be made from the current humidity, temperature and recent rainfall (Marsden-Smedley and Catchpole 2001).

3.11.1.4 Prediction of fuel moistures from models

Fuel moisture models, using easily measured environmental parameters such as temperature, RH, dew point temperature, wind speed, solar radiation and/or recent rainfall can be used to predict fuel moistures under operational conditions. These models have the advantage of being able to make predictions using remotely collected data (eg data from automatic weather stations), but also have the major disadvantage that the fuel moisture models are vegetation-specific and should only be used within the bounds of the data used to develop the model.

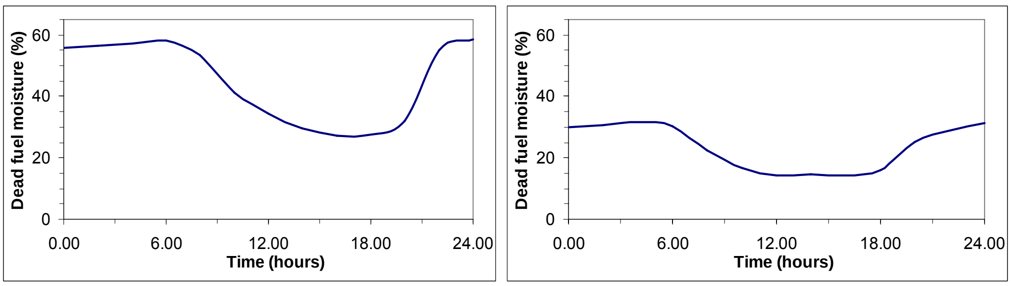
In buttongrass moorlands, Marsden-Smedley and Catchpole (2001) found that the best predictors of fuel moisture in the absence of precipitation, are the current RH and dew point temperature (see Figure 3.4a). The dew point temperature can be predicted from the RH and dry bulb temperature. The other major influence on buttongrass moorland fuel moisture is recent precipitation (Marsden-Smedley 1998b). The effect of precipitation typically lasts for up to 24 to 48 hours following significant rain events (eg greater than about 5 to 10 millimetres) and only about one to three hours following overnight dew fall (ie 0.05 to 0.2 millimetres), as shown in Figure 3.4b.



a) b)

Figure 3.4 Fuel moisture in buttongrass moorland.
a) effects of relative humidity, temperature and b) recent rainfall.
Marsden-Smedley (1998b), Marsden-Smedley and Catchpole (2001).

Fuel moistures typically show marked diurnal variation due to the effects of overnight increases in humidity, decreases in temperature and dewfall. For example, in buttongrass moorlands fuel moistures typically reach their minimum values in the early to mid-afternoon, and rapidly rise in the late afternoon and evening due to increasing humidity, decreasing temperature and dewfall. They reach their maximum values in the early morning before steadily falling during the mid-to-late morning (see Figures 3.5a and 3.5b).



a) b)

Figure 3.5 Predicted diurnal variation in fuel moisture in buttongrass moorland.
a) "typical" autumn and b) "typical" summer conditions.
Adapted from Marsden-Smedley (1998b), Marsden-Smedley and Catchpole (2001).

Aspect also influences fuel moisture in many vegetation types, particularly in low wind speed conditions. Anecdotal evidence suggests that there is a marked aspect effect, especially in autumn, winter and spring when the variation in solar radiation between different aspects is at its greatest (Nunez 1983). On different aspects in buttongrass moorland, Marsden-Smedley and

Catchpole (2001) found differences of about 2% in mid-day fuel moistures with the order from driest to wettest being:

northwest < northeast < southwest < flat = southeast.

A major shortcoming of the fuel moisture models is that they only use current conditions for humidity, temperature and, in the case of buttongrass moorlands, recent rainfall. As such, these models assume “average” conditions, which is acceptable for exposed very fine fuels, however, these models tend to perform poorly when conditions are outside those used for model development. For example, if conditions are windy, have low cloud covers and/or the season is mid-summer, then the actual fuel moisture may be lower than that predicted by the model. Conversely, under calm cloudy conditions and/or during late autumn, winter or early spring (ie when the level of solar radiation is low) then the actual fuel moisture may be higher than predicted.

The Matthews fuel moisture model (Matthews 2006; Matthews et al. in prep.) is recommended for use in Tasmanian dry eucalypt forests. In all other Tasmanian vegetation associations the buttongrass moorland fuel moisture model (including the recent rainfall function) is recommended (Marsden-Smedley et al. 1999; Marsden-Smedley and Catchpole 2001). This issue is discussed further in Section 4.2.

3.11.2 Soil Dryness Index and Drought Factor

The other major tools used in Tasmania to estimate fuel moisture are the Soil Dryness Index (SDI, Mount 1972) and the Drought Factor (DF, McArthur 1967). The SDI estimates the amount of rainfall required to saturate the soil profile and includes estimates of the effective rainfall once the effects of vegetation interception, runoff and evapotranspiration are taken into account. Although the SDI provides reliable information on heavy fuel moisture, it needs to be used with caution and anchored by data from the fireground.

The major concerns with the SDI relate to the rainfall interception, energy budget, the location of data prediction sites and the requirement to extrapolate the data to other locations in Tasmania. In addition, for much of the past decade the generally dry conditions across most of central and eastern Tasmania has resulted in the SDI not falling to zero at any time (and hence being re-set), resulting in the potential for cumulative errors to build up in the predictions of soil moisture. The rainfall interception relationship in the SDI is based on data measured in mature eucalypts and pine in NSW. These relationships have not been tested in Tasmania and it is not known how representative they are of Tasmanian conditions. In the SDI, the energy budget for evapotranspiration is estimated from the temperature. Observational evidence suggests that while this relationship works well in summer, it works poorly between late autumn and early spring. Most of the about 80 sites for which the SDI is calculated are in urban areas and hence it is necessary to extrapolate the SDI data and incorporate topographical effects to create the SDI map (see Figure 3.6). This means that the SDI can only provide a regional indication of soil moisture. Many planned burn sites will have different SDI values due to variation in precipitation, aspect, topography and/or altitude. Hence, although the SDI is a very useful and robust tool, it is critical that it is checked in the field prior to ignition.

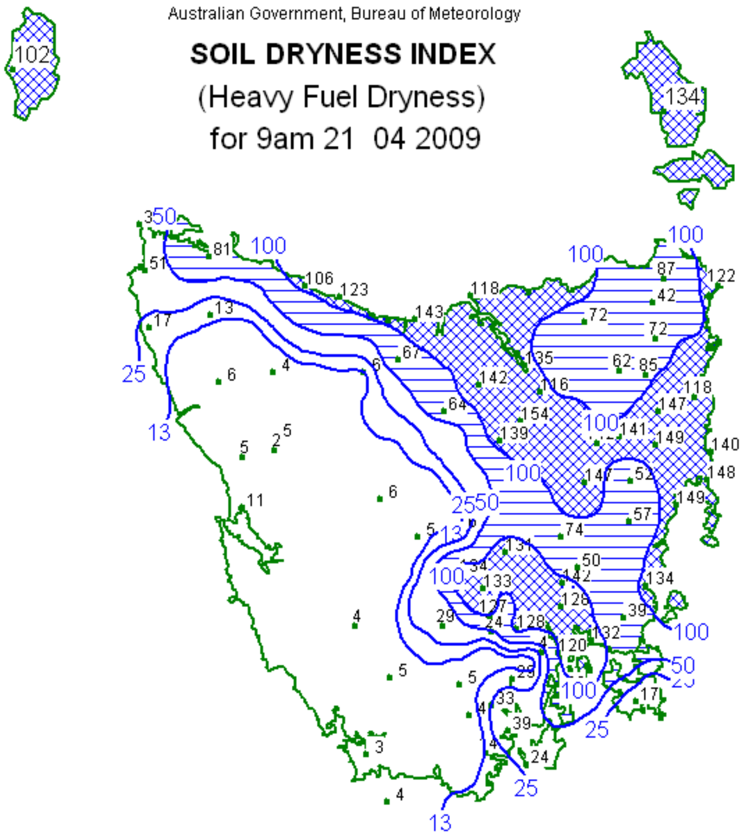


Figure 3.6 Soil Dryness Index map for 21 April 2009.

The SDI is mainly used to predict the relative flammability of different vegetation types (see Table 3.5) and fuel removal during planned burns. For example, if buttongrass moorland burns are performed with the SDI below 10, wet scrub boundaries will be too wet to burn and will form safe fire control lines. Similarly, wet gullies in dry forest may fail to sustain burning when the SDI is below about 25. The SDI also strongly influences the fuel moisture profile, with fuels under low SDI conditions (ie less than 10 in buttongrass moorlands and less than 25 in dry forests) typically showing a strong gradient in surface-fuels moisture between the moist lower fuels and drier upper fuels. This means that for planned burning to be effective for fuel management at least moderate SDI levels are required (eg in buttongrass moorland SDI between 10 and 25, and in dry forests SDI >50). In contrast, during ecological management burns the aim may be to leave significant amounts of fuel unburnt and this can be achieved by burning with a low SDI (eg in buttongrass moorland a SDI between five and 10, and in dry forests a SDI between 25 and 50). The relationships between vegetation flammability and SDI are summarised in Marsden-Smedley et al. (1999) and FT (2005a, 2005b).

Table 3.5 Vegetation flammability at different levels of Soil Dryness Index.

SDI	Community type	Flammability
≤10	buttongrass moorland	high
	wet scrub, dry eucalypt forest	very low
	all other vegetation types	non-flammable
11-15	buttongrass moorland	very high
	wet scrub, dry eucalypt forest	low
	wet-eucalypt forest	very low
	rainforest	non-flammable
16-25	buttongrass moorland	very high
	wet scrub	high
	dry eucalypt forest, wet-eucalypt forest	mod
	rainforest	non-flammable
26-50	buttongrass moorland	very high
	wet scrub, dry eucalypt forest	high
	wet-eucalypt forest	mod
	rainforest	low
>50	buttongrass moorland, wet scrub, dry eucalypt forest	very high
	wet-eucalypt forest	high
	rainforest	mod

Note: rainforest normally requires moderate or higher fire danger rating to burn.
Table summarised from Marsden-Smedley et al. (1999), FT (2005a, 2005b).

The DF combines the effects of recent rainfall and the days since rain with the longer term soil moisture conditions predicted by the SDI to estimate the fine fuel moisture. The DF estimates the proportion of the surface fuel that is dry enough to burn, and varies between 0 (all of the surface fuel is too wet to burn) and 10 (all of the surface fuel is dry enough to burn) and is used as one of the inputs in the McArthur Forest Fire Danger Meter (McArthur 1967).

3.12 Slope

The relationship between slope and fire behaviour was examined by McArthur (1967; see also Noble et al. 1980), who predicted that the rate of fire spread would double for every 10º of slope uphill and halve for every 10º of slope downhill (Figure 3.7). While McArthur (1967) provides no application bounds for this relationship, K Tolhurst (personal communication) suggests that the relationship should not be used on slopes outside the range of -10º to +20º.

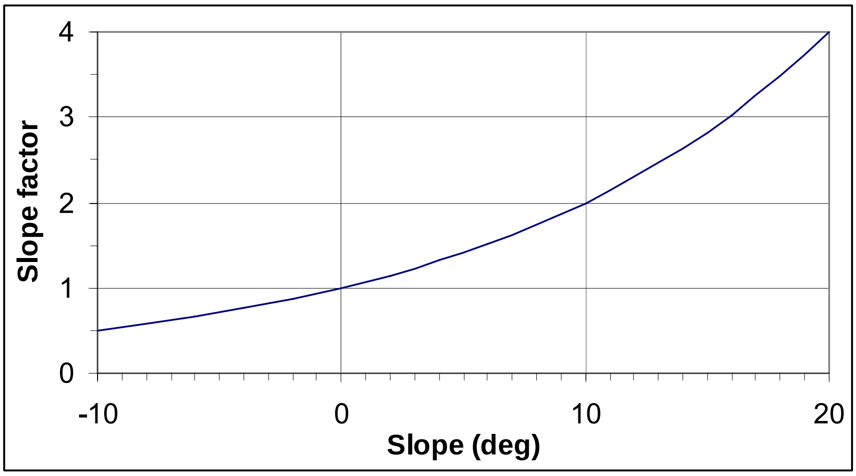


Figure 3.7 Relationship between slope and rate of fire spread.
McArthur (1967); Noble et al. (1980).

McArthur's (1967) slope correction factor has not been comprehensively tested in Tasmanian vegetation types. However, some data is available from buttongrass moorland fires burning up and down slopes of up to 30º. This data suggests McArthur's (1967) slope correction factor provides an appropriate system for correcting the rate of fire spread (Marsden-Smedley and Catchpole 1995b; Marsden-Smedley 1998b).

The slope correction factor developed by McArthur (1967) assumes that fires are travelling straight up or down the slope and that the fire has reached its quasi-steady state. In many cases, this will not be the situation with many fires being observed to burn across the slope. In order to address this issue, a spreadsheet has been developed which estimates the slope in the direction of fire travel. The available data suggests that the effective slope spreadsheet provides realistic corrections in Tasmanian dry eucalypt forests, heathlands and buttongrass moorlands (JB Marsden-Smedley unpublished data).

The time period required for fires to adjust their quasi-steady state when fires burn into areas with different slopes has not currently been researched. This is particularly an issue if fires are lit as a spot fire, or spot onto a slope. However, it is probable that the relationships covered below describing the effects of fireline length on the rate of fire spread will provide an adequate adjustment to the fire spread rate.

3.13 Fire behaviour

The main factors influencing fire behaviour are wind speed, fuel characteristics and fuel moisture with wind speed being the dominant factor (Sullivan 2009). However, the relative importance of these factors on fire behaviour varies at different wind speeds. At low to moderate wind speeds (ie <25 km/h) wind speed and fuel characteristics have similar levels of influence on fire behaviour in buttongrass moorlands and dry eucalypt forests (Marsden-Smedley 1998b; Gould et al. 2007a). At higher wind speeds (ie >25 km/h), wind speed becomes the dominant influence on fire behaviour (Marsden-Smedley and Catchpole 1995b). For example, in buttongrass moorlands burning with a wide range of high wind speeds (ie up to about 55 km/h) the proportion of the variation in fire spread rate explained by wind speed increases to about 40%, with fuel moisture and fuel characteristics both accounting for between 15 and 20% of the observed variation in fire spread rate (Marsden-Smedley and Catchpole 1995b).

3.13.1 Rate of fire spread

The rate of fire spread is normally estimated from its quasi-steady state. The quasi-steady state is the fire's average spread rate once minor variation resulting from short term changes in wind speed (eg gusts), fuel characteristics and/or topography have been accounted for.

The main components of a fire are the head fire, flank fire and back fire. The ratio between the head, flank and back fires is dependent on the vegetation type, wind speed and/or slope. McArthur (1966) reported temperate grassland head to flank fire ratios increased from 1:1 in the absence of wind to 6:1 for fires burning under strong wind conditions. Cheney and Bary (1969) suggest that the ratio between grassland head and flank fires was about 4:1. In arid spinifex grasslands, flank and back fires frequently do not sustain resulting in fires normally burning as long narrow wind driven head fires (Allan and Southgate 2002). Van Wagner (1969) in Canadian forests and Peet (1967) in Western Australian jarrah forests reported that the ratio between the head and flank fire spread rates averaged about 2:1. In Tasmanian buttongrass moorlands, Marsden-Smedley and Catchpole (1995b) found that the head to flank fire and head to back fire ratios average about 1.25:1 and 10:1 respectively.

3.13.2 Fire intensity

Fire intensity is normally described using Byram's Intensity (Byram 1959) and is based on the fuel's energy content, load and the rate of fire spread. Fire intensity can be used to predict flame height, with relationships being available for dry eucalypt forests, heathlands and buttongrass moorlands (Marsden-Smedley and Catchpole 1995b; Anon 1998; Catchpole et al. 1998; Gould et al. 2007a, 2007b).

Flames are normally described from their height, length, depth and residence time (see Figure 3.8; Tolhurst and Cheney 1999). The flame height is the average vertical height above the ground surface of the top of the flaming zone. The flame length is the average distance down the leading edge of flames. Note that when flames are vertical, flame height equals flame length. The flame angle is the angle between a line through the centre of the flaming zone and the ground surface on the leading edge of the flames. The flame depth is the width of the continuously flaming zone and is a function of the rate of fire spread and the residence time (ie the time taken for flaming combustion to burn out fuels).

