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Fuel in Tasmanian Dry Eucalypt Forests: Prediction of Fuel Load and Fuel Hazard Rating from Fuel Age

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Abstract: This paper presents equations for fuel load and fuel hazard rating (FHR) models based on the time since last fire for dry eucalypt forests in eastern Tasmania. The fuel load equations predict the load of the surface/near-surface and elevated fine fuel. The FHR equations predict the surface, near-surface, combined surface and near-surface, bark, and overall FHR. The utility of the "Overall fuel hazard assessment guide" from Victoria, Australia, is assessed for Tasmanian dry eucalypt forests: we conclude that, when fuel strata components are weighted according to their influence on fire behaviour, the Victorian guide provides a rapid, robust, and effective methodology for estimating FHR. The equations in this paper will be used for operational planning and on-the-ground performing of hazard reduction burning, prediction of fire behaviour for fire risk assessments and bushfire control, and providing inputs into the new Australian Fire Danger Rating System.

Keywords: fuel hazard rating; fuel load; fuel accumulation curves; fire modelling; eucalypt forest; Tasmania

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1. Introduction

1.1. Paper Aims and Background

Fire management planning is a fundamental aspect of managing the Australian natural environment for land and ecosystem management, fire risk assessment, planned burning, and bushfire control. A comprehensive knowledge of the available fuel for burning in a particular fuel type and age is of critical importance when predicting fire behaviour.

World-wide, a range of fuel classification systems have been developed, addressing different fire dynamics and control strategies. These fuel classification systems have been reviewed in the Australian context [1,2]. In addition, a review of the fire behaviour models used in Australian vegetation types, including the influence of fuel characteristics, is given in [3,4].

Prior to about 15 years ago, the term *fuel characteristics*, as used in Australia, referred solely to the litter and near surface fuel load [5,6] or the top and profile litter fuel load [7]. However, the results of the 'Project Vesta' experimental burns in Western Australia determined that fire spread rate was more highly correlated with fuel structure and composition [4,8–12]. Fuel load does, however, have significant influence on fire intensity and flame height [13].

Two major systems of categorising fuel characteristics according to flammability (e.g., cover, continuity, percentage dead fuel) were developed in the late 1990s and early 2000s: *fuel hazard rating* (FHR), outlined in the Victorian and South Australian fuel hazard guides to prescribed burning [14,15], and *fuel hazard score* (FHS) developed by Project Vesta experimental burns in eucalypt forests [9–12]. In Tasmania, fuel hazard ratings are used to characterise forest vegetation. Both FHR and FHS increase with fuel age (time since last fire) in a similar way to fuel load, so age can be used to predict these if suitable accumulation curves are developed for the relevant vegetation type [12].

To assist with operational on-the-ground fire management in Tasmania, the aims of this paper are twofold:

1. To develop fuel load and fuel hazard rating (FHR) models based on the time since the last fire (i.e., fuel accumulation models);
2. To test, under Tasmanian conditions, the "Overall fuel hazard assessment guide" from Victoria, Australia [14].

The fuel accumulation models developed in this paper will be used primarily for fire behaviour prediction. In Australian dry eucalypt forests, the four methods currently utilised when predicting fire spread rate are McArthur's Control Burning in Eucalypt Forests (CBEF) [16], the Forest Fire Danger Meter (FFDM) [17–19], and the Project Vesta fire behaviour prediction models, Vesta and Vesta II [11,20]. The CBEF and FFDM require as input the amount of fine litter and near-surface fuel present at a site [16,18,19]. The original Vesta model was formulated into two forms based on either FHS or FHR. Vesta II model [20] requires combined surface and near-surface fuel loads and height and cover of near-surface and elevated fuel.

In the early 2000s, fire simulation programs have come into operational use based on one or more of the fire prediction models above, such as Phoenix RapidFire [21,22] and Spark [23–25]. Phoenix RapidFire requires inputs of combined surface and near-surface, elevated, and bark fuel loads [21,22]. The forest prediction model in Spark [24] is based on Vesta II [20] with the required inputs given above.

The amount of fuel present at a site is used in the proposed Australian bushfire fuel classification system [25,26], a component of the National Fire Danger Rating System [27]. Fuel load is also used in the Australian Standard for building in bushfire-prone areas [28].