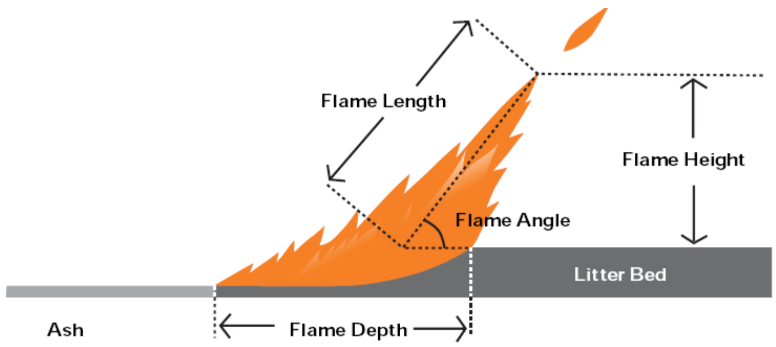


Figure 3.8 Flame dimensions.
Copied from Figure 3.7 in Tolhurst and Cheney (1999).

Good estimates of variation between head, flank and back fire intensities can be made from the rate of fire spread, fuel load and fuel energy content. However, variation between head, flank and back fire flame heights is more complicated due to the effects of flame angle variation between head, flank and back fires. The only study known to have specifically examined this variation (Marsden-Smedley and Catchpole 1995b) found that flank and back fire flame heights respectively averaged 60 and 50% of head fire flame heights.

3.13.3 Effect of fireline length on fire spread rate and intensity

Following ignition at a point, fires go through an acceleration phase with the vegetation type and wind speed influencing the length of fireline required for fires to reach their quasi-steady state (Cheney and Gould 1995). This length varies from between 50 and 100 metres for buttongrass moorland fires burning with wind speeds of up to about 30 km/h (Marsden-Smedley and Catchpole 1995b), about 100 metres for grasslands and up to about 300 to 450 metres for forest fires burning with high wind speeds (Gould et al. 2007b).

When fires are burning under constant conditions (ie when there is no variation in wind direction, wind speed, fuel conditions and topographic features) the head, flank and back fires will steadily increase according to the length to breadth ratio for that wind speed and vegetation type (see above). This means that with increasing time since ignition, there is a steady increase in the fireline length and as a result an increase in the rate of fire spread until the quasi-steady state is reached (see Figure 3.9). However, environmental conditions are rarely if ever constant, particularly wind direction, resulting in firelines switching between head, flank and back fires. This increase in flank fire spread results in an increase in fireline length and a marked reduction in the time taken for fires to reach their quasi-steady state (Figure 3.10; Cheney and Sullivan 1997).

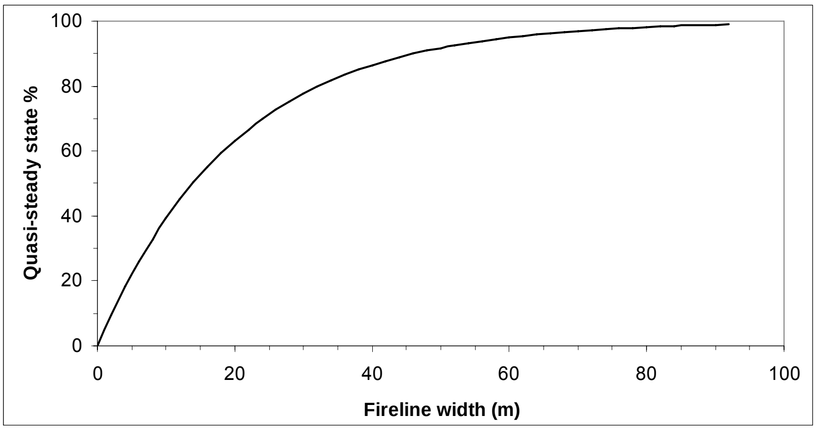


Figure 3.9 Effect of fireline width, as a percentage of the quasi-steady fire spread rate. Adapted from grassland fire behaviour models (Cheney and Gould 1995).

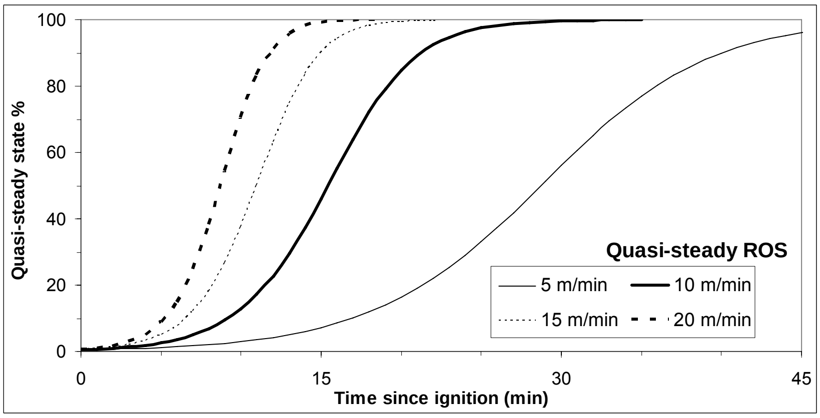


Figure 3.10 Rate of spread build up from a point ignition, as a percentage of the quasi-steady fire spread rate. Adapted from grassland fire behaviour models (Cheney and Gould 1995).

3.13.4 Scorch height

The tree scorch height has been examined by several studies, with the main factors influencing scorch height being fire intensity (ie flame height and Byram's Intensity), temperature and wind speed. Scorch is mainly a concern in dry eucalypt forest fuel management burning, due to its potential to increase litter fall and/or result in overstorey tree damage or death. For example, O'Connell et al. (1979) in Western Australian Jarrah forest found a five-fold increase in litter fall from 0.7 t/ha to 3.4 t/ha in the six months following a fire which extensively scorched and partly consumed the forest canopy.

Van Wagner (1973) developed a predictive equation for Canadian pine forests which uses Byram's Intensity and temperature to predict scorch height. Gould et al. (1997) extended van Wagner's work and developed a series of predictive equations which incorporate the effects of wind speed, which acts to push flames down and disperse the heat released by the fire. However, it needs to be noted that although for a given fire intensity an increase in wind speed has the potential to decrease the potential for canopy scorch, in most situations the effect of increasing the wind speed will be to increase fire intensity and hence increase the degree of canopy scorch.

There is considerable variation in predicted scorch height between different systems. The equations in Gould et al. (1997) suggest that scorch height will average about three to 10 times the flame height, depending on fire intensities, temperatures and wind speeds. FT (2005b) states that the scorch height is dependent on the wind speed, fuel load, RH and temperature, and averages about five times the flame height. QPWS (2008a, 2008b) predicts scorch height will average about five times the flame height. ACT (2008) and DSE (2008) predict scorch height will average six to eight times the flame height in spring, and 10 to 14 times the flame height in autumn due to the typically drier fuels in autumn. Overall, the system detailed in DSE (2008) is recommended for use in Tasmanian dry eucalypt forest fuels.

Where trees less than about 10 to 15 metres tall occur within planned burning blocks it is normally not possible to prevent scorching (and frequently torching) due to the entire canopy being within the flaming zone. This situation is particularly an issue during burns in heathlands, buttongrass moorlands and dry eucalypt woodlands.

Scorch is mainly an issue following asset management burns due to the potential for leaf fall to increase the level of surface fuel-hazard immediately following planned burning. This issue is particularly a problem where the planned burn targets bark removal in dry eucalypt forest and hence, requires fires to be burnt at moderate intensities and/or with dry fuels. Canopy scorch may also result in increased economic damage to standing trees in dry eucalypt production forests (FT 2005b). The probability of canopy scorch during dry eucalypt forest burns can be minimised by ensuring burns are conducted at four to six year intervals (and hence with low to moderate surface and near surface fuel loads and fuel-hazards).

However, canopy scorch is not necessarily an issue in areas reserved for conservation. In these areas, current ecological theory is suggesting that the potential for ecological values to be maintained will be enhanced under a fire regime which includes a wide range of fire intensities, including in some circumstances, high intensity fires (see below).

3.13.5 Sustaining versus non-sustaining fires

The issue of whether fires will sustain or self-extinguish is of critical importance to fire management in general and planned burning specifically. In some situations planned burns are undertaken on large sites which do not contain internal boundaries, and where the aim is to only burn part of the site. In these situations, the ability to predict when fires will self-extinguish (ie go out without fire suppression or the use of boundaries) is required.

Systems examining the thresholds between sustaining and non-sustaining fires have been performed using field experiments in Tasmanian buttongrass moorlands (Marsden-Smedley et al. 2001), Tasmanian native grasslands (Leonard 2009) and Portuguese maritime pine (Fernandes et al. 2008). Laboratory experiments have tested NSW heathland fuels (Plucinski 2003) and Californian chaparral (Weise et al. 2005). These systems use a range of fuel, weather and site variables to estimate the probability that fires will sustain. These factors include fuel moisture (dead and live), wind speed, fuel load, fuel bulk density, fuel continuity, fuel type, slope and site productivity.

In buttongrass moorlands, the main factors influencing the likelihood of fires sustaining are wind speed, fuel moisture and site productivity (Marsden-Smedley et al. 2001). In native grasslands, the main factors influencing the likelihood of fires sustaining are fuel moisture, fuel load and wind speed (Leonard 2009). However, in these vegetation associations the thresholds at which fires sustain or self-extinguish are very different, with the fuel moisture of extinction in buttongrass moorlands and native grasslands being about 76% and 24% respectively (Marsden-Smedley et al. 2001; Leonard 2009).

3.13.6 Fire danger rating

The primary aim of the fire danger rating is to provide a description of fire suppression difficulty and was developed in Australia by Luke (1953) with further development by Douglas (1957) and Luke and McArthur (1978; see also Cheney 1988).

In Tasmania, three systems are used for estimating fire danger:

1. Forest Fire Danger Rating (FFDR, McArthur 1973)
2. Scrub Fire Danger Rating (SFDR, Marsden-Smedley 2002)
3. Moorland Fire Danger Rating (MFDR, Marsden-Smedley et al. 1999).

In Bureau of Meteorology fire weather forecasts a time since fire of 10 years is assumed in the MFDR and SFDR.

The fire danger rating integrates the influences of fuel, site factors and weather on fire behaviour, into a dimensionless index of fire behaviour and control (ie suppression) difficulty. The fire danger rating system has recently been updated and consists of a numerical value and a rating class. The numerical values vary between 0 (fires will not sustain) up to in excess of 100. The rating classes vary between:

- low	0 to 5	fire control relatively easy
- moderate	6 to 11	direct attack on fires possible if well resourced
- high	12 to 24	fire control difficult and frequently fails
- very high	25 to 49	fire control very difficult
- severe	50 to 74	fire control unlikely to be feasible or safe
- extreme	75 to 99	fire control not feasible or safe
- catastrophic	100+	very high level threats to life and property.

3.13.7 Fire behaviour prediction systems used in Tasmania

To date, fire behaviour prediction systems have been developed for Tasmanian buttongrass moorlands (Marsden-Smedley et al. 1999) and heathlands (Anon 1998; Catchpole et al. 1998, 1999; Marsden-Smedley 2002). For dry eucalypt forest the McArthur Forest Fire Danger model

(McArthur 1973) has been the standard system for over 30 years with the Vesta Fire Model being recently developed (Gould et al. 2007a, 2007b). While predictions of grassland fires are not routinely made in Tasmania, the Northern Territory grassland model (Cheney et al. 1993) has been used by some practitioners. Leonard (2009) developed a system for predicting sustaining versus non-sustaining fires in native grasslands.

The Department of Sustainability and Environment in Victoria is currently coordinating a project collecting standardised fire data from planned burns and wildfires (https://fireweb.dse.vic.gov.au/argus/dms/welcome). The aim of this data collection is to examine the effects and impacts of a wide range of fires for the purposes of determining appropriate fire management practices. For example, this data collection will be used to test fire prediction tools (including the Vesta dry eucalypt forest model), effectiveness of fuel management strategies and the impacts of fire on ecological factors such as species and/or structural diversity.

A standardised fire prediction spreadsheet has been developed for southern Australia as part of the Fire Behaviour Analyst course run by the Department of Sustainability and Environment in Victoria. The spreadsheet FireBehaviourCalcs_SouthernAustralia.xls incorporates the following models:

- dry eucalypt forest — McArthur Forest Meter: McArthur (1973)Project Vesta: Gould et al. (2007a, 2007b)
- CSIRO grass — Cheney et al. (1993, 1998), Cheney and Sullivan (1997)
- heathland — Anon (1998), Catchpole et al. (1998, 1999)
- buttongrass moorland — Marsden-Smedley and Catchpole (1995b, 2001), Marsden-Smedley et al. (1999, 2001)
- WA Red Book — Beck 1995
- WA mallee — McCaw 1998.

When predictions of fire behaviour are made in Tasmanian vegetation types, the fire behaviour prediction systems detailed in Table 3.6 are recommended. With the exception of wet scrub these predictions can be made using the standardised fire prediction spread sheet. When fire predictions are required for wet scrub vegetation types, the Scrub Fire Danger Prediction system (Marsden-Smedley 2002) should be used.

Table 3.6 Fire behaviour prediction systems recommended for use Tasmanian vegetation associations.

Vegetation association		Fire prediction system	Reference
Dd, Df	dry eucalypt forest and woodland	McArthur Forest Fire Danger Meter Project Vesta	McArthur 1967 Gould et al. 2007a, 2007b
Bs	buttongrass moorland	Buttongrass moorland fire prediction model	Marsden-Smedley et al. 1999
Ds, Hh	heathland, dry scrub	Heathland fire model	Anon 1998; Catchpole et al. 1998, 1999
Ws	wet scrub	Scrub Fire Danger prediction system	Marsden-Smedley 2002
Gr	native grassland	CSIRO grassland fire prediction model	Cheney et al. 1993
We	flammable weeds	Scrub Fire Danger prediction system	Marsden-Smedley 2002

3.14 Implementing planned burning operations

The previously used methods for conducting planned burning in Tasmania were detailed in FT (2005b). The methodology for planned burning operations has been revised using published sources, unpublished reports and expert opinion from experienced practitioners, and are presented below.

3.14.1 Ignition methodology, lighting patterns, control lines and test fires

The methodology used to ignite burns, and the location of the ignition points relative to site conditions, will have a major influence on the resulting rate of fire spread, fire intensity, spotting potential and fire control options. In this area, the major factors include the intensity of ignition spacing, fireline length ignited, orientation of the ignition to site slope and wind direction along with variation within the burn area in fuel type and fuel moisture.

The length of active fireline has major influences on the rate of fire spread, fire intensity and spotting potential (see Figures 3.9 and 3.10). For example, in grassland fires burning with fireline lengths of about 10, 25, 50 or greater than 100 metres, will burn with about 40%, 75%, 90% or 100% respectively of their potential fire spread rates (see Cheney and Gould 1995). This means that if the length of active fireline is kept short by careful ignition techniques the resulting level of fire behaviour can also be kept low.

The level of fire behaviour is also strongly influenced by the orientation of the ignition line to the direction of the site slope and/or wind direction.

The relationship between the rate of fire spread and site slope was described by McArthur (1967) with the rate of fire spread upslope predicted to double for every 10º upslope and conversely to halve for every 10º down slope (see Figure 3.7). This means that in sites with slopes of greater than about 5º the level of fire behaviour can be strongly influenced, with the rate of fire spread being increased or decreased as appropriate.

The orientation of the fireline to the prevailing wind direction will determine whether a fire will burn as a head, flank or back fire. With the exception of buttongrass moorlands, the relationships between head, flank or back fire rates of fire spread are poorly understood. In buttongrass moorlands, flank and back fires typically burn with about 40% and 10% respectively of the head fire rate of spread (Marsden-Smedley and Catchpole 1995b).

When planned burns are conducted, variations in fuel type and moisture within the burn area can be utilised to influence fire behaviour. In most sites, ridgelines and north-to-northwest facing slopes will have lower fuel moistures and less available water than gullies and south-to-southeast facing slopes. This results in ridgelines and north-to-northwest facing slopes typically having more open vegetation, shallower soils, lower fuel loads and more frequent fires than gullies and south-to-southeast facing slopes. This variation can be used during planned burning to influence the level of fire behaviour and the location of fire control lines. For example, when planned burns are conducted when the fuel moisture in gullies and/or south-to-southeast facing slopes is too high to sustain burning, these areas can be used as control lines resulting in fires only burning ridgelines and/or north-to-northwest facing slopes.

The most common ignition patterns utilised during planned burning are back fire ignition, flank fire ignition, head fire ignition, spot fire ignition, centre fire ignition and perimeter fire ignition.

Backing fire ignition is where fires are lit such that their direction of fire travel is back into the prevailing wind direction and/or down slope, resulting in the rate of fire spread and intensities being kept to a minimum. This technique is normally utilised when fuels are relatively dry and/or weather conditions are such that head and/or flank fires would burn with excessive rates of fire spread, intensity, scorch and/or spotting. Hence, the critical aim of this lighting strategy is to keep the level of fire behaviour as low as practical. Flank fire ignition is where fires are lit as lines parallel to the direction of fire spread and/or straight up-down slopes, resulting in intermediate level rates of fire spread and intensity. Head fire ignition is where fires are lit as lines with the wind and/or straight across slopes, resulting in rate of fire spread and intensity being maximised. This technique is normally used when fuels are relatively moist and/or under mild weather conditions.