To satisfy the requirements of Spark [20] and Phoenix RapidFire [21,22], the following fuel characteristic models are required: combined surface and near-surface, elevated and bark fuel loads, and height and cover of near-surface and elevated fuel. Models for these characteristics (except for bark fuel, which was not assessed) are given below. Total fuel load required for estimating fire intensity of a fire in the understorey (including elevated and bark fuels) can be obtained by adding these models. As the bark fuels were not assessed in this project, bark load can only be estimated from bark type and age as described in [25]. The fuel hazard ratings used in Vesta I [11] are not used in Vesta II [20] but are still used in many parts of Australia to assess fire risk, so fuel hazard models were also developed.

The work referred to in this paper originally formed part of a report describing fuel load and FHR in Tasmanian dry forests [29]. However, as part of summarising this report for this paper, the fuel load and FHR models have been updated and additional models developed.

1.2. Fuel Load Assessment

Litter fuel load accumulation models have previously been developed on the mainland of Australia: Western Australia for *Eucalyptus diversicolor* (karri) and for *Eucalyptus marginata* (jarrah) [30–35]; New South Wales for mixed dry eucalypt forest, with or without an understorey [36] and *Eucalyptus pilularus* (blackbutt) [37]; Queensland for open grassy eucalypt woodland [38]; and Victorian for *E. obliqua* and *Eucalyptus radiata* [6]. Over 40 New South Wales fuel accumulation studies (many unpublished) have been summarised and models have been developed for rainforest, wet and dry sclerophyll forest, and grassy woodlands [39]. In Tasmania, fuel accumulation models have been developed for southeast (SE) Tasmanian dry eucalypt forest [40], northeast (NE) Tasmanian dry eucalypt forest [41], buttongrass moorland [42], and native grassland [43].

During the 1990s and early 2000s, fuel load modelling studies in dry eucalypt forests were undertaken in NE Tasmania by the Parks and Wildlife Service (PWS), and in SE Tasmania [44,45]. This paper utilises the data collected during these studies in NE and SE Tasmania and presents fuel load accumulation models.

The fuel load models in this paper have been formulated in SI units. To convert the outputs of these models into the units used for fire management (tonnes per hectare), the fuel loads need to be multiplied by ten (i.e., 1 kg m^{-2} is equal to 10 t ha^{-1}).

1.3. Fuel Hazard Rating Assessment

Fuel hazard assessment systems which characterise fuel structure rather than fuel load have been developed [9,10,14,15,46]. In these systems, the most important factors are the ratio of dead fuel to live fuel, continuity (primarily horizontal, but also vertical), the cover and height of different strata, and the relative proportions of the different fuel strata [9,12,14]. These fuel hazard assessment systems divide the fuels into four strata: surface, near-surface, elevated and bark fuels. In addition, the systems combine the effects of these strata to provide an estimate of overall fuel hazard. Apart from the South Australian FHR system [15], which is intended to be used in the full range of South Australian vegetation types, these FHR systems are primarily intended for use in dry eucalypt forest.

Information on surface, near-surface, and elevated fuel continuity (also sometimes referred to as connectivity); vegetation density; surface fuel cover and depth; near-surface and elevated fuel cover; height and percentage of dead vegetation; as well as bark type, amount, and attachment is used to determine the FHR of different strata [14]. The Victorian and South Australian fuel hazard assessment systems are intended to assist fire suppression operations but can also be used to provide information for fire behaviour prediction. These systems use different cover, height, and continuity thresholds to the Project Vesta fuel hazard scores, which are intended primarily for predicting fire behaviour [9–12].

Very little published research is available for fuel hazard accumulation. In Western Australian dry eucalypt forests, the relationship between age and fuel hazard has been reported to have a similar form to the relationship between age and fuel load, but the models developed were for fuel hazard scores rather than fuel hazard ratings [35]. The fuel hazard ratings and accumulation curves of eight NSW vegetation types have been examined so that the Vesta equations could be tested [40]. Hazard accumulation curves have also been developed for Victorian vegetation types, but the work is unpublished and not readily available. Except for the current study, no published or unpublished work has been published on fuel hazard assessment in Tasmania.

2. Methodology

2.1. Study Sites

The data reported in this paper were collected during three projects in eastern Tasmanian dry forests (Figure 1; Table A1 (Appendix A)). The first two projects identified study sites and collected fuel load data in SE and NE Tasmania. The third project collected FHR data from a subset of the sites used for examining fuel load.