Spot fire ignition is where fires are lit as a series of independent spot fires so that the spots will join up in the cool of the evening and/or burn into and self-extinguish in less flammable fuels (eg gullies or south to southeast slopes). The aim of this technique is normally to minimise fire junction zones and excessive levels of fire behaviour. However, if fuels are relatively moist and/or the weather conditions are mild, this technique can be used to intensively light up areas with the fire junction zones acting to increase the level of fire behaviour and reduce the burnout time.

Centre fire ignition is where fires are lit in the centre of a block so the fire creates its own wind and pulls the fire away from the boundary. This strategy is most effective when the wind speeds are low, the atmosphere is unstable (increasing the potential for the fire to form updrafts) and/or where the block has a central hill so up-slopes can be utilised.

Perimeter fire ignition is where the block is lit, normally as strips from pre-existing fire breaks (eg roads, tracks and/or rivers), and allowed to burn into the block.

The control lines used during planned burning will be dependent on whether any pre-existing firebreaks exist, the characteristics of the burning block, fuel moisture, level of fuel-hazard and the prevailing weather conditions. The utility of constructing fire breaks for fire management has been extensively reviewed by Gill (2008). The main types of control lines used are hand trails, tracks, roads, rivers, fuel reduced areas and natural boundaries which are too wet to burn. The mechanisms through which fires cross control lines are mainly via direct flame contact across the track, spot fires and to a lesser extent radiant heat igniting fuels on the unburnt side of the track (Wilson 1988). The issue of when natural boundaries will be too wet to burn has been covered above in the section on the Soil Dryness Index. Where planned burning is performed using narrow four-wheel drive tracks or handlines, the upper fire intensity limit should be about 500 kW/m, or a flame height of about 1 to 2 m.

The most significant factors influencing fire crews' ability to hold fire breaks are the length of fireline, ease of access, wind speed and fuel-hazard (McCarthy et al. 2003). The last two of these factors are also major influences on the level of fire intensity and potential for spot fires.

The length of fireline capable of being held by a six person hand crew varies from about 30 to 60 metres in wet sclerophyll forests, up to about 420 metres in light open fuels (eg grassland). For tankers, the rates of fireline capable of being held per tanker range between about 100 metres in areas with high levels of fuel-hazard and/or difficult terrain, and up to about 1000 metres in flat areas with low levels of fuel-hazard (McCarthy et al. 2003).

The most significant factors influencing fire crews' ability to hold firelines are spot fire number and distance. The major influences on spot fire number and distance are RH, wind speed and bark hazard (where present). There are two main spot fire types, short range spotting from where a fire burns up to a boundary and the column collapses, versus longer range spotting from firebrands carried aloft in a fire's column which are still alight when they fall out of the column and land in unburnt fuels (Gould et al. 2007a).

When planned burns are lit, the main ignition methods are hand lighting using drip torches or incendiary launchers, or aerial ignition using incendiary capsules or aerial drip torches.

A major issue associated with planned burn ignition is balancing the intensity at which the burn is lit (eg the length of fireline lit and/or the number of incendiary capsules used) against the required level of fire behaviour. If fires are lit with a close spacing there will be a high potential to rapidly form junction zones, cause enhanced local wind speeds and resultant increases in the rate of fire spread, intensity and potential for spot fires.

The data in Table 3.7 indicates the recommended spacing between capsules and/or drip torch lines of fire. Where drip torch lines of fire shorter than 10 metres are used, the fire build-up time will be slower, and faster if lines longer than 10 metres are used.

Table 3.7 Planned burn ignition spacing (m).

Hours available to burn out block	Fire spread rate (m/min)							
	0.5	0.75	1.0	1.5	2.0	2.5	3.0	5.0
Incendiary capsule spacing (m)								
1	5	10	20	40	70	110	125	250
2	10	40	70	125	200	275	325	600
3	30	80	135	225	325	440	525	925
4	60	130	200	325	450	600	725	1250
5	90	180	250	425	600	775	925	1500
6	125	225	325	525	725	925	1125	2000
Spacing (m) between lines if using aerial or handheld drip torch: assumes 10 metres of fireline lit								
1	20	30	50	75	100	140	170	300
2	50	75	100	175	240	300	370	630
3	75	125	175	270	370	470	570	960
4	100	175	225	370	500	635	765	1300
5	140	225	300	470	635	800	965	1625
6	175	275	370	570	765	965	1160	2000

Table calculated using quasi-steady state rates of fire spread and estimates of fire build-up time using relationships in Cheney and Gould (1995).

Test fires can be used to indicate the likely level of fire behaviour once the main fire has been lit. However, in order to be effective, test fires need to be applied in sites representative of the main burning block, and be allowed to expand until they reach their quasi-steady state. This will require fireline lengths of at least 50 m, meaning that if the level of fire behaviour is too high, fire suppression will normally be very difficult and may be impossible. If information is collected from test fires burning with shorter fireline lengths, the predicted level of fire behaviour will need to be estimated using the relationship described in Figure 3.9.

3.14.2 Smoke management

The proportion of the fuel array converted to smoke depends on the fuel moisture and fire intensity, and varies from less than 0.5% in very dry wildfires, about 2 to 4% during flaming combustion in planned fires to about 15% in smouldering combustion (Valianatos et al. 2003).

Smoke colour provides an indication of the level of fire behaviour. White smoke is an indication of high fuel moistures and typically low levels of fire behaviour, grey smoke indicates moist fuels and mild to moderate intensity fires, black smoke indicates a high proportion of large particulates and soot from incomplete combustion of dry fuels and high to very high fire intensities while copper-bronze smoke indicates very small particulates, very dry rapidly burning fuels and very high to extreme fire behaviour (Valianatos et al. 2003).

The impact of smoke will be dependent on the relative balance between smoke production verses smoke dispersal, and the relative location of burns to urban areas, the characteristics of the fuels burnt, the amount of fuel burnt and the condition of the atmosphere. As was noted above, the fuel moisture will influence the proportion of the fuel load that is converted to smoke. Once smoke has been produced, the degree of atmospheric ventilation, along with the presence and height of atmospheric inversions, will influence the ability of the atmosphere to disperse and remove smoke.

Smoke management guidelines are currently being trialled in Tasmania by the Forests Practices Authority and the Environmental Protection Authority, affecting all planned burns conducted by the Parks and Wildlife Service, Forestry Tasmania and the forest industry. Currently, burns on private land are not included.

The primary aim of the smoke management guidelines is to minimise adverse impacts on urban areas containing 200 or more residents (FPA 2009). It works on the assumption that the atmosphere is capable of absorbing a set amount of smoke before exceeding planned limits. This capacity is dependent on the atmospheric ventilation, presence of inversions and the direction and extent of plume dispersal. The smoke management system then prescribes limits on the amount of fuel which can be burnt under different conditions. The system divides the atmosphere into two zones: above 1500 metres where smoke is assumed to disperse; and below 1500 metres where smoke may be trapped if there is a inversion. When burns are planned they are allocated to one of the nine zones or airsheds used in the Bureau of Meteorology’s smoke dispersion model, which predicts the speed and direction of smoke travel and the locations that will potentially be impacted by smoke. The other main factor used in the smoke management system is the amount of smoke produced, which is dependent on the fuel load and vegetation type.

4. Fuel, Fire Behaviour and Fire Ecology Research

The aim of this section of the report is to review fuel characteristics, fire behaviour and fire ecology research (both published and unpublished), along with expert knowledge that has not been previously incorporated into the systems used for conducting planned burning in Tasmania.

The main areas covered in this section of the report are:

- fuel-hazard rating in dry eucalypt forest
- fuel moisture models
    - dry eucalypt forest
    - heathlands, dry scrub, wet scrub
    - native grassland
- fire behaviour
    - dry eucalypt forest
    - heathlands, dry scrub, wet scrub
    - native grasslands
    - weed management using fire
- planned burning systems used in Australia
- expert opinion regarding planned burning operations in Tasmania
- ecology, geomorphology, fire regime modelling and climate change
    - fire ecology
    - geomorphology
    - weed management with fire
    - fire regime modelling and climate change
- knowledge gaps and further research required.

4.1 Dry eucalypt forest fuel-hazard

The most appropriate fuel characteristics input for assessing fire danger and predicting fire behaviour in dry eucalypt forest are the fuel-hazard ratings of the surface, near-surface, elevated and bark stratums (Gould 1993; McCarthy et al. 1999; Gould et al. 2007a). To date, dry eucalypt forest fuel-hazard rating systems have been developed in Victoria, South Australia and Project Vesta in Western Australia.

As was covered above, the Victorian and South Australian dry eucalypt forest fuel-hazard rating systems are intended to be a guide to fire suppression operations and use different cover, height and continuity thresholds than the Project Vesta fuel-hazard rating system, which is intended to provide information for fire behaviour prediction (McCarthy et al. 1999; DEH 2008; Gould et al. 2007a, 2007b). In order to address these issues the Victorian Department of Sustainability and Environment has developed a fuel-hazard assessment system for southeastern Australia (see Table 2.2).

The published Victorian fuel-hazard rating system provides information on the surface, elevated and bark fuels (Table 4.1; McCarthy et al. 1999). The South Australian fuel-hazard systems extends the Victorian system to include the mallee fuel types and incorporates information on the near-surface fuel-hazard layer into the surface fuel layer (Table 4.2; DEH 2008). The Project Vesta fuel-hazard assessment system provides information on the surface, near-surface, elevated and bark fuels (Table 4.3; Gould et al. 2007a, 2007b).

Table 4.1 Victorian fuel-hazard rating system. (McCarthy et al. 1999).

Hazard rating	Description
Surface fuel-hazard	
Low	litter depth including duff: <15 mm, <4 t/ha.
Mod	litter depth including duff: 15 - 25 mm, 4 - 8 t/ha.
High	litter depth including duff: 25 - 35 mm, 8 - 12 t/ha.
Very high	litter depth including duff: 35 - 50 mm, 12 - 20 t/ha.
Extreme	litter depth including duff: >50 mm, >20 t/ha.
Near-surface fuel-hazard	
Where >40% cover of grass tussocks, dead bracken, low shrubs or wiregrass up to 0.5 m increase the surface fuel-hazard score to the next higher hazard class.	
Elevated fuel	
Low	very little elevated fuel.
Mod	sparse and dispersed fuels with <20% cover with little or no dead material.
High	moderately dense fuels mostly 0.5 to 1 m tall with <20% dead material.
Very high	heath, bracken and shrubs 0.5 to 1.5 m tall dense enough to suspend bark, twigs and leaves, 20 - 30% dead material, most fuel particles <2 mm thick; wiregrass 0.5 to 1 m tall dense enough to suspend bark, twigs and leaves; dense grasses and annuals >1 m tall which are ≥80% cured.
Extreme	tea-tree, paperbark, heath or wiregrass with continuous fuels from the ground to 3 m tall; >30% dead material, large amounts of suspended dead bark, leaves and twigs <2 mm thick; total fuel load >10 t/ha.
Bark fuel	
Low	no bark available to burn.
Mod	stringybarks: bark tightly held for a substantial proportion of the trunk; platy/subfibrous barks: bark very tightly held onto trunk; smooth/gum barks: no long bark ribbons.
High	stringybarks: few pieces of loosely held bark, bark tightly held, most of the of trunk charred; platy/subfibrous barks: bark tightly held onto trunk; smooth/gum barks: long ribbons of bark, smooth trunk; in mixed species stands, stringybark trees with a very high bark hazard but comprising <10% of trees.
Very high	stringybarks: significant amounts of loosely held bark, 10 - 50% of trunk charred; platy/subfibrous barks: bark loosely held onto trunk; smooth/gum barks: long ribbons of bark hanging to ground level.
Extreme	stringybarks: outer bark weakly attached and easily dislodged, <10% of trunk charred; platy/subfibrous barks and smooth/gum barks: does not occur.

Table 4.2a South Australian fuel-hazard ratings for different vegetation strata. (DEH 2008).

Hazard rating	Description
Surface fuel-hazard	
Low	litter depth including duff: <15 mm, <4 t/ha.
Mod	litter depth including duff: 15 - 25 mm, 4 - 8 t/ha.
High	litter depth including duff: 25 - 35 mm, 8 - 12 t/ha.
Very high	litter depth including duff: 35 - 50 mm, 12 - 20 t/ha.
Extreme	litter depth including duff: >50 mm, >20 t/ha.
Near-surface fuel-hazard	
Low	fuel cover <10%, little or no influence on fire behaviour.
Mod	10 - 20% cover of tussock grasses, low sedges and rushes, hummock grasses and low shrubs with little or no suspended bark and leaves.
High	20 - 40% cover with >20% dead of tussock grasses, low sedges, rushes, ± suspended bark and twigs or 30 - 50% cover with <20% dead of tussock grasses, low sedges and rushes, ± suspended bark and twigs; 20 - 35% cover of hummock grasses; 20 - 40% of low shrubs, ± suspended bark and twigs.
Very high	40 - 60% cover with >20% dead of tussock grasses, low sedges, rushes or 50 - 80% cover of tussock grasses, low sedges, rushes with <20% cover of dead grass, bark and twigs; 35 - 60% cover of hummock grasses; 40 - 60% of low shrubs.
Extreme	>60% cover of tussock grasses, low sedges, rushes with >30% dead grass, leaves and bark or >80% cover of tussock grasses, low sedges, rushes with <30% dead grass, leaves and bark; >60% cover of hummock grasses or low shrubs.
Elevated fuel	
Low	very little elevated fuel.
Mod	<20% cover or no fine fuel within 1 m of the ground, little or no dead material.
High	20 - 50% cover or little fine fuel within 0.5 m of the ground, <20% dead material or, if the vegetation is 5+ m tall then it has little fine fuel within 2 - 4 m of the ground.
Very high	20 - 50% dead material, high vertical and horizontal density and continuity, fuel particles mostly <1 - 2 mm thick, average height >0.5 m and usually >1 m high, 50 - 80% of fuel >0.5 m and usually >1 m high.
Extreme	>20% dead material, high vertical and horizontal density and continuity and at least 2 - 3 m tall, >10 t/ha, large amounts of suspended leaves, twigs and bark, >70% of fuel >1 m (and usually >2 m) tall.
Bark fuel	
Low	stringybarks: 100% of trunk charred; platy/subfibrous barks: >90% of trunk charred; smooth/gum barks: no bark ribbons.
Mod	stringybarks: bark tightly held, >90% of trunk charred; platy/subfibrous barks: bark very tightly held onto trunk; smooth/gum barks: no long bark ribbons.
High	stringybarks: few pieces of loosely held bark, bark tightly held, 50 - 90% of trunk charred; platy/subfibrous barks: bark tightly held onto trunk, long unburnt; smooth/gum barks: long ribbons of bark but smooth trunk.
Very high	stringybarks: significant amounts of loosely held bark, 10 - 50% of trunk charred; platy/subfibrous barks: bark loosely held onto trunk; smooth/gum barks: long ribbons of bark hanging to ground level.
Extreme	stringybarks: outer bark weakly attached and easily dislodged, <10% of trunk charred; platy/subfibrous barks and smooth/gum barks: does not occur.

Table 4.2b Adjustment to the surface fuel-hazard due to the characteristics of the near-surface fuel-hazard rating in the South Australian fuel-hazard rating system.
L = low, M = moderate, H = high, VH = very high, E = extreme; Litter depth in millimetres ;DEH (2008).

Surface fuel-hazard		Near-surface fuel-hazard rating										
Rating	Depth	Low	Mod	High	Very high	Extreme	Depth	Low	Mod	High	Very high	Extreme
Low	<8	L	L	M	M	H	8-15	L	M	M	H	VH
Mod	15-20	M	M	H	H	VH	20-25	M	H	H	VH	E
High	25-30	H	H	VH	VH	E	30-35	H	VH	VH	E	E
Very high	35-43	VH	VH	E	E	E	43-50	VH	E	E	E	E
Extreme	>50	E	E	E	E	E						

Table 4.3 Project Vesta fuel-hazard ratings for different vegetation strata.
(Gould et al. 2007a, 2007b).