The fuel load data from SE Tasmania were collected from 68 sites in 1998 [44,45], and the NE Tasmanian fuel load data were collected from 67 sites in 2002 (Figure 1; Table A2 (Appendix B)). The fuel hazard rating research was conducted in 2011. During the time gap between the fuel load and fuel hazard research, some sites had been burnt while other sites had been cleared, developed, and/or replanted. Thus, the third project only collected data from a total of 74 of the original sites, 33 in NE Tasmania and 41 in SE Tasmania (Figure 1; Table A3 (Appendix C)).

In NE Tasmania, all of the sites consisted of dry eucalypt forest dominated by *Eucalyptus amygdalina* (Black peppermint) and/or *E. obliqua* (Stringybark). In this paper, all plant species names follow the census of Tasmanian plant species names [47]. Analysis of the TasVeg vegetation map [48] indicated that these are the most common and widespread dry forest types in NE Tasmania, accounting for 70% of the region's dry forest. The understoreys in the NE Tasmanian sites were dominated by bracken, heath, grass, and/or litter. The data collection sites also included a few sites in which *Eucalyptus sieberi* (Ironbark) was sub-dominant. However, fuel loads in *E. sieberi*-dominated forests were not targeted because fuel load prediction models had already been developed for this fuel type [41].

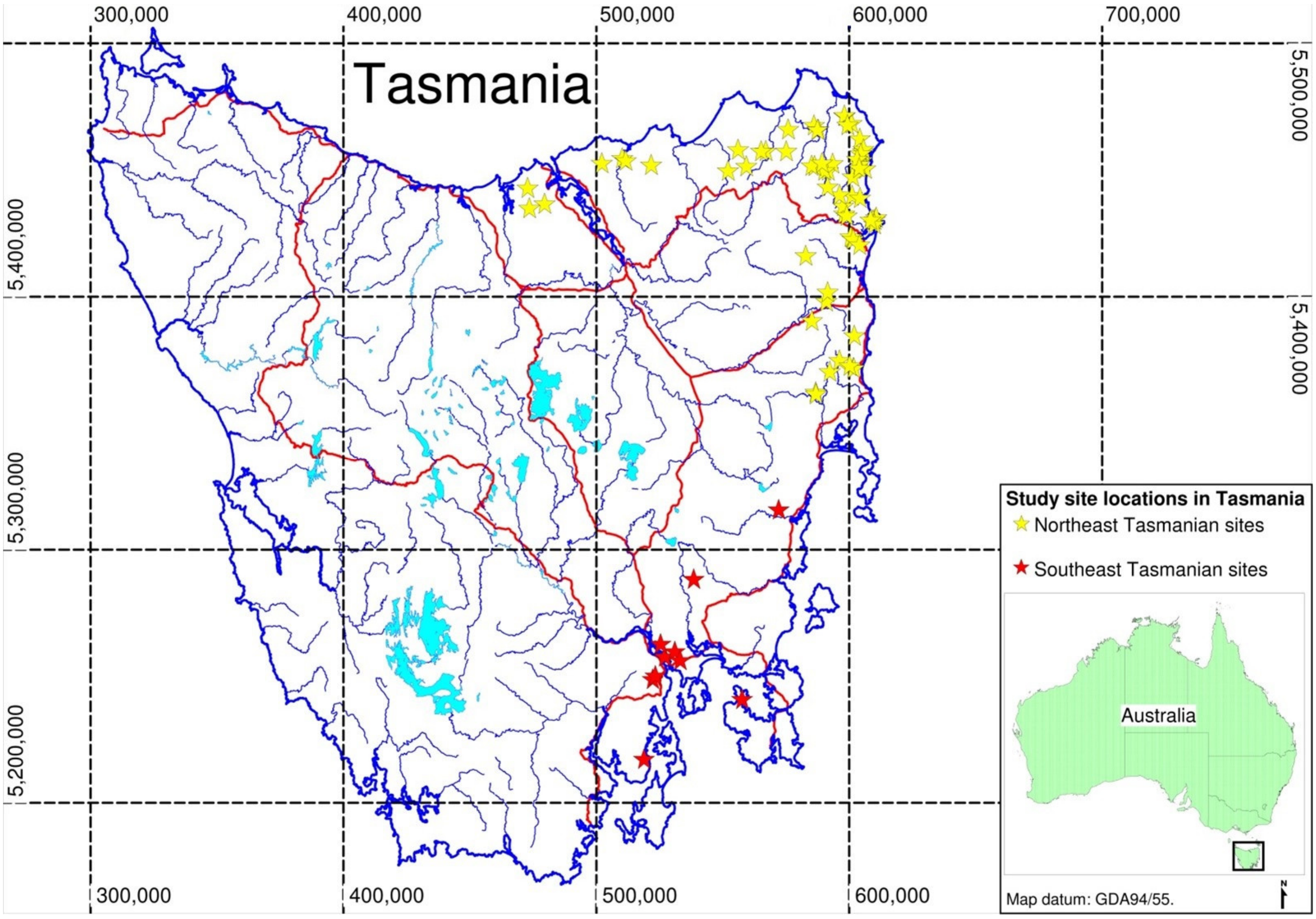

Figure 1. Study site locations in Tasmania.

In SE Tasmania, the sites consisted of a range of dry forest types dominated by *E. amygdalina, E. pulchella* (White peppermint), *E. globulus* (Blue gum), *E. viminalis* (White gum), *E. tenuiramis* (Silver peppermint), and/or *Allocasuarina verticillata* (She-oak). The understoreys in the SE Tasmanian sites were as described for the NE Tasmanian sites.