Hazard rating	Description	Hazard score	Fuel (t/ha)
Surface fuel-hazard			
Nil	no surface fuel, bare ground.	0	0
Low	very thin discontinuous layer, no decomposition, depth <10 mm.	1	2 - 6
Mod	thin continuous layer, no decomposition, depth 10 to 20 mm.	2	6 - 10
High	established continuous layer, decomposing, depth 15 to 25 mm.	3	10 - 14
Very high	thick continuous decomposing layer, duff may be present, depth 15 to 25 mm.	3.5	12 - 16
Extreme	very thick continuous layer with duff, depth >25 mm.	4	16+
Near-surface fuel-hazard			
Nil	no near-surface fuel.	0	0
Low	sparse dispersed fuel, little dead material.	1	1
Mod	scattered suspended leaves, twigs and bark, <20% dead fuel.	2	2
High	suspended leaves, twigs and bark starting to obscure logs, rocks, 20 to 50% dead fuel.	3	3
Very high	40 to 60% cover of suspended leaves, twigs and bark, 20 to 50% dead fuel.	3.5	3.5
Extreme	very large amounts of suspended leaves, twigs and bark, vegetation senescent and obscuring logs and rocks, >50% dead fuel	4	4
Elevated fuel-hazard			
Nil	no elevated fuel.	0	0
Low	sparse and dispersed.	1	0 - 1
Mod	sparse and dispersed, brush against occasionally.	2	1 - 2
High	little fine fuel at base, patchy or mesic shrubs.	3	2 - 3
Very high	difficult to walk through, good vertical continuity of dead material.	3.5	3 – 5
Extreme	difficult to walk through, vertical continuity of fine dead fuel from ground up.	4	5 – 8
Bark fuel-hazard			
Low	no fibrous bark, no spotting.	0	0
Mod	stringy-barks: bark well charred, tightly held on whole trunk; ironbarks: very tight, platy or fibrous bark; smooth-barks: no long bark ribbons.	1	1
High	most bark tightly held on trunk, stringy-barks: most bark on lower trunk black; bloodwoods: long unburnt with tight fibrous bark; smooth-barks: long bark ribbons but smooth to ground surface.	2	2
Very high	stringy-barks: <50% of trunk black, upper trunk may be uncharred; long unburnt platy or fibrous bark on lower trunk, smooth-barks: long loose bark ribbons.	3	5
Extreme	stringy-barks: large easily dislodged bark flakes; huge amounts of bark for spotting, outer bark loosely held, minimal charring on trunk (grey appearance).	4	7

The effects of planned burning on dry eucalypt forest fuel-hazard in southeast Tasmania have been researched by Davis (in prep.). This study found that planned burning was highly effective at reducing surface, near-surface and elevated fuel-hazards, but ineffective at removing bark fuel-hazard - unless fires were conducted at moderate to high intensity. This means that in order to be effective at removing bark fuel-hazard, flame heights of two to four metres are required.

Davis (in prep.) found that in heathy dry eucalypt forests surface, near-surface and elevated fuel-hazard respectively reached equilibrium at about 20 to 30 years, about 15 to 20 years and about 13 years post fire. In grassy dry eucalypt forests Davis (in prep.) found that surface, near-surface and elevated fuel-hazard respectively reached equilibrium at about 10 years, about 20 years and about 10 years post fire. The data presented indicates that in order to be effective in asset-protection zones, planned burning in heathy and grassy dry eucalypt forests needs to be conducted at four to eight year intervals, and at four to 10 year intervals in strategic management zones.

4.2 Fuel moisture

Given sufficient time, constant humidities and temperatures and in the absence of precipitation, fuel moisture will reach an equilibrium moisture content. Pippin (2007; see also King and Linton 1963) found that the equilibrium moisture content will typically be about 0.5 to 1.5% lower when fuels are undergoing absorption (ie gaining moisture from the atmosphere) than when fuels are undergoing desorption (ie losing moisture to the atmosphere). However, under operational conditions, when it is not normally known if fuels are undergoing absorption or desorption, models are required which are applicable under both absorption and desorption conditions.

Enhanced fuel moisture predictions could potentially be made by using fuel-level data for humidity, temperature and solar radiation (eg Matthews 2006). However, due to the difficulty of collecting fuel-level weather data, the low correlation between screen and fuel-level weather data and the poor performance of the available systems for predicting fuel-level weather (Pippin 2007), systems utilising fuel-level inputs are not practical.

Precipitation acts to elevate fuel moistures above that expected from the effects of temperature and humidity alone. The effect of precipitation on fuel moisture varies between different vegetation types, probably mainly due to the influence of canopy interception (if present), fuel structure, fuel particle diameter and rainfall duration (Plucinski 2003), with the amount of water required to saturate fine fuel particles being about one millimetre (Luke and McArthur 1978; Marsden-Smedley and Catchpole 2001). The drying rate once rainfall stops will be dependent on many factors, with the major factors being exposure to wind, solar radiation and humidity.

The Matthews (2006) fuel moisture model is probably the most robust fuel moisture model available for dry eucalypt forests. Comprehensive testing of the Matthews (2006) fuel moisture model has been undertaken in a range of dry eucalypt forest and woodland types (Pippin 2007; S Matthews personal communication) indicating that this model has the potential to provide good fuel moisture predictions. However, the Matthews (2006) model is highly complex, requiring input data from about 26 factors, many of which are not available under operational conditions. As a consequence, the model is currently being reformulated to only require screen level temperature, RH, wind speed and solar radiation and should be available in the second half of 2009 (S Matthews personal communication). Data on temperature, RH and wind speed can easily be collected in the field or obtained from the Bureau of Meteorology. Solar radiation data can be obtained from day of the year, aspect, slope and cloud cover using the methods in Nunez (1983, also available as a updated excel spreadsheet).

Pippin (2007) tested the Matthews (2006) model in Sydney Basin dry eucalypt forest, heathy forest and heathy woodland over a wide range of conditions. This suggests that it has the potential to provide good predictions in Tasmanian conditions.

From a Tasmanian perspective, fuel moisture models have only been developed for buttongrass moorlands (Marsden-Smedley et al. 1999; Marsden-Smedley and Catchpole 2001). Leonard (2009) tested models for predicting fuel moistures in Tasmanian native grasslands under planned burning conditions, and although none of the tested models gave adequate predictions, the buttongrass moorland fuel moisture model performed significantly better than the other models tested. This is most likely due to its incorporation of the effects of recent precipitation (which is accounted for in the buttongrass model but not in the other models). The buttongrass moorland fuel moisture model also has the potential to provide good predictions in sedgy heathland and sedgy woodland (data in Pippin 2007).

Pippin (2007) also performed extensive fuel moisture model testing in Sydney Basin sedgy heathland and sedgy woodland. Pippin (2007) found that the buttongrass moorland fuel moisture model provided good predictions of fuel moisture when fuels were undergoing absorption, but poor predictions when fuels were affected by recent precipitation. However, Pippin (2007) did not incorporate the recent rainfall component of the buttongrass moorland fuel moisture model (Marsden-Smedley et al. 1999; see also Figure 3.6), which when included resulted in this model providing adequate predictions in sedgy heathlands (mean error and mean absolute errors respectively of 1.7% and 6.8%) and sedgy woodlands (mean error and mean absolute errors respectively of 1.6% and 7.1%).

4.3 Fire behaviour

Over the past decade models have been developed for predicting dry eucalypt forest fire spread rate, intensity and spot fire distance along with models for predicting the thresholds between sustaining versus non-sustaining fires in heathlands, native grasslands and gorse.

4.3.1 Dry eucalypt forest fire behaviour

Prior to 2009, the McArthur Forest Fire Danger Meter was the most widely utilised fire behaviour prediction model used in Australia (Luke and McArthur 1978). While the McArthur Forest Fire Danger Meter has been used in a wide range of other fuel types, including sedgy, heathy and shrubby dry eucalypt forests and wet eucalypt forests, its reliability has not been systematically tested. Over the past decade the Project Vesta fire behaviour model has been developed by the CSIRO and the Department of Conservation and Land Management in Western Australia (Gould et al. 2007a, 2007b). This model was intended to address some of the concerns with the McArthur Forest Fire Danger meter using data from experimental fires. For example, suggestions have been made that the McArthur Forest Fire Danger Meter under-predicts dry eucalypt forest fire spread rates at moderate or higher levels of fire danger (Gould et al. 2007a; McCaw et al. 2008a). A major change between the McArthur Forest Fire Danger Meter and the Vesta Fire Model is the change-over from using fuel load to fuel-hazard. The Vesta Fire Model uses as inputs the wind speed, fuel-hazard and fuel moisture (which can be predicted from the RH and temperature) and predicts the rate of fire spread, flame height and spotting distance.

4.3.2 Heathland and wet scrub fire behaviour

The Heathland Fire Model was developed as part of a cooperative project between land management agencies in Australia and New Zealand. The Heathland Fire Model uses as inputs wind speed and fuel height and does not incorporate fuel moisture. The issue of the heathland model not incorporating fuel moisture is a major problem during planned burning, as burning is normally conducted under higher fuel moisture conditions than typically occur during wildfires.

Marsden-Smedley (2002) attempted to address this by developing the Scrub Fire Danger Rating System (SFDR) which incorporates a moisture damping function along with an equation based on age for estimating fuel height. As originally developed, the SFDR was intended primarily for use in wet scrub and not for dry heathlands and scrub in eastern Tasmania. The SFDR predicts the rate of fire spread, flame height and Scrub Fire Danger Rating, prescriptions for planned burning and fire control options. To date, the SFDR has only been tested against about 20 planned fires and wildfires (although these fires occurred over a wide range of conditions, with observed rates of spread of up to about 40 m/min) with the model providing good predictions of fire behaviour (JB Marsden-Smedley unpublished data).

A major issue with fires in heathlands, dry scrub and wet scrub relates to the tight threshold between sustaining versus non-sustaining fires. The normal situation is that when conditions are below the sustaining versus non-sustaining threshold, fires will only burn within individual bushes and fail to form sustaining fires. The Heathland Fire Model strongly suggests that this threshold corresponds to a surface wind speed of about 10 km/h. Additional information on the fuel moisture during Tasmanian heathland and scrub fires suggests that there is also a fuel moisture threshold at about 20%, above which fires burn poorly and may fail to sustain (JB Marsden-Smedley unpublished data). This threshold means that minor changes in environmental conditions (eg minor increases in wind speed, increases in slope or decreases in fuel moisture) can result in fires rapidly transforming from very low intensity fires requiring intensive lighting into high intensity fires with moderate spread rates.

4.3.3 Native grassland

Fuel loads and the threshold between sustaining versus non-sustaining fires in Tasmanian native grasslands has been modelled by Leonard (2009). This study found that Tasmanian native grasslands sustained burning when the dead fuel moisture was <24% and the fuel load was greater than two tonnes per hectare (or if the fuel load was between one and two tonnes per hectare, the wind speed must be >2.5 km/h).

4.3.4 Weed management using fire

Heathland and gorse fire prediction models have been developed by Fernandes (2001) and Baeza et al. (2002). These models incorporate the influence of fuel moisture and wind speed (and fuel height in the case of the Fernandes 2001 model). Due to the small number of fires, the very limited range of wind speeds and fuel moistures, and the short fireline lengths used in the development of the models, the utility of their systems for predicting fire behaviour is uncertain. However, the Fernandes (2001) and Baeza et al. (2002) models do provide some insights into the likely fire behaviour during low intensity weed (ie gorse) management burns and have been used in the development of the planned burning guidelines.

The threshold between sustaining versus non-sustaining fires in gorse (*Ulex europaeus*) in New Zealand were examined by Anderson and Anderson (in prep.). This study found a clear difference between the conditions which would support ignition only (fuel ignites but does not spread beyond a single bush or clump) and conditions that are conducive to fire spread (fuel ignites and develops into a spreading fire) with the critical factor being the moisture content of the elevated dead fuel. Fires failed to ignite when the moisture content was >36% and sustained ignition only occurred when the moisture content was <19%.

When predictions of fire behaviour are required in gorse fuels, the SFDR system should be used.

4.4 Planned burning systems in use in Australia

A range of planned burning systems are in use elsewhere in Australia (DSE 2008; NPWS 2006; RFS 2006, 2007; QPWS 2008a, 2008b). These systems have been developed iteratively by experienced practitioners using expert opinion. The fuel types covered include temperate grasslands, semi arid and arid hummock grasslands, grassy woodlands, heathlands and dry eucalypt forest. With the exception of the maximum temperature acceptable for conducting burning, the recommended weather conditions in the mainland Australian systems are very similar to those detailed in FT (2005b).

4.4.1 Previously published Tasmanian planned burn prescriptions

The previous prescriptions for conducting planned burning in Tasmania have been published in:

- dry eucalypt forest FT (2005b)
- heathland and scrub Marsden-Smedley (2002)
- buttongrass moorland FT (2005b), Marsden-Smedley et al. (1999).

There are no published prescriptions for the use of fire for weed management or in native grasslands, other than the statement in FT (2005b) that grasslands can be burnt at any time of the year at two to three year intervals.

4.4.1.1 Types, aims and objectives of planned burning in Tasmania

The currently utilised types, aims and objectives for planned burning in Tasmania have been detailed in FT (2005b) and covered in more detail in the sections above. The main types of planned burning are fuel management burning and ecological management burning. The published planned burning aims and objectives (FT 2005b) are strongly targeted towards dry eucalypt forest burning and include:

Fuel management burning

- perform burns safely and minimise escapes
- remove fuel from at least 70% of the block
- keep the area of crown scorch to below 10%.

Ecological management burning

- perform burns safely and minimise escapes
- ensure the burn outcomes are consistent with the burn aims, including
    - promote rare, endangered and/or poorly reserved species and/or associations
    - protect viewfields and/or other values.

4.4.1.2 Review of dry eucalypt forest planned burning prescriptions

The prescriptions for low intensity dry eucalypt forest burning have been developed and refined iteratively over several decades, mainly by practitioners working in the forest industry. The dry eucalypt forest planned burning prescriptions have been published in a series of burning manuals, including FC and TFS (1984) and FT (2005b). The previously published dry eucalypt forest planned burning prescriptions are summarised in Table 4.4.

Table 4.4 Previously published dry eucalypt forest planned burning prescriptions. (FT 2005b).

SDI	25 to 50
Wind speed at 10 m	≤20 km/h
Temperature	≤20 º C
Relative humidity	40 to 60 %
Typical fire frequency	4 to 20 years
Forest Fire Danger Index	Low 1 to Mod 6

One major issue with the planned burning prescriptions in Table 4.4 relates to the SDI. In most of eastern and northeastern Tasmania the SDI has remained above 50 for most of the past 10 years, resulting in these sites being outside the published prescriptions.

Hazard-sticks have been used by some practitioners to predict the likely fire behaviour within the burning block and/or the whether the vegetation surrounding the block is dry enough to burn. The interactions between hazard stick moisture and fire behaviour are detailed in FT (2005a) and summarised in Table 4.5.

Table 4.5 Hazard stick moistures versus eucalypt forest fire behaviour. (Eron 1991 and FT 2005a, 2005b).

Hazard stick moisture	Description of fire behaviour
≤9	too dry, erratic fire behaviour
10 - 14	intense fire behaviour
14 - 16	moderate fire behaviour
17 - 24	too wet for effective burning
>24	fires unlikely to sustain

4.4.1.3 Review of heathland, dry scrub and wet scrub planned burning prescriptions

A draft system for conducting heathland, dry scrub and wet scrub planned burning was developed as part of the Scrub Fire Danger Rating System (SFDR; Marsden-Smedley 2002). Prior to the SFDR being developed, heathland and scrub fire predictions were made using an unpublished combination of the McArthur forest fire behaviour model (McArthur 1973) and the SDI, which failed to provide adequate fire behaviour predictions. This was probably due to the different fuel types in dry eucalypt forests compared with heathland and scrub. The SFDR was developed from the heathland fire behaviour model, which had been developed cooperatively by fire behaviour and management personnel in Australia and New Zealand (Anon 1998; Catchpole et al. 1998, 1999).

Tasmanian heath and scrub associations are highly variable in their cover, height, structure and species composition. They range from low open dry heaths less than 0.5 m tall, with cover as low as 30 to 50%, up to closed wet scrub approximately two to eight metres tall, with multiple stratums and cover exceeding 100% (Kirkpatrick and Harris 1999; Harris and Kitchener 2005). These communities are typically dominated by eucalypts (*Eucalyptus* spp.) tea-tree (*Leptospermum* spp.), paper-bark (*Melaleuca* spp.), banksia (*Banksia marginata*) and/or *Acacia* spp.

A major issue with the heathland fire behaviour model (Anon 1998; Catchpole et al. 1998, 1999) is that it uses wind speed and fuel height, with no regard to fuel moisture. Data on wind speed can be easily obtained from weather forecasts or weather observations (either from Bureau of Meteorology automatic weather stations or field observations). Data on fuel load and height can only be obtained from field observations and/or predictive models. In order to make the heathland fire behaviour model usable as an operational fire management system, Marsden-Smedley (2002) developed relationships estimating vegetation height and fuel moisture damping. Although these relationships were based on a wide range of observational data they were not systematically researched.