The time since last fire (i.e., site age) for each of the sites was determined from *Banksia marginata* (banksia) node counts, *Leptospermum* spp. (tea-tree) and *Eucalyptus* spp. ring counts [49], written records (e.g., PWS unpublished fire history database), and oral accounts. In SE Tasmanian, the aim was to sample as wide a range of fire ages as practical. However, because the majority of the SE Tasmanian sites were burnt in the extensive February 1967 bushfires, the maximum fire age was about 30 years at the time the fuel load data were collected.

Information on geological type was obtained from digital geology maps [50,51] with ground checking to ensure the geology map was correct.

The site data collected are in Appendix A while the fuel load and hazard data are in Appendices B and C. In Appendix D, Tables A4 and A5 contain a description of the site data and fuel data collected. Summary statistics for the fuel load and fuel hazard data are given in Tables 1 and 2.

Table 1. Fuel load data range.

	NE Sites			SE Sites			All Sites		
Variable	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Age, Years	**12.39**	**0.74**	**27.65**	**9.77**	**0.10**	**29.50**	**11.07**	**0.10**	**29.50**
Surface fuel load									
cover, %	81.53	28.50	97.75	76.12	30.00	100.00	78.80	28.50	100.00
Depth, m	0.0195	0.0039	0.0353	0.022	0.0116	0.0366	0.0208	0.0039	0.0366
Load, kg m^{-2}	0.825	0.157	1.657	0.592	0.095	1.348	0.708	0.095	1.657
Near-surface fuel load									
cover, %	35.86	7.63	65.75	58.07	0.00	100.00	47.05	0.00	100.00
Height, m	0.3151	0.1513	0.5325	0.1879	0.05	0.4225	0.2511	0.05	0.5325
Live load, kg m^{-2}	0.114	0.005	0.319	0.125	0.006	0.279	0.12	0.005	0.319
Dead load, kg m^{-2}	0.246	0.012	0.661	0.071	0.014	0.298	0.158	0.012	0.661
Load, kg m^{-2}	0.36	0.025	0.894	0.197	0.059	0.574	0.278	0.025	0.894
Elevated fuel load									
cover, %	1.59	0	6.5	24.31	0	80	13.03	0	80
Height, m	1.216	0	4	0	0	0	2.498	0.85	6.8
Live load, kg m^{-2}	-	-	-	0.085	0	0.304	0.061	0	0.304
Dead load, kg m^{-2}	-	-	-	0.05	0	0.236	0.035	0	0.236
Load, kg m^{-2}	-	-	-	0.135	0	0.462	0.096	0	0.462
Total load, kg m^{-2}	1.185	0.252	1.946	0.923	0.206	1.769	1.053	0.206	1.946

Table 2. Fuel hazard rating data range.