The methodology developed by Marsden-Smedley (2002) for estimating fuel height in the SFDR uses an asymptotic relationship (Olson 1963; Walker 1981) based on the time since the last fire. The moisture damping function in the heathland fire behaviour prediction system was based on the product of two functions which are derived from the fuel moisture and the SDI. The fuel moisture function was based on the buttongrass moorland fuel moisture model (Marsden-Smedley and Catchpole 2001) with the addition of canopy interception (Marsden-Smedley 2002). The bounds of the fuel moisture function are between 0 (fires will not sustain) and 1 (fires sustain). The SDI function uses the SDI to predict flammability, and in common with the fuel moisture function, is bounded to be between 0 and 1.

The outputs from the SFDR have been used to estimate fire behaviour under conditions suitable for planned burning (Table 4.6). These prescriptions for planned burning have only had very limited field testing.

Table 4.6 Previously published heathland and scrub planned burning prescriptions. (Marsden-Smedley (2002).

	Fuel management			Ecosystem management		
	Optimum	Min	Max	Optimum	Min	Max
Fire frequency, years	10 - 15	8	20	15 - 20	12	30
days since rain	3 - 5	2	-	3 - 5	2	-
temperature, ° C	15 - 20	12	25	15 - 20	12	25
relative humidity, %	50 - 60	45	75	50 - 60	45	75
wind speed at 1.7 to 2 m, km/h	6	3	10	6	3	10
Soil Dryness index, mm	15 - 20	10	25	15 - 20	10	25

4.4.1.4 Review of buttongrass moorland planned burning prescriptions

The previously published buttongrass moorland planned burning prescriptions were developed during a buttongrass moorland fire behaviour research project (Marsden-Smedley and Catchpole 1995a, 1995b, 2001; Marsden-Smedley et al. 2001, 1999). When these planned burning prescriptions were developed, a major requirement during burning was to keep the level of fire behaviour low and minimise the risk of escapes. In order to meet these requirements the allowable wind speeds were kept to a maximum of 10 km/h and the SDI to a maximum of 10 (Marsden-Smedley et al. 1999).

The buttongrass moorland planned burning prescriptions cover two types of burning: fuel management and ecosystem management (Table 4.7). The prescriptions also specify whether the burn has boundaries suitable for controlling fires. Secure boundaries include: vegetation which is too wet to burn; roads; rivers; and/or the coast. Where secure boundaries are not available, increasing the risk of escape, the burning prescriptions are restricted. Burning under these conditions is normally referred to as unbounded burning. Such burning may be used if: a site has poor boundaries; the aim is to only burn part of the site; and/or the aim is to enhance ecological values.

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 in these moorland types rapidly increase overnight due to decreases in temperature, increases in RH 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 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.

Table 4.7 Previously published buttongrass moorland planned burning prescriptions. (Marsden-Smedley et al. 1999, FT 2005b).

	Fuel management burning			Ecosystem management burning		
Season						
autumn	April to early May			April to June		
spring	September to early October			August to early October		
	Optimum	Min	Max	Optimum	Min	Max
Fire frequency, years				variable, dependent on the		
low productivity sites	7 - 10	5	15	species and/or community		
medium productivity sites	5 - 8	5	10	type being managed		
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 to 2 m wind speed, km/h	6	3	10	4 - 6	0	10
Soil Dryness Index, mm	5	0	10	5	0	10
Acceptable 3.fire behaviour						
rate of fire spread, m/min		≤ 8			≤ 8	
flame height, m		≤ 5			≤ 5	
Moorland Fire Danger Rating, dimensionless		≤ 5			≤ 5	

In buttongrass moorlands the site productivity has a strong influence on the density of the fuel array (Marsden-Smedley and Catchpole 1995a) with higher productivity sites typically having fuel covers approaching 100%, resulting in the lower parts of the fuel being shaded. If fires occur in these sites when the SDI is below about five only the upper parts of the fuel array will be dry enough to burn, resulting in fires leaving large amounts of unburnt fuel after the fire (Marsden-Smedley and Catchpole 1995b, 2001). For example, fires occurring at low SDI in higher productivity buttongrass moorlands often leave about 35% of the pre-fire fuel load unburnt as a thatch layer, with the weight of thatch decreasing by two thirds and the depth halving over a two year period (Marsden-Smedley 1998b; JB Kirkpatrick and JB Marsden-Smedley unpublished data).

The issue of thatch formation following buttongrass moorland planned burns could be addressed by burning under drier conditions (eg higher levels of the SDI). If burns are conducted at higher levels of the SDI then the risk of the natural boundaries surrounding most burn sites failing to contain the burn will be greatly increased. This will especially be the situation if the SDI exceeds about 20 when wet scrub will be highly flammable (Table 3.5).

Alternatively, double (or triple) burning can be conducted, with each burn removing the top (and hence driest) layer of fuel. The major issue with this strategy is that each burn requires a full complement of fire control resources, along with the possibility of causing adverse impacts to seed regenerating species. During the second (and subsequent) burns the fuel array normally consists of a dense mat of thatch which is made up entirely of dead fuel. Although the subsequent burns will have reduced fire intensities, the rates of fire spread are normally greater due to the lack of damping by live fuel (JB Marsden-Smedley unpublished data). Multiple burns have the potential to impact on seed regenerating species, especially if there is enough time between burns for seedlings to germinate and then be killed by the subsequent burn(s).

Draft ecological management guidelines (Table 4.8) were proposed by the Resource Management and Conservation Branch of the Department of Primary Industries, Parks, Water and Environment in 2004. The aim of these prescriptions were to minimise the risk of adverse impacts to organosols whilst maintaining fire-dependent fauna and flora.

Table 4.8 Draft buttongrass moorland ecological management burning prescriptions.

Burning aim	- maintain the status-quo; - reduce adverse impacts to fire-dependent species; - reduce the area of old moorland and increase structural and age diversity;
Season	- where possible and practical about 75% of the burning should be performed in autumn or winter and about 25% in spring.

Frequency	- variable frequency with max 2 long or 2 short consecutive burn intervals;
	- burning intervals:
	  - low productivity sites: short interval - 20 to 30 years, long interval - ≥30+ years;
	  - medium productivity sites: short interval - 5 to 12 years, long interval - >12 years.

Burning pattern	- small plains (≤100 ha):
	  - where possible leave ≥10% of plain unburnt and do not burn to boundaries;
	  - maximum of about 500 m between unburnt areas >0.25 ha;
	- large plains (>100 ha):
	  - where possible burn ≤50% of the plain;
	  - maximum of about 500 m between unburnt areas >0.25 ha;
	- lighting pattern:
	  - dispersed spots.

Soil Dryness Index	- since the end of March the SDI must have fallen to zero and then at least an additional 10 mm of rain must have fallen; - maximum SDI of 10.

Monitoring	- where practical sites to be monitored following burning for the following:
	  - weather conditions, area burnt and patchiness;
	  - fuel removal and thatch remaining;
	  - ensuring burn is extinguished, including peat, logs and burn boundaries.

4.4.2 Planned Burn Risk Assessment Tool

The Burn Risk Assessment Tool (BRAT, Slijepcevic et al. 2007) provides a standardised framework for assessing planned burning risks versus benefits. The BRAT is based on the Standards Australia risk management standard (Standards Australia 2004) and was developed by the Department of Sustainability and Environment in Victoria and the Tasmanian Parks and Wildlife Service using as a structure the Forestry Tasmania burn risk assessment system (Marsden-Smedley and Chuter 1999).

The BRAT system assesses the risk of fires escaping (ie likelihood of impact), potential of escapes to do damage (ie consequence), effects of escape mitigation strategies in reducing the probability of escapes, and the potential benefits of the burn in meeting fire management objectives (ie benefits).

When using the BRAT the practitioner assesses each of the escape risk factors, potential impact factors and the potential risk reduction benefit of the burn by applying a low, moderate or high rating to each of the factors. The system then calculates the burn's risk score for the likelihood of the fire escaping, the risk of the burn causing damage and the level of benefit that could be potentially gained.

The major benefit of the BRAT system is its ability to provide an objective, consistent, standardised and reproducible process for assessing planned burning risks. The system also allows the practitioner to identify the criteria which have the greatest influence on the level of fire risk and hence how the risk may be reduced. If a burn has excessive risk, the practitioner can modify selected criteria to determine which parameters are elevating the burn's risk, and which could be modified to minimise burn risk. For example, if a burn has excessive risks associated with spotting, the burn's risk profile could be reduced by burning with higher fuel moistures (eg higher SDI, higher RH and/or in a cooler season), increased resources could be used where spotting is predicted to be an issue, additional boundary works could be completed and/or the burn's boundaries could be moved to a lower risk location.

The BRAT system also provides a record of the risk assessment process which can be used to assess operational performance and quantify improvements to risk management.

As part of this review of planned burning, the BRAT system will be comprehensively updated and refined so that it reflects current fuel-hazard assessment systems, fuel moisture models and fire behaviour prediction systems along with the revised guidelines for planned burning.

4.4.3 Expert opinion on performing planned burning in Tasmania

Meetings were held with planned burning practitioners around Tasmania and on the mainland (Table 4.9). The meetings in Tasmania were facilitated by Sandra Whight (PWS) with Jon Marsden-Smedley (PWS) also being present at all meetings.

Table 4.9 Meetings held with planned burning practitioners and researchers.
Note: TFS = Tasmania Fire Service, FT = Forestry Tasmania, PWS = Parks and Wildlife Service.

Date	Meeting location	Attendees
Tasmanian meetings		
22 Apr 09	PWS Hobart	Lindsay Suhr (TFS), Hugh Jones (TFS), Nigel Richardson (FT), Barry Hunt (FT).
24 Apr 09	FT Geeveston	Graeme Richards (FT), Craig Wilson (FT).
29 Apr 09	PWS Lutana	John Duggan (PWS), Kent McConnell (PWS), Shayne Mundy (PWS), Rod Watson (PWS), Laurence Clark (PWS), Paul Black (PWS), James Shaw (PWS).
30 Apr 09	FT Camdale	Willie Gale (PWS), Dean Sheehan (FT), Leigh Clark (FT), Bob Knox (FT).
01 May 09	PWS Launceston	Phil Duggan (PWS), Jeff Harper (TFS), Kris Bezemer (FT), Hafwen Pearce (FT), Robert Featherstone (TFS).
Mainland meetings		
9 May	Parks ACT	Dylan Kendall (ACT Parks, Conservation and Lands).
12 May 09	DSE Melbourne	Francis Hines (Vic Department of Sustainability and Environment), Lachie McCaw (WA Department of Environment and Conservation), Mike Wouters (SA Department of Environment and Heritage), Peter Kinkead (NSW Rural Fire Service), Liz Tasker (NSW Department of Environment and Climate Change), Margaret Kitchin (ACT Parks, Conservation and Lands).

The objectives of the Tasmanian meetings were:

1. To obtain expert opinion on where the previously developed planned burning prescriptions were working, and where the prescriptions require updating. Consideration was also given to any other factors that were restricting the application of planned burning in Tasmania.
2. To provide information to practitioners regarding the aims, timeline and anticipated outcomes of this review.

The outcomes of the practitioner meetings are summarised in Table 4.10. The main aims of the mainland meetings were to inform mainland fire agencies of the review's aims and timelines.

Table 4.10 Issues reviewed in the Tasmanian planned burning practitioner meetings.

General issues

- need to have a higher level of preparedness for planned burning so that more burning can be performed when conditions are suitable;
- planning of burning block design needs to be improved, especially boundary type and location;
- the guidelines need to be linked to burn objectives;
- the prevailing seasonal conditions are more important than the calendar date for determining when burning can be performed;
- require enhanced inter-agency co-operation to maximise the use of resources to increase burning;
- the approval process needs to be streamlined, especially for burns across multiple tenures.

Issues with the previous prescriptions

- the acceptable burning window is poorly defined;
- the Soil Dryness Index has too large an influence, especially between late autumn and early spring;
- test fires are poorly performed despite being a major component of planned burning training courses and in their current form are of limited usefulness;
- restrictions on fire rate of spread, flame height and scorch height are impossible to meet.

Required changes in the guidelines

- the burning objectives need to be better targeted to measurable benchmarks and outcomes;
- the acceptable burning window needs to be better defined and the burning guidelines streamlined and refined in order to make them more operationally applicable and flexible;
- burning between mid spring and early autumn (ie over summer) should be allowed subject to it being performed within tight guidelines;
- use a more effective system to indicate acceptable planned burning conditions for different objectives;
- change from using fuel load to fuel-hazard rating.

4.5 Ecology, geomorphology, fire regime modelling and climate change

There has been considerable discussion in Tasmania over past decades regarding the ecological and geomorphological impacts of fire in the published and unpublished literature, and in scientific forums. However, most of this research has been descriptive in nature and only limited experimental work has been performed (Davis 1940; Gilbert 1959, 1979; Green 1967, 1968; Jackson 1968, 1977; Harwood and Jackson 1975; MacLean 1978; Mount 1979; Bowman 1980; Macpail 1980; Brown and Podger 1982; Hill 1982; Bell 1983; Davies 1983; Jarman et al. 1982, 1984, 1988a, 1988b; Jarman and Brown 1983; Hocking and Guiler 1983; Hill and Read 1984; Kirkpatrick and Dickinson 1984; Kirkpatrick et al. 1988; Taylor et al. 1985; Pemberton 1988, 1989; Barker 1991; Driessen and Comfort 1991; Brown 1993; Taylor and Comfort 1993; Marsden-Smedley 1990; Bridle et al. 1997, 2003; Macphail et al. 1999; Brown et al. 2002). Some of this research has been summarised and reviewed in Brown (1993); Hannan et al. (1993); Jackson and Brown (1999); and Mallick et al. (unpublished).

4.5.1 Fire ecology

The impact of fire on ecological values ranges from: high level, long term adverse impacts; to short term, low level impacts; and to the dependence on frequent fire to maintain species and structural diversity. The most dramatic example of the former of these impacts is the effect of fire on western Tasmanian native conifers (in particular Pencil pine, King Billy pine and Huon pine) and fagus (Deciduous beech). These species are highly fire-sensitive, typically have their covers and dominance greatly reduced by a single fire (often by >99%) and take over 500 years to recover from a single fire (Gibson 1986; Brown 1988; Peterson 1990; Robertson and Duncan 1991).

When managing for ecological purposes a range of strategies can be applied for determining the most appropriate fire management regime. The following questions should be considered:

- Is the aim to use a fire regime similar to that used by Aboriginals prior to European settlement in Australia?
- Is the aim to maintain the current regime?
- Is the aim to develop a new regime based around plant and animal attributes?

The merits and restrictions inherent with using Aboriginal-style fire regimes in southwest Tasmania has been reviewed by Marsden-Smedley and Kirkpatrick (2000). The most likely fire regime utilised by Tasmanian Aboriginal people would have been frequent (e.g. on average less than about 20 years between fires) mostly low-intensity fires when scrub, eucalypt forest, rainforest and alpine areas were too wet to burn (Marsden-Smedley 1998a, 1998b; Marsden-Smedley and Kirkpatrick 2000). This regime is analogous to the firestick farming regime proposed by Jones (1969). This study found that such a fire regime, modified to meet some contemporary requirements of asset protection, had the potential to provide for appropriate management for ecological values. However, the study also determined that the strategy would not be suitable in all areas due to contemporary land management goals. For example, the use of Aboriginal fire management could potentially conflict with: current land use management for viewfields; smoke management; impact on agricultural or urban areas; result in landscape fragmentation; and/or could advantage exotic weed or pest species.

If the fire management aim is to maintain the current fire regime, it needs to be asked if the regime is in keeping with the current risk management strategies, and ecological requirements of the species and associations present. The strategy for addressing these concerns adapted in Victoria and NSW (DSE 2006) has been to classify the vegetation association according to species vital attributes (Noble and Slatyer 1980), and use fire thresholds to determine the most appropriate fire regime (where information is available). This fire regime should include as much variability as practical (Bradstock and Kenny 2003; RFS 2007; Gill 2008; van Wilgen 2008; RMC unpublished 2009).

A major issue with using fire for ecological management is the rudimentary nature of the available information resulting in the requirement for management to be highly precautionary (Cawson and Muir 2008). However, this precautionary approach should not exclude the use of planned burning. The exclusion of planned burning from fire adapted vegetation associations, even in the absence of comprehensive ecological data, is likely to be a high risk strategy given the known consequences of wildfires burning under severe weather conditions.

All of the vegetation associations suitable for planned burning (see Table 3.2) have a low fire sensitivity, high to very high flammability, and are ecologically adapted to recurrent fire. With a few exceptions, the vegetation types not suitable for planned burning (see Table 3.3) have high to extreme fire sensitivity, low to moderate flammability and in some cases fire results in marked reductions to species diversity (Pyrke and Marsden-Smedley 2005).

The degree to which a fire burns a site (and hence the proportion left unburnt) is of major ecological concern, particularly for species that are removed from a site by a burn and have to re-invade from unburnt areas. As the time since fire increases, when fires occur there is a corresponding increase in the proportion of the site burnt and decrease in the size of unburnt patches. For example, during both the 2003 Arthur-Pieman and 2006 Reynolds Creek fires <1% of the area of buttongrass moorland remained unburnt in areas last burnt at least 25 years previously while in younger areas >50% remained unburnt (Figure 4.1; Parks and Wildlife Service unpublished fire data).

a) last burnt 2002/03　　b) last burnt 1969/70

Figure 4.1 Proportion of buttongrass moorland burnt in sites with different ages. Photographs show areas burnt during the major fire run on 18/02/2006 during the Reynolds Creek fire.

A critical aspect of ecological management burning is the identification of clear goals and targeted management outcomes. This means that ecological burning should only be performed where the fire management strategy clearly identifies the fire regime targeted, and an effective pre and post-fire monitoring program is in place.

4.5.1.1. Fire ecology of buttongrass moorlands

From a Tasmanian context, the fire ecology of buttongrass moorland is the most comprehensively studied vegetation association (eg Davis 1940; Jackson 1968, 1978; Mount 1979; Bowman and Jackson 1981; Moscal 1981; Brown and Podger 1982; Bowman et al. 1986; Jarman et al. 1988a, 1988b; Balmer 1990; Marsden-Smedley 1990; Brown 1996, 1999; Jackson 1999; Jackson and Brown 1999; Brown et al. 2002; King 2004a, 2004b; King et al. 2006, 2008; Mallick et al. unpublished).

Species diversity in low and medium productivity buttongrass moorlands is highly resilient to changes in fire frequency and time since fire (Jarman et al. 1988a, 1988b; Marsden-Smedley 1990; Brown et al. 2002), although frequent fire has greater effects in low productivity than medium productivity sites. For example, in medium productivity sites on the Navarre Plains, frequent fire appears to have minor influences on species and structural diversity (JM Balmer unpublished data). In contrast, in higher productivity low altitude sites in northern Tasmania, in the absence of fire, buttongrass moorlands may be structurally transformed into a wet scrub association by about 30 years post-fire (Marsden-Smedley and Williams 1993).

As regards fauna in buttongrass moorlands, structural factors may be more important than fire age. Gellie (1980) considered that Southern Emu wrens, Striated Field wrens, Swamp rats, Broad-toothed mice and Swamp Antechinus require dense vegetation for cover and nesting, and that species may take up to 15 years to recolonise areas following fires, unless suitable pockets of unburnt vegetation are left as breeding areas. This is consistent with the findings of Driessen (unpublished data), who reports that once vegetation densities regain about 75% of their pre-fire levels small mammals regained their pre-fire densities. Arkell (1995) found a similar situation regarding small mammal diversity in buttongrass moorlands, with species diversity and number being highly correlated with moorland cover, but poorly correlated with fire age. This means that the time period required for small mammal populations to recover following fires varies from about four or five years in medium productivity moorlands and up to about 10 to 20 years in low productivity moorlands (ie once cover values have reached about 65 to 75%).

Chaudhry (2007) found that the critical factors controlling bird diversity appeared to be related to food availability and whether scrub boundaries and scrub along creek lines had been burnt and were not related to moorland fire age. This situation is similar to that found by Bryant (1991), who found that ground parrots in buttongrass moorland were common in sites older than about one year, with peak densities at four to seven years since fire. The situation with Orange-bellied parrots is more complex. Observational evidence suggests the parrots require buttongrass moorland feeding areas burnt within the past three to 12 years (with older areas unsuitable) and long unburnt scrub and wet eucalypt forest required for nesting (Brown and Wilson 1984).

The effect of fire age on the abundance and diversity of invertebrates in buttongrass moorland was investigated by Greenslade and Driessen (1999) who found that both abundance and diversity was highest in intermediate aged sites (11 to 19 years) with some evidence of declines in species diversity in sites older than 20 years. The invertebrate species groups most strongly influenced by fire age were mites, spiders, springtails, beetles, flies and moths. In contrast, Green (2007) suggests mite diversity and abundance increases in buttongrass moorland unburnt for <30 years. Mallick et al. (unpublished) also suggest that buttongrass moorland invertebrate species diversity will be maintained in patches as small as 50 by 50 m while small mammals may require patches of up to one hectare. For burrowing crayfish in buttongrass moorlands the fire management critical issue is ensuring that dry soil (eg when the SDI is <50) wildfires are minimised.

No research has been conducted on the interactions between reptiles, amphibians and fish in buttongrass moorlands (Mallick et al. unpublished).

No quantitative information is available on the effects of burn season and frequency in buttongrass moorlands.

4.5.1.2. Fire ecology of dry eucalypt forest

For dry eucalypt forests, some information is available on the ecological impact of planned burning from the southeastern mainland of Australia.

In southeast NSW Penman et al. (2008) found that frequent planned burning increased the species diversity in the understorey but decreased species diversity in the overstorey with a maximum species diversity being recorded at between one and five years post fire. However, Penman et al. (2008) also found an overall trend to decreased species diversity, probably due to there having been no high intensity wildfires at their site for about 30 years. This long term decrease in species diversity may also be related to a shift in fire type and season of burning from dry summer mixed intensity wildfires to low intensity moist autumn, winter and spring planned burning.

In the Wombat Forest in Victoria, frequent planned burning had minor impacts to birds, small mammals and invertebrates with species diversity returning to pre-fire levels within four to five years. The research also suggested that although few changes in soil parameters were observed following frequent planned burning, it is possible that burns more frequent than every 10 years may result in reductions to soil fertility and carbon (DSE 2003).

Some differences were observed between autumn and spring fires which probably relate to fuel dryness. In general, autumn burns had lower fuel moistures resulting in greater levels of fine fuel removal, burning of logs and bark consumption than occurred during spring burning. The higher intensities and greater levels of fuel removal in autumn burning also resulted in greater regeneration of seed regenerating species while spring burning resulted in greater regeneration of resprouting species (DSE 2003).

The research in the Wombat Forest also suggested that in order to maximise ecological values at least 40% of the site should be left unburnt in areas containing a mixture of fuel and vegetation types (eg gullies, slopes and ridges), with at least 10% of each vegetation type being left unburnt. The research indicated that average fire frequencies of 10 years between fires should be adequate to maintain species diversity but that 20 years between fires will be required to maintain structural diversity (DSE 2003).

Regarding fire management for threatened species in Tasmanian dry eucalypt forests, Bryant and Jackson (1999) recommend low intensity mosaic burns at 8 to 14 year intervals for Swift parrots, 10 to 14 year intervals for 40 Spotted pardalotes, and 20 to 30 year intervals for Velvet worms. In *Poa* grasslands burnt for Ptunarra Brown butterfly management, Bryant and Jackson (1999; see also Bell 1999) recommended mosaic burns in autumn and winter at four to seven year intervals, when the basal fuels in *Poa* tussocks are wet so that impacts to butterfly larva were minimised.

4.5.2 Geomorphology

Fire has the potential to impact soil and geomorphological values in a number of ways. Fire can heat soils, cause changes to nutrient and/or carbon levels, expose the soil surface to impacts from rain, increase surface flow rates and/or reduce soil infiltration rates (DSE 2003; MacDonald and Huffman 2004). In addition, if soils have high organic contents (ie are organosols) then they may be directly impacted by being burnt in peat fires. Organosols are defined as having ≥20% soil organic matter where the clay content is <15%, or ≥30% soil organic matter if clay content is >15% (Eggleton 2001; Whinam and Hope 2005).

In Tasmania there is limited understanding of the impacts of fire on geoconservation values. Pemberton (1988, 1989) and Pemberton and Cullen (1995) considered that a large proportion of buttongrass moorland soils had been degraded by fire. They also proposed that continued fire (including planned burning) had the potential to further adversely impact on soils through direct burning (ie peat fires), increased post-fire soil drying and enhanced erosion by water and wind. However, these studies did not present any evidence of deeper and less degraded soils, making the level of degradation difficult to quantify, or relate to a single impact such as fire.

Subsequent research by Bridle et al. (2003) attempted to address this issue by examining pre and post-fire dynamics in low productivity buttongrass moorland. However, due to the short time period over which this research was performed, and significant non-fire related variation between treatment sites, combined with equipment failures, they were unable to provide much additional information on this issue.

Extensive research by di Folco (2007) found that about 75% of buttongrass moorlands are underlain by mineral soils (ie not by organosols) and that the majority of sites that did have organosols were located in very wet areas that rarely dry out. Di Folco (2007) also found that minimal erosion occurred in buttongrass moorlands following both dry soil wildfires and wet soil planned burns. As a result, di Folco (2007, personal communication; see also Storey 2008) considers that the risk of soil erosion and degradation from planned burning in buttongrass moorlands (which are conducted when the SDI is low) is extremely low.

The rate of organosol formation in Tasmania is currently unknown. Di Folco (2007) suggests that in buttongrass moorlands the rate of organosol formation is slow with no significant changes being observed over a six year period. The rate at which wet scrub and wet eucalypt forest duff layers are transformed into organosol is currently unknown.

The effects of planned burning on buttongrass moorland soils are currently being researched by the Geodiversity Conservation section of the Department of Primary Industries, Parks, Water and the Environment at Gelignite Creek in southwest Tasmania. This site has low organic content soils, was burnt in autumn 2009 and will be monitored for a number of years.

4.5.3 Weed management with fire

Extensive areas of highly pyrogenic weeds are a feature of some parts of Tasmania (Harris and Kitchener 2005; Pyrke and Marsden-Smedley 2005). There are extensive areas of gorse on the urban fringe of Hobart, Launceston and other cities and towns, in forest plantations in northwest Tasmania, and areas of gorse and broom are close to highly fire sensitive native conifers on Tasmania's west coast.

Where fire is utilised for weed control, highly organised and integrated management is essential (Dewey et al. 1995). Fire can be used to open up dense stands and allow access, but is also highly effective at stimulating vegetative and seedling regeneration resulting in rapid re-establishment and frequently enhanced weed dominance. The effectiveness of burning can be enhanced if preceded by herbicide spraying, scrub rolling and/or slashing in order to increase burn intensity, soil heating (causing the death of shallowly buried seeds and/or enhanced seedling germination of deeper buried seeds) and increased consumption of above ground biomass.

Follow-up treatments are required prior to the weed species setting seed. Fire could potentially be used for follow-up treatment if preceded by spraying to increase the proportion of dead fuel. In most sites, multiple follow-up treatments will be required (DiTomaso et al. 2006). An additional issue with this type of intensive weed management is that it will result in extensive areas of bare ground, requiring revegetation to reduce the subsequent reinvasion by weeds. The costs associated with such intensive weed management are such that it will probably only be justified in areas adjacent to, or within high value ecological or natural assets.

In Tasmania, the main species for which fire is used for weed management are gorse (*Ulex europaeus*), and to a lesser extent broom (*Cytisus* spp. and *Genista* sp.), Spanish heath (*Erica lusitanica*) and blackberry (*Rubus fruticosus*). Fire is a major problem in gorse infested areas due to its ability to sustain burning over a wide range of conditions, and gorse rapidly regenerates following fire (Hobbs and Gimingham 1984; Fernandes 2001; Fernandes and Botelho 2003; De Luis et al. 2004; Baeza et al. 2002, 2003, 2006; DiTomaso et al. 2006; Anderson and Anderson in prep.).

Research in New Zealand indicates gorse flammability can be estimated from the fuel moisture of elevated dead fuel (Anderson and Anderson in prep.). Their research found that when the elevated dead fuel moisture is over 36%

fires will not sustain, when the fuel moisture was between 30 and 36% individual gorse bushes could be burnt without fires sustaining between bushes, and when the fuel moisture was between 26 and 30% fires spread poorly between bushes. Anderson and Anderson (in prep.) also found that low intensity sustaining fires could be performed in gorse when the fuel moisture was between 19 and 26%, and that fires sustained and burnt well when the fuel moisture was below 19%.

4.5.4 Fire regime modelling and climate change

A major challenge for fire management planning is predicting what the long term consequences of planned burning might be. With fuel management burning, the wildfire that is being pre-empted may not occur for several decades, resulting in multiple planned burns being undertaken in the intervening time period. With ecological management burning, the challenge is to understand the potential impacts of multiple burns, performed in different seasons, frequencies, sizes, locations and/or intensities. Fire regime modelling has the potential to provide a long term perspective on these issues (Cary 2002).

To date in Tasmania, fire regime modelling has only been conducted for southwest Tasmania, with King (2004a, 2004b) and King et al. (2006, 2008) modelling fire regimes under a number of different scenarios. The modelling examined the effects of: varying the amount of buttongrass moorland planned burning; the burning strategy (ie broad scale versus strategic burning); the size and distribution of burning blocks; the implications of climate change on the total area burnt; and importantly, the area of fire-sensitive rainforest and alpine vegetation burnt.

The southwest Tasmanian fire regime modelling indicated that, regardless of the amount of planned burning conducted, the total area of buttongrass moorland burnt remained fairly constant. However, the area of fire sensitive vegetation burnt decreased as the area of planned burning increased. This suggests that planned burning has the potential to transform the fire regime from mostly high intensity wildfires that burn all vegetation types to mostly lower intensity buttongrass moorland planned burns. When the effects of variation in burning block size and distribution were examined, the modelling indicated that for a given amount of planned burning, smaller, randomly located burning blocks provided for a higher level of protection than did larger systematically located blocks (King 2004a, 2004b; King et al. 2006, 2008).

The implications from climate change can also be examined using fire regime modelling. In southwest Tasmania the modelling indicated that the projected changes in climate have the potential to increase the average annual area of rainforest and alpine areas burnt by about 38%. The modelling also indicated that if broad scale fuel management burning was performed it is necessary to annually burn a minimum of 10% of buttongrass moorlands in order to reduce the area of rainforest and alpine areas burnt. However, the modelling showed that if burns were conducted strategically in proximity to assets and/or aiming to cut the major fire corridors, similar levels of asset protection could be obtained by burning three percent of buttongrass moorlands annually (King 2004a, 2004b; King et al. 2006, 2008).

The degree to which climate change will impact on Tasmania is uncertain, with some of the modelling suggesting only minor impacts (Lucas et al. 2007). However, anecdotal evidence is strongly suggesting that major changes in climate are currently occurring in Tasmania. For example, there appear to have been marked decreases in rainfall in northern, eastern and central Tasmania with smaller changes elsewhere in Tasmania (Figure 4.2; Bureau of Meteorology unpublished data).

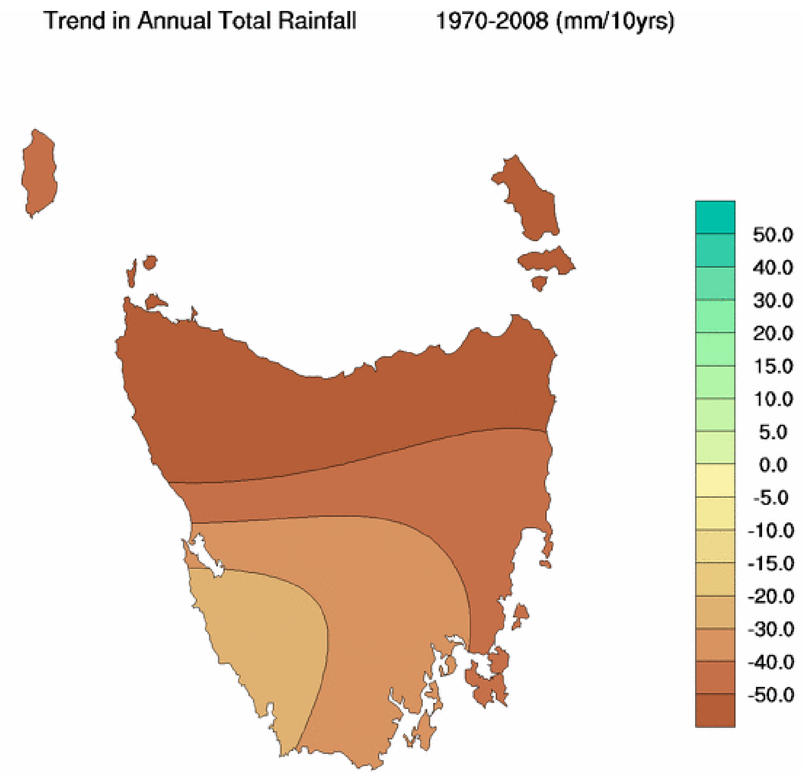


Figure 4.2 Changes in average annual rainfall in Tasmania since the 1970s.
Source: Bureau of Meteorology, available from: http://www.bom.gov.au/silo/products/cli_chg/.

As regards lightning fires, there have been large increases in both the number and area burnt by lightning fires over about the past four decades in northwestern, western and southwestern Tasmania (Figure 4.3; Marsden-Smedley 2007).