	NE Sites			SE Sites Except *Allocasurina*			All Sites		
Variable	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Age	**16.89**	**0.20**	**33.81**	**15.38**	**3.18**	**28.22**	**15.43**	**0.20**	**33.81**
Surface FHR									
continuity	4.16	2.00	5.00	2.84	1.00	4.90	3.43	1.00	5.00
Cover, %	73.67	30.00	94.50	47.32	10.00	87.00	58.90	10.00	94.50
Depth, m	0.0595	0.001	0.105	0.0536	0.013	0.120	0.0545	0.010	0.120
Rating	3.93	1.53	4.90	2.72	1.13	4.60	3.25	1.13	4.90
Near-surface FHR									
continuity	2.56	1.00	4.10	2.36	0.50	4.00	2.54	0.50	4.10
Cover, %	34.86	5.00	69.50	34.82	2.25	70.50	36.94	2.25	76.50
Dead, %	53.39	4.50	96.50	48.22	5.00	98.00	51.43	4.50	98.00
Rating	3.42	1.00	4.98	2.98	0.35	4.58	3.26	0.35	4.98
Combined surface and near-surface FHR rating	4.62	1.70	5.00	3.99	1.60	5.00	4.33	1.60	5.00
Elevated FHR									
horizontal continuity	1.81	0.00	4.20	1.19	0.00	3.40	1.53	0.00	4.20
Vertical continuity	2.19	0.00	5.00	1.37	0.00	3.60	1.77	0.00	5.00
Cover, %	23.47	0.00	67.00	13.20	0.00	59.50	18.80	0.00	67.00
Dead, %	27.03	0.71	61.50	7.03	2.78	18.50	17.51	0.71	61.50
Rating	2.24	0.00	4.88	1.07	0.00	4.37	1.62	0.00	4.88
Bark FHR rating	3.24	1.90	5.00	2.12	1.00	3.50	2.61	1.00	5.00
Overall FHR rating	4.26	1.60	5.00	3.05	1.40	4.80	3.60	1.40	5.00

2.2. Fuel Load Data Collection

At each site sampled for fuel load, data on surface, near-surface, and elevated fuels were collected from 10 randomly located 1 by 1 m quadrats. In the NE sites, the range of fuel conditions present at each site was assessed using four 50 m long transects which contained 40 quadrats. Ten of these quadrats were then randomly selected and sampled. In the SE sites, each site was subjectively assessed and then 10 plots at each site were randomly located by throwing a quadrat square behind the researcher. The fuel was separated in the field into live and dead components with dead bark, leaves, twigs, and sticks up to six millimetres in diameter and live leaves, twigs, and sticks up to two millimetres in diameter being collected. In addition, wads of bark which were likely to be burnt in a fire were also collected (some bark wads were greater than six millimetres in diameter). The surface fuel stratum was assumed to be less than about 0.1 m in height, near-surface fuel to be less than about 0.6 m and elevated fuel to be less than about 2.5 m. The actual height of each stratum in each plot was averaged from 10 random locations within each quadrat. The fuel load samples collected in the field were oven dried at 105 °C for 24 h.

2.3. Fuel Hazard Rating Data Collection

At each site assessed for FHR, data for surface, near-surface, elevated, and bark fuel were determined from 10 quadrats, each 2 by 2 m in size, which were located at 10 m intervals on a randomly orientated transect.

The data for surface, near-surface and elevated foliage projective cover (i.e., the area covered by vegetation [52]) and the percentage of near-surface and elevated dead fuel was visually estimated to the nearest 5%. This system of estimating vegetation cover and percentage of dead fuel has been shown by the authors to be robust and accurate, provided standardisation against measured values is used [42,43]. Since the surface fuel stratum was assumed to consist entirely of dead fuel, any live fuel within the surface fuel stratum was included as near-surface fuel.

The height (or depth) of each stratum was estimated by looking across the upper part of the fuel stratum and subjectively estimating the height below which most (typically about 75 to 90%) of the fuel occurred. This system was developed for use in buttongrass moorlands [42], has been subsequently tested [29,43], and has been shown to provide rapid, consistent, and accurate estimates of fuel stratum height.

The data for fuel continuity, bark attachment, and bark amount [14] were collected as ordered categorical variables between 1 and 5. The categorical data were assigned a value of 1 when they were in the low category, 2 when moderate, 3 when high, 4 when very high, and 5 when extreme. The technique used for each stratum to combine these attributes when estimating the level of FHR is discussed in the below. Not all the sites contained the full range of fuel strata. Where a plot was missing a fuel stratum, the height, percentage dead, continuity, bark type, and/or bark attachment were treated as missing values (i.e., not as zero), and height and cover were assumed to be zero. The categorical data collected for each variable at a site was averaged from the ten sub-plots and used as continuous data in the analysis.

Two photographs were taken at each site when the level of FHR was assessed, aiming to show the site's range in fuel characteristics (Figure 2).

In the data, there was a high correlation between cover and continuity ($r > 0.8$) for all strata, but lower correlations between surface depth and continuity/cover ($0.4 \leq r \leq 0.5$) and between percentage of dead fuel and continuity/cover ($r < 0.5$). For example, some recently burnt sites, particularly those with a bracken understory, had low percentages of dead fuel (e.g., <20%) but moderate to high covers (e.g., <60%) and high continuities (e.g., few gaps the fuel array). The tables in the Victorian fuel hazard guide [14] suggest that these sites should have high to extreme levels of FHR, while in reality their low percentages of dead fuel result in low flammability. In contrast, some older sites, particularly on low fertility substrates, had high percentages of dead fuel but low to moderate covers and continuities. This indicates that in order to use the Victorian fuel hazard assessment guide, it is necessary to make decisions as to the relative importance of different fuel characteristics.

(**a**)

(**b**)

Figure 2. Typical dry forest vegetation structure. (**a**) Site 16: *E. amygdalina* dry forest, North Fraser Track in NE Tasmania, 17.4 years since fire. (**b**) Site 55: *E. pulchella* dry forest, Waterworks Reserve, SE Tasmania, 13.2 years since fire.

When assessing FHR, the Victorian fuel hazard guide [14] recommends that:

"*choices for the hazard rating of fuels that fit across several descriptors may be informed by the effect that different levels of attributes have on fire behaviour*".

In order to do this, be consistent, and ensure that FHR are as robust as possible, weightings were subjectively applied to the field data for surface, near-surface, and elevated fuels. As an example of the weightings used, when near-surface FHR was assessed, the percentage of dead fuel was assumed to be the most important factor with cover and continuity being assumed to have equal influences. The percentage of dead fuel was assigned a weighting of 50%, and cover and continuity were each assigned a weighting of 25%. Weightings were not used when estimating the level of bark hazard as bark FHR was estimated from only one variable in the case of candle and ribbon bark, and two variables for other bark types. The weightings used to estimate the level of FHR from the data are shown in Table 3. The weighting of the fuel stratum characteristics when estimating FHR generally resulted in small increases in the correlation coefficients between age and the FHR in each fuel stratum.

Table 3. Weightings used to estimate the level of fuel hazard rating.

	Horizontal	**Vertical**			
	Continuity	**Continuity**	**Cover**	**Height**	**Dead %**
Surface	0.50		0.25	0.25	
Near-surface	0.25		0.25		0.50
Elevated	0.25	0.10	0.15		0.50

2.4. Statistical Analysis

The fuel load and FHR data were initially analysed using the modified Olsen model [40,53]:

$$F = S_{ss}(1 - \exp(-kt)) + S_0 \exp(-kt) \tag{1}$$

where F is the fuel variable being predicted (i.e., fuel load or FHR), t is the time since last fire, S_{ss} is the equilibrium fuel level, S_0 is the amount of fuel left over following the previous fire, and k is the growth rate. When fuel loads were analysed using Equation (1), the symbols S_{ss} and S_0 were replaced with W_{ss} and W_0 and they were replaced with H_{ss} and H_0 when FHR was analysed.

The amount of fuel remaining post-fire, S_0, will be strongly influenced by the fire's intensity when the site was burnt [54] for which no information was generally available. When fuel loads were analysed, W_0 was estimated from the fuel load data collected from sites less than or equal to 0.2 years, giving an estimate of 0.15 kg m^2 (1.5 t ha^{-1}). However, for the FHR data, no information was available for sites immediately post fire, so H_0 was estimated from the fitted model.

Models for surface/near-surface loading were fitted using maximum likelihood estimation (using *optim* in the *stats* library of the R software [55] with the "L-BFGS-B" optimization method [56]). Fuel load errors were assumed to be normally distributed. A constant variance model was used as models with increasing variance with mean load, which is sometimes assumed, generally gave smaller likelihoods. The assumption of normality was checked with residual plots of the standardised residuals and the Shapiro–Wilk test of normality [57]. Tests of the models combining species or understorey type against those having separate parameters for each species or understorey type were carried out using likelihood ratio tests and the Akaike Information Criterion [58] (AIC: note that a smaller AIC means a better-fitting model). Levene's test [59] was used to test the residuals for equal variance across the groups.

The hazard scores were truncated at 1 and 5 so a normal distribution could not be assumed. Models were fitted using non-linear least squares (which gives the same parameter estimates as maximum likelihood). The minimization was bounded by 1 and 5. Models were fitted separately in each region for each fuel strata. Standard errors were found from asymptotic normal theory and thus are only approximate.