However, it also needs to be noted that some of this increase in lightning fires may be a reflection of increases in fire age due to old buttongrass moorland sustaining burning over a wider range of conditions than young buttongrass moorland (and hence, are more likely to be ignited by lightning strikes). Of the 35 lightning fires recorded to have started in buttongrass moorland over the past 27 years in the Tasmanian Wilderness World Heritage Area (WHA), none of these fires started in regrowth sites (ie <15 years since fire), 11% started in mature sites (ie 15 to 35 years since fire) and 89% started in old-growth sites (ie >35 years since fire). It is also worth noting that the lightning fires starting in mature buttongrass moorland burnt about two percent of the area that got burnt while the remaining 98% of the area burnt resulted from fires starting in old-growth sites (Marsden-Smedley 2007). In comparison, these figures on the proportion of fires starting in different aged buttongrass moorlands need to be compared to the moorland's age class distribution, where regrowth, mature and old growth buttongrass moorland currently make up about 12%, 23% and 65% respectively of the area of buttongrass moorland (Marsden-Smedley 2007).

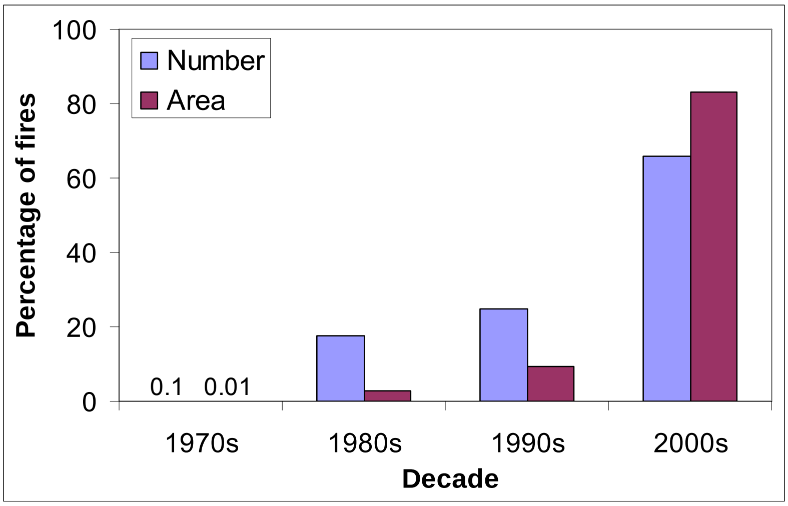


Figure 4.3 Change in the number and area burnt by lightning in the Tasmanian Wilderness World Heritage Area since the 1970s. Source: Marsden-Smedley (2007).

4.6 Knowledge gaps and further research required

The main knowledge gaps and further research required for conducting planned burning in Tasmania are related to:

Dry eucalypt forest
- use of fire prediction models
- relative utility of the Vesta versus McArthur models
- improved ecological knowledge, including species and structural diversity versus fire age, fire frequency, season and intensity.

Heathland, dry scrub and wet scrub
- improved and/or enhanced fire behaviour models
- enhanced guidelines for planned burning.

Buttongrass moorland
- effect of fire on organosols and other soils.

Native grassland
- fire behaviour in Tasmanian native grasslands
- interactions between fire and animal grazing.

Weed management with fire
- prediction of fuel moistures.

Some of these issues are currently being addressed.

The utility of the Vesta fire model in south-eastern Australian dry eucalypt forests is being examined by a project being coordinated by the Department of Sustainability and Environment (DSE) in Victoria.

The effects of fire on buttongrass moorland organosols is currently being researched by the Geodiversity Conservation and Management Section in the Department of Primary Industries and Water.

Interactions between native animal grazing and fire potential are being researched in the School of Geography and Environmental Studies at the University of Tasmania with the projects results being due to be completed over the next 18 months.

Information relevant to many of the other further knowledge and research areas identified could potentially be obtained opportunistically by collecting fire data from planned burns and wildfires. This data collection should form part of the Australia-wide fire standardised behaviour data collection being coordinated by the DSE. This data should be summarised using the current data collection proforma and entered into Argus database held by DSE (https://fireweb.dse.vic.gov.au/argus/dms/welcome).

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6. Appendices

6.1 Appendix 1 Glossary

This glossary has been summarised from the wildfire glossary developed by the Australasian Fire and Emergency Service Authorities Council (AFAC). The complete glossary is available from the Fire Knowledge Website: http://knowledgeweb.afac.com.au/national_data__and__glossary/wildfire_glossary.

Adsorption	The taking in of water vapour from the air by dead plant material.
Aerial ignition	Ignition of fuels by dropping incendiary devices or materials from aircraft.
Area ignition	Ignition of several individual fires throughout an area, either simultaneously or in rapid succession, and so spaced that they add to and influence the main body of the fire to produce a hot, fast-spreading fire condition.
Assets	Anything valued by people which includes houses, crops, forests and, in many cases, the environment.
Automatic weather station	The Bureau's standard automatic weather stations (AWS) use sensors to monitor temperature, humidity, wind speed and direction, pressure and rainfall. Various advanced sensors are available for specialised applications. These sensors can monitor cloud height (ceilometer), visibility, present weather, thunderstorms, soil temperature (at a range of depths) and terrestrial temperature.
Backing fire	The part of a fire which is burning back against the wind or down slope, where the flame height and rate of spread are reduced.
Bark fuel	The flammable bark on tree trunks and upper branches.
Beaufort wind scale	A system for estimating wind speeds based on observation of visible wind effects. A series of descriptions of visible wind effects upon land objects or sea surfaces is matched with a corresponding series of wind speed ranges, each being allocated a *Beaufort number.*
Burn plan	The plan which is approved for the conduct of prescribed burning. It contains a map identifying the area to be burnt and incorporates the specifications and conditions under which the operation is to be conducted.
Burning program	A program of prescribed burns scheduled these for a designated area over a nominated time, normally looking ahead over one fire season (for the coming spring to the following autumn), but can also look ahead five years or more.
Burning rotation	The period between reburning of a prescribed area for management purposes.
Burning unit	A specified land area for which prescribed burning is planned.
Bushfire management	All those activities directed to prevention, detection, damage mitigation, and suppression of bushfires. Includes bushfire legislation, policy, administration, law enforcement, community education, training of fire fighters, planning, communications systems, equipment, research, and the multitude of field operations undertaken by land managers and emergency services personnel relating to bushfire control.
Candle (Candling)	A tree (or small clump of trees) is said to candle when its foliage ignites and flares up, usually from the bottom to top.
Candlebark	Long streamers of bark that have peeled from some eucalypt species that form fire brands conducive to very long distance spotting.
Canopy	The crowns of the tallest plants in a forest – the overstorey cover.
Central ignition	A method of prescribed burning in which fires are set in the centre of an area to create a strong convective column. Additional fires are then set progressively closer to the outer control lines causing indraft winds to build up. This has the effect of drawing the fires towards the centre.
Coarse fuels	Dead woody material, greater than 25mm in diameter, in contact with the soil surface (fallen trees and branches). Some researchers categorise forest fuels as: fine <6 mm diameter; twigs 6-25 mm diameter; coarse >25 mm diameter.
Critical burnout time	Total time a fuel can burn and continue to feed energy to the base of a forward-travelling convection column.

Crown scorch Browning of the needles or leaves in the crown of a tree or shrub caused by heat from a fire.

Dead fuel Fuels with no living tissue in which moisture content is governed almost entirely by absorption or evaporation of atmospheric moisture (relative humidity and precipitation).

Desorption The loss of moisture to the atmosphere from dead plant material.

Dew The moisture which collects in small droplets on the surface of substances and vegetation by atmospheric condensation, chiefly at night.

Drought index A numerical value reflecting the dryness of soils, deep forest litter, logs and living vegetation.

Duff The layer of decomposing vegetative matter on the forest floor below the litter layer, the original structure still being recognisable.

Ecological burning A form of prescribed burning. Treatment with fire of vegetation in nominated areas to achieve specified ecological objectives.

Edge burning A term used to describe perimeter burning of an area in mild conditions prior to large scale prescribed burning. This practice is used to strengthen buffers and to reduce mop-up operations.

Elevated fuel The standing and supported combustibles not in direct contact with the ground and consisting mainly of foliage, twigs, branches, stems, bark and creepers.

Equilibrium moisture content The equilibrium moisture content (EMC) content that a fuel element would attain if exposed for an infinite period in an environment of specified constant dry-bulb temperature and relative humidity. When a fuel element has reached its EMC, it neither gains nor loses moisture as long as conditions remain constant.

Fine fuel Fuel such as grass, leaves, bark and twigs less than 6mm in diameter that ignite readily and are burnt rapidly when dry.

Fire behaviour prediction Prediction of probable fire behaviour usually prepared by a fire behaviour analyst in support of fire suppression or prescribed burning operations.

Fire behaviour model A set of mathematical equations that can be used to predict certain aspects of fire behaviour.

Fire behaviour prediction system A system that uses a set of mathematical equations to predict certain aspects of fire behaviour in wildland fuels when provided with data on fuel and environmental conditions.

Fire brand A piece of flaming or smouldering material capable of acting as an ignition source. eg eucalypt bark.

Fire danger Sum of constant danger and variable danger factors affecting the inception, spread, and resistance to control, and subsequent fire damage; often expressed as an index.

Fire danger class A segment of a fire danger index scale identified by a descriptive term (e.g. Low, Moderate, High, Very High, Extreme) and/or a colour code. The classification system may be based on more than one fire danger index.

Fire danger index A relative number denoting an evaluation of rate of spread, or suppression difficulty for specific combinations of temperature, relative humidity, drought effects and wind speed.

Fire danger rating A relative class denoting an evaluation of rate of spread, or suppression difficulty for specific combinations of temperature, relative humidity, drought effects and wind speed. Rated as low, moderate, high, very high or extreme, indicating the relative evaluation of fire danger.

Fire frequency A general term referring to the recurrence of fire in a given area over time.

Fire front The part of a fire within which continuous flaming combustion is taking place. Unless otherwise specified, the fire front is assumed to be the leading edge of the fire perimeter. In ground fires, the fire front may be mainly smouldering combustion.

Fireground The area in the vicinity of a fire suppression operations, and the area immediately threatened by the fire. It includes burning and burnt areas; constructed and proposed fire lines; the area where firefighters, vehicles, machinery and equipment are located when deployed; roads and access points under traffic management control; tracks and facilities in the area surrounding the actual fire; and may extend to adjoining area directly threatened by the fire.

Fireline A natural or constructed barrier, or treated fire edge, used in fire suppression and prescribed burning to limit the spread of fire.

Fireline intensity The rate of energy release per unit length of fire front usually expressed in kilowatts per metre (Kw/m), defined by the equation $I=Hwr$,
where I = fireline intensity (kW/m), H = heat yield of fuel (kJ/kg)-16,000 kJ/kg w = dry weight of fuel consumed (kg/m2), r = forward rate of spread (m/s).

Fire regime	The history of fire in a particular vegetation type or area including the frequency, intensity and season of burning. It may also include proposals for the use of fire in a given area.
Fire risk	Processes, occurrences or actions that increase the likelihood of fires occurring.
Fire season	The period during which wildfires are likely to occur, spread and do sufficient damage to warrant organised fire control.
Fire wind	The inflow of air close to a fire caused by the action of convection. It is not to be confused with a prevailing wind.
Flame angle	The angle of the flame in relation to the ground, caused by wind direction or the effect of a slope.
Flame depth	The depth of the zone within which continuous flaming occurs behind the fire edge.
Flame height	The average maximum vertical extension of flames at the leading edge of the fire front. Occasional flashes that rise above the general level of flames are not considered. This distance is less than the flame length if flames are tilted due to wind or slope.
Flame length	The distance between the flame tip and the midpoint of the flame depth at the base of the flame (generally the ground surface), an indicator of fire intensity.
Forest	An area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding 2 metres and with existing or potential crown cover of overstorey strata about equal to or greater than 20 per cent. This definition includes Australia's diverse native forests, woodlands and plantations, regardless of age.
Forward rate of spread	The speed with which a head fire moves in a horizontal direction across the landscape.
Fuel	Any material such as grass, leaf litter and live vegetation which can be ignited and sustains a fire. Fuel is usually measured in tonnes per hectare.
Fuel age	The period of time lapsed since the fuel was last burnt.
Fuel bed depth	Average height of surface fuels contained in the combustion zone of a spreading fire front.
Fuel continuity	The degree or extent of continuous or uninterrupted distribution of fuel particles in a fuel bed thus affecting a fire's ability to sustain combustion and spread. This applies to aerial fuels as well as surface fuels.
Fuel depth	The average distance from the bottom of the litter layer to the top of the layer of fuel, usually the surface fuel.
Fuel load	The oven dry weight of fuel per unit area. Commonly expressed as tonnes per hectare.
Fuel model	Simulated fuel complex for which all fuel descriptors required for the solution of a mathematical rate of spread model have been specified.
Fuel moisture content	The water content of a fuel expressed as a percent of the oven dry weight of the fuel particle. (%ODW)
Fuel moisture differential	A term used to describe the situation where the difference in the moisture content between fuels on adjacent areas results in noticeably different fire behaviour on each area.
Grassland curing	The proportion of dead material in grasslands – usually increases over summer as tillers die off and dry out, increasing the risk of grassland fire.
Grid ignition	A method of lighting prescribed fires where ignition points are set individually at a predetermined spacing through an area.
Hand line	A fireline constructed with hand tools.
Head fire	The part of a fire where the rate of spread, flame height and intensity are greatest, usually when burning downwind or upslope.
Heli-torch	An aerial ignition device hung from or mounted on a helicopter to disperse ignited lumps of gelled gasoline. Used for backburns, burnouts, or prescribed burns.
High intensity fire	Fires with an average intensity greater than 3000 kW.m-1 and flame heights greater than 3 m, causing complete crown scorch or possibly crown fires in forests. Uncontrollable by direct attack. The term is also applied to stationary fires burning in very high fuel loads (such as logging slash).

Ignition pattern	The manner in which a prescribed burn, backburn, or burnout is set, determined by weather, fuel, ignition system, topographic and other factors having an influence on fire behaviour and the objective of the burn.
Instability	The tendency for air parcels to accelerate when they are displaced from their original position; especially, the tendency to accelerate upward after being lifted. Instability is a prerequisite for severe weather - the greater the instability, the greater the potential for severe thunderstorms.
Inversion	A layer of the atmosphere in which temperature increases with increasing elevation. A condition of strong atmospheric stability.
Lag time	The time delay in fuel moisture content responding to changing environmental conditions (for example, relative humidity). Technically, it is the time necessary for a fuel particle to lose approximately 63% of the difference between its initial moisture content and its equilibrium moisture content.
Litter	The top layer of the forest floor composed of loose debris of dead sticks, branches, twigs, and recently fallen leaves and needles, little altered in structure by decomposition. (The litter layer of the forest floor).
Litter bed fuel	Dead fine fuel, including surface fuel and fuel lower in the fuel profile.
Litter fall	The addition of litter that falls from vegetation to the forest floor.
Living fuels	Fuels made up of living vegetation.
Low intensity fire	A fire which travels slowly and only burns lower storey vegetation, like grass and lower tree branches, with an average intensity of less than 500 kW.m-1 and flame height less than 1.5m. Usually causes little or no crown scorch and is easily controlled.
Mosaic	Used in reference to the spatial arrangement of burnt and unburnt fuels at either a local or a landscape scale.
Near surface fuels	Fuels above surface fuels with a vertical component to their structure and are generally less than about 30 cm above the ground, but may be as high as 60 cm.
Patch burning	Burning in patches to prepare sites for group planting or sowing or to form a barrier to subsequent fires.
Predicted rate of spread	The rate of spread predicted by the application of fire spread models utilising appropriate inputs of fuel conditions, topography and weather.
Prescribed burning	The controlled application of fire under specified environmental conditions to a predetermined area and at the time, intensity, and rate of spread required to attain planned resource management objectives. It is undertaken in specified environmental conditions.
Prescribed fire	Any fire ignited by management actions to meet specific objectives. A written, approved burn plan must exist, and approving agency requirements (where applicable) must be met, prior to ignition.
Prescription	A written statement defining the objectives to be attained during prescribed burning.
Psychrometer	The general name for instruments designed for determining the relative humidity of the air. A psychrometer consists of wet and dry bulb thermometers, generally with the aid of psychrometric tables or a psychrometric slide rule.
Rain gauge	The general name for instruments designed to measure the amount of rain that has fallen.
Rate of spread	The speed with which a fire moves in a horizontal direction across the landscape at a specified part of the fire perimeter.
Relative humidity	The amount of water vapour in a given volume of air, expressed as a percentage of the maximum amount of water vapour the air can hold at that temperature.
Residence time	The time required for the flaming zone of a fire to pass a stationary point; the width of the flaming zone divided by the rate of spread of the fire.
Risk analysis	A systematic use of available information to determine how often specific events may occur and the magnitude of their likely consequences.
Risk	The exposure to the possibility of such things as economic or financial loss or gain, physical damage, injury or delay, as a consequence of pursuing a particular course of action. The concept of risk has two elements, i.e. the likelihood of something happening and the consequences if it happens. (AS4360)
Scorch height	1. The height above ground level up to which foliage has been browned by a fire. 2. A measurement for determining the acceptable height of flame during prescribed burning.

Scrub	Refers to vegetation such as heath, wiregrass and shrubs, which grows either as an understorey or by itself in the absence of a tree canopy.
Smoke management	Used by land managers and meteorologists planning a prescribed burn, to ensure that smoke does not cause problems downwind of the burn.
Soil Dryness Index	A form of Drought Index, usually with slightly more detailed inputs than the Keetch-Byram Drought Index. May be on a scale of 0-200 like the KBDI, but some versions have different scales (for example, Western Australia: 0-2000).
Spot fire	1. Isolated fire started ahead of the main fire by sparks, embers or other ignited material, sometimes to a distance of several kilometres. 2. A very small fire that requires little time or effort to extinguish.
Spot ignition	An ignition pattern using a series of spaced points of ignition.
Spotting	Behaviour of a fire producing sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire.
Strip burning	1. An ignition pattern using lines of continuous fire. 2. In hazard reduction, burning narrow strips of fuel and leaving the rest of the area untreated by fire.
Surface fire	Fire that burns loose debris on the surface, which includes dead branches, leaves, and low vegetation.
Surface fuel	Fuels lying on or near the surface of the ground, consisting of leaf and needle litter, dead branch material, downed logs, bark, tree cones, and low stature living plants.
Urban Interface	The line, area, or zone where structures and other human development adjoin or overlap with undeveloped bushland.
Temperature (dew point)	This is a measure of the moisture content of the air and is the temperature to which air must be cooled in order for dew to form. The dew-point is generally derived theoretically from dry and wet-bulb temperatures, with a correction for the site's elevation.
Temperature (dry bulb)	The ambient air temperature recorded by an exposed thermometer.
Temperature (wet bulb)	Wet bulb temperature is measured by placing a moist, single-layer, muslin sleeve over the bulb of a dry bulb thermometer. The difference between dry and wet bulb readings is used to determine relative humidity and dewpoint values.
Test fire	A controlled fire ignited to evaluate fire behaviour.
Wildfire	An unplanned vegetation fire. A generic term which includes grass fires, forest fires and scrub fires.
Wind speed	The rate of horizontal motion of the air past a given point expressed in terms of distance per unit of time.
Woodland	A subset of forest plant communities in which the trees form only an open canopy (between 20% and 50% crown cover), the intervening area being occupied by lower vegetation, usually grass or scrub

6.2 Appendix 2 Fire prediction equations

The equations for predicting fire behaviour in different vegetation associations are listed below.

Rate of fire spread correction on slopes (all vegetation associations)

ROS_s = ROS_f*exp(0.069*$slope_{deg}$)

McArthur (1967); Noble et al. (1980).

Byrams Intensity (all vegetation associations)

I_B = (H*W*ROS)/600

Byram (1959).

Dry eucalypt forest

Dry eucalypt fuel characteristics

Surface fuel depth and hazard: Vesta fire model

$Fuel_{sur\ dph}$ = ((24.08*(1-exp(-0.025*age*12)))+(26.4*(1-exp(-0.02*age*12))))/2

$Fuel_{sur\ haz}$ = ((3.31*(1-exp(-0.035*age*12)))+(3.381*(1-exp(-0.03*age*12))))/2

Surface- and near-surface fuel load: Vesta fire model

$Fuel_{ns\ load}$ = (((16.04*(1-exp(-0.022*age*12)))+(17.67*(1-exp(-0.013*age*12))))/2)

Near-surface fuel height and hazard: Vesta fire model

$Fuel_{ns\ hgt}$ = ((20.02*(1-exp(-0.035*age*12)))+(23.33*(1-exp(-0.025*age*12))))/2

$Fuel_{ns\ haz}$ = ((2.85*(1-exp(-0.018*age*12)))+(3.34*(1-exp(-0.017*age*12))))/2

Elevated fuel height and hazard: Vesta fire model

$Fuel_{elev\ hgt}$ = (148.1*(1-exp(-0.022*age*12)))/100

$Fuel_{elev\ haz}$ = ((2.18*(1-exp(-0.038*age*12)))+(2.62*(1-exp(-0.028*age*12))))/2

Bark fuel-hazard: Vesta fire model

$Fuel_{bark\ haz}$ = ((3.15*(1-exp(-0.019*age*12)))+(2.41*(1-exp(-0.026*age*12))))/2

Dry eucalypt forest fuel moisture

$Mf_{eucalypt}$ = $((2.143+0.0322*T_{dry}-0.0006135*T_{dry}^{2})*(663.6+17.8*T_{dry})+((193-1.366*T_{dry})*RH^{(0.9367+0.00487*Tdry)}))/((663.6+17.8*T_{dry})+RH^{(0.9367+0.00487*Tdry)})$

$Mf_{factor\ Vesta}$ = $Mf_{eucalypt}^{-1.495}/0.0545$

Dry eucalypt forest fire behaviour: Vesta fire model

ROS_{Vesta} = $(30+3.102*if(wind_{10}<5,0,(wind_{10}-5))^{0.904}*exp(0.279*Fuel_{sur\ haz}+0.611*Fuel_{ns\ haz}+0.013*Fuel_{ns\ hgt}))*Mf_{factor\ Vesta}$

FH_{Vesta} = $0.0193*ROS_{Vesta}^{0.723}*exp(0.64*Fuel_{elev\ hgt})$

Dry eucalypt forest fire behaviour: McArthur Forest Fire Danger Meter

FFDR = $1.25*DF*exp(((T_{dry}-RH)/30)+(0.0234*Wind_{10}))$

$ROS_{McArthur}$ = ((0.0012*FFDR*fuel load)*16.667

$FH_{McArthur}$ = $13*(ROS_{McArthur}*0.06)+0.24*$fuel load-2

$Spot_{McArthur}$ = $(ROS_{McArthur}*0.06)*(4.17-0.033*$fuel load)-0.36

McArthur (1967); Noble et al. (1980); Gould et al. (2007a, 2007b).

Heathland, dry scrub and wet scrub

Fuel characteristics

Fuel load and height, wet scrub

$Fuel_{ws\ load}$ = 67*(1-exp(-0.04*age))

$Fuel_{ws\ hgt}$ = 4*(1-exp(-0.075*age))

Marsden-Smedley (2002).

Heathland, dry scrub and wet scrub fuel moisture

Mf_{ws} = exp(1.66+0.0214*RH-0.0292*(((1/273.16-0.000184*ln(((0.611*exp((17.2694* ((T_{dry}+273.16)-273.16))/((T_{dry}+273.16)35.86)))*(RH/100))/0.611))-1)-273.16))

$Mf_{ws\ stick}$ = exp(1.193+0.7626*Ln(hazard stick))

Rf_{ws} = (67.128*(1-exp(-3.132*(if(rain<1,0, if(rain<2,(rain-1)*0.25,if(rain<3,(rain-2)*0.5+0.25,if(rain<4,(rain-3)*0.75+0.75, (rain-1.5))))))))*exp(-0.0858*hours))

$Mf_{ws\ factor}$ = if((1.5+0.025*Mf_{scrub})>1,1,(1.5+0.025*Mf_{scrub}))*if((0.05*SDI)>1,1,(0.05*SDI))

Marsden-Smedley (2002).

Heathland and dry scrub fire behaviour

ROS_{heath} = (0.049*($wind_{surface}$ * 0.28)$^{1.21}$*Fuel $height_{heath}^{0.54}$)*60

Anon (1998); Catchpole et al. (1998, 1999).

Wet scrub fire behaviour

ROS_{ws} = (0.049*($wind_{surface}$ * 0.28)$^{1.21}$*Fuel $height_{ws}^{0.54}$)*60*$Mf_{ws\ factor}$

FH_{ws} = 0.0325*(((18637-(24*Mf_{ws}))*Fuel*ROS_{ws})/600)$^{0.56}$

SFDR = 0.83*ROS_{ws}

Anon (1998); Catchpole et al. (1998, 1999); Marsden-Smedley (2002).

Buttongrass moorland

Buttongrass moorland fuel characteristics

Buttongrass moorland fuel load in low and medium productivity sites

$Fuel_{bg\ low}$ = 11.73*(1-exp(-0.106*age))

$Fuel_{bg\ med}$ = 44.61*(1-exp(-0.041*age))

Buttongrass moorland fuel moisture

Buttongrass moorland rainfall and humidity factors

Rf_{bg} = 67.128*(1-exp(-3.132*rain))*exp(-0.0858*hours)

Hf_{bg} = exp(1.66+0.0214*RH-0.0292*(((1/273.16-0.000184*ln(((0.611*exp((17.2694* ((T_{dry}+273.16)-273.16))/((T_{dry}+273.16)35.86)))*(RH/100))/0.611))-1)-273.16))

Buttongrass moorland fuel moisture

Mf_{bg} = Rf_{bg} + Hf_{bg}

Buttongrass moorland fire behaviour

Buttongrass moorland rate of head fire spread, all sites

ROS_{bg} = 0.678*$wind_{surface}^{1.312}$*exp(-0.0243*Mf_{bg})*(1-exp(-0.116*age))

Buttongrass moorland head fire flame height, low and medium productivity sites

$FH_{bg\ low}$ = 0.148*(((18637-(24*Mf_{bg}))*$Fuel_{bg\ low}$*ROS_{bg})/600)$^{0.403}$

$FH_{bg\ med}$ = 0.148*(((18637-(24*Mf_{bg}))*$Fuel_{bg\ med}$*ROS_{bg})/600)$^{0.403}$

Moorland Fire Danger Rating

MFDR = 0.65*$ROS_{bg}^{1.02}$

Probability that buttongrass moorland fires will be sustained

P_{bg} = 1/(1+exp(-(-1+0.68*$wind_{surface}$-0.07*Mf_{bg}-0.0037*$wind_{surface}$*Mf_{bg}+2.1*productivity)))

Buttongrass moorland flank and back fires

$ROS_{bg\ flank}$ = 0.4*ROS_{bg}

$FH_{bg\ flank}$ = 0.6*FH_{bg}

$ROS_{bg\ back}$ = 0.1*ROS_{bg}

$FH_{bg\ back}$ = 0.5*FH_{bg}

Marsden-Smedley and Catchpole (1995a, 1995b, 2001); Marsden-Smedley et al. (1999, 2001).

Native grassland

$Fuel_{grass}$ = ((0.0089*(∑$GrassHgt_{spp}$*$GrassCvr_{spp}$)+0.3434*(∑$GrassHgt_{spp}$*$GrassCvr_{spp}$)$^{-0.5}$)^2)*0.01

Mf_{grass} = (97.7+4.06*RH)/(T_{dry}+6)-0.00854*RH+3000/curing-30

ROS_{grass} = 0.4539*($Wind_{10}$*0.2778)$^{0.951}$*exp(-0.0966*Mf_{grass})*60

P_{grass} = 1/(1+exp(-(-1.61-0.14*Mf_{grass}+0.34*$Fuel_{grass}$+0.04*curing)))

McArthur (1966) Noble et al. (1980); Cheney et al. (1993); Leonard (2009).

Appendix 2 Fire prediction equations, continued

Table A2.1 Fire behaviour equation symbols and units.

age	time since the last fire, years;
$cover_{spp}$	cover of individual species in native grassland, %;
curing	proportion of dead grass in the fuel array, %;
DF	Drought Factor, dimensionless;
FFDR	Forest Fire danger Rating, dimensionless;
$FH_{bg\ back}$	buttongrass moorland back fire flame height, m;
$FH_{bg\ flank}$	buttongrass moorland flank fire flame height, m;
$FH_{bg\ low}$	buttongrass moorland flame height in low productivity sites, m;
$FH_{bg\ med}$	buttongrass moorland flame height in medium productivity sites, m;
$FH_{McArthur}$	dry eucalypt forest flame height from McArthur (1973), m;
FH_{ws}	wet scrub flame height, m;
FH_{Vesta}	dry eucalypt forest flame height from the Vesta model, m;
Fuel	total fuel load, all vegetation associations, t ha^{-1};
$Fuel_{grass}$	native grassland fuel load, t ha^{-1};
$Fuel_{bark\ haz}$	dry eucalypt forest bark fuel-hazard from the Vesta model, dimensionless;
$Fuel_{bg\ low}$	buttongrass moorland fuel load in low productivity sites, t ha^{-1};
$Fuel_{bg\ med}$	buttongrass moorland fuel load in medium productivity sites, t ha^{-1};
$Fuel_{elev\ haz}$	dry eucalypt forest elevated fuel-hazard from the Vesta model, dimensionless;
$Fuel_{elev\ hgt}$	dry eucalypt forest elevated fuel height from the Vesta model, m;
$Fuel_{ns\ haz}$	dry eucalypt forest near-surface fuel-hazard from the Vesta model, dimensionless;
$Fuel_{ns\ hgt}$	dry eucalypt forest near-surface fuel height from the Vesta model, m;
$Fuel_{ns\ load}$	dry eucalypt forest near-surface fuel load from the Vesta model, m;
$Fuel_{sur\ dph}$	dry eucalypt forest surface fuel depth from the Vesta model, m;
$Fuel_{sur\ haz}$	dry eucalypt forest surface fuel-hazard from the Vesta model, dimensionless;
$Fuel_{ws\ hgt}$	wet scrub fuel height, m;
$Fuel_{ws\ load}$	wet scrub fuel load, t ha^{-1};
Fuel $height_{ws}$	wet scrub fuel height, m;
$GrassCvr_{spp}$	cover of individual species in grassland, %;
$GrassHgt_{spp}$	height of individual species in grassland, cm;
Hazard stick	hazard stick, 12 mm diameter wood, moisture, %
Heat	fuel energy content, kW kg^{-1};
Hf_{bg}	buttongrass moorland humidity factor, %;
hours	time since the rain and/or dewfall stopped, hours;
IB	Byrams Intensity (Byram 1959), kW m^{-1};
Mf_{bg}	buttongrass moorland dead-fuel moisture, %;
MFDR	Moorland Fire Danger Rating, dimensionless;
$Mf_{eucalypt}$	dry eucalypt forest fuel moisture, %;
$Mf_{factor\ Vesta}$	dry eucalypt forest fuel moisture factor, dimensionless;
Mf_{grass}	native grassland fuel moisture, %;
Mf_{ws}	wet scrub fuel moisture, %;
$Mf_{ws\ factor}$	wet scrub fuel moisture factor, dimensionless;
$Mf_{ws\ stick}$	wet scrub fuel moisture predicted from 12 mm hazard sticks, %;
$height_{spp}$	height of individual species in native grassland, cm;
P_{bg}	probability buttongrass moorland fires will sustain ($P>0.3$) or self-extinguish ($P<0.3$);
P_{grass}	probability native grassland fires will sustain ($P>0.45$) or self-extinguish ($P<0.45$);
productivity	buttongrass moorland productivity, low productivity = 1, medium productivity = 2;
rain	rain and/or dewfall in the last 48 hours, mm;
Rf_{bg}	buttongrass moorland rainfall factor, %;
RH	relative humidity, %;
ROS	rate of fire spread, all vegetation associations, m min^{-1};
ROS_{bg}	buttongrass moorland head-fire rate of spread, m min^{-1};
$ROS_{bg\ back}$	buttongrass moorland back fire rate of fire spread, m min^{-1};
$ROS_{bg\ flank}$	buttongrass moorland flank fire rate of fire spread, m min^{-1};
ROS_f	rate of fire spread on flat ground, all vegetation associations;
ROS_{grass}	native grassland rate of fire spread, m min^{-1};
$ROS_{McArthur}$	dry eucalypt forest fuel rate of fire spread predicted by McArthur (1973), m min^{-1};
ROS_s	slope adjustment factor for rate of fire spread, m min^{-1};
ROS_{ws}	wet scrub rate of fire spread, m min^{-1};
ROS_{Vesta}	dry eucalypt forest fuel rate of fire spread predicted by the Vesta model, m min^{-1};
SDI	Soil Dryness Index, dimensionless;
SFDR	Scrub Fire danger Rating, dimensionless;
$slope_{deg}$	slope angle, degrees;
$Spot_{McArthur}$	spot fire distance predicted by McArthur (1973), km;
T_{dry}	dry bulb temperature, °C;
$wind_{surface}$	wind speed, measured at 1.7 m above the ground surface, km hr^{-1};
$wind_{10}$	wind speed, measured at 10 m above the ground surface, km hr^{-1}.

CONTACT DETAILS

Parks and Wildlife Service
Department of Primary Industries,
Parks, Water and Environment
GPO Box 1751
Hobart, Tasmania, 7001

Ph: 1300 135 513

www.parks.tas.gov.au

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