Goodness-of-fit statistics [60] were used to assess the fit of the models. The statistics used were the root mean square error (RMSE); the mean absolute error (MAE), which is less sensitive to outliers; and the mean bias error (MBE).

Confidence bands for the regression curve at age t were found by bootstrapping the data and refitting the model 5000 times [61]. Confidence intervals could then be found from the bootstrapped predictions for each value of t. For each t the variance of the predictions (σ_t^2) was also obtained. The variance (σ_{pt}^2) used in calculating prediction intervals for a new site was obtained from the sum of the variance σ_t^2 and the variance, σ_ε^2, about the regression curve. Approximate normal theory then gives a 95% prediction interval for F_t at age t as:

$$F_t \pm 2\sigma_{pt} = F_t \pm 2\sqrt{\sigma_t^2 + \sigma_\epsilon^2} \tag{2}$$

For the fuel load models, σ_ε^2 was obtained from maximised likelihood, while for the fuel hazard models it was estimated from the variance of the bootstrapped estimates of the residuals.

For fuel height and elevated load data, Equation (2) provided a poor fit. The data for these parameters were analysed using a simple step model which was fitted using m_1, the mean of the data when the age was less than some critical value c, and m_2, the mean of the data when the age was greater than c. The critical value was determined by maximum likelihood using *optim* with the Nelder–Mead optimization method [62], which worked better than the "L-BFGS-B" method. This model was compared with the mean of the data to estimate the average value of the variable. Prior to this analysis, an analysis of the data with age greater or equal to 10 years was done to determine how the data should be grouped in terms of region or understorey type using analysis of variance and Tukey's HSD tests [63].

Information on height and cover was available from both loading and hazard rating data sets. However, even though there were more data in the loading data set, the method of measuring height and cover in the hazard data set was deemed more reliable.

3. Results

3.1. Fuel Load Results

3.1.1. Combined Surface and Near Surface Fuel Load

In addition to time since fire, there were several factors in the field data which have the potential to influence fuel accumulation, including region, geology, over storey species, and understory type. However, these factors were highly correlated and there were differences in proportions of the other factors between the regions, so a choice had to be made of the factors used. In developing the models, it was important to ensure that the predictive models developed were operationally practical and applicable for usage by field workers, and that there were sufficient samples in each group to result in robust models.

The main over storey eucalypt species sampled in NE Tasmania was *E. amygdalina*, and the understorey types were litter, grass, bracken, or heath. This species was also sampled in the SE Tasmanian sites, where it had either a grassy or heathy understorey. The NE sites were on granite, mudstone, and dolerite, while the SE sites were primarily on sandstone. To determine the effect of other factors without the complication of species difference, the *E. amygdalina* was first considered. Equation (1) was fitted to this surface/near-surface fuel load data (with $W_0 = 1.5$ kg m^{-2}). For all the groupings, there were significant differences between the groups. The AIC grouped by region was 265 compared with 283 for geology, and 292 for understorey. Because of this, the correlation between region and geology/understorey and the ease of determining region, the full data set was split by region.

The NE forest types were dominated by *E. amygdalina*, *E. obliqua*, and *E. sieberi*. There were only 5 data points in *E. sieberi*, so they were amalgamated with *E. amygdalina*, with which it is sub-dominant, which provided a slightly better model than amalgamating with *E. obliqua*. Thus, the NE data were grouped as *(i) E. amygdalina* and *E. sieberi* and *(ii) E. obliqua*, and a model fitted to all the data with separate growth rates and equilibrium loads for the two groups. Residual analysis was satisfactory, and the variances of the residuals for each group were not significantly different, justifying the use of the whole data set to generate the models and thus improving the precision of the parameters. In addition, a model was made for the whole NE region for operational use when the species may be unknown. The final models are shown in Figure 3a. The growth curves are similar up to 6 years, but the *(i) E. amygdalina*/*E. sieberi* model has a higher asymptote (1.54 kg m^{-2}) compared to the *E. obliqua* model (1.27 kg m^{-2}). Estimated parameters and their standard errors are given in Table 4, and goodness-of-fit statistics are in Table 5 for these models and for the SE models. The goodness of fit statistics show that the model with separate species is only a minor improvement on the combined model. Confidence bands and prediction bands for a new site for the NE region combined model are shown in Figure 4a overlaid on the data.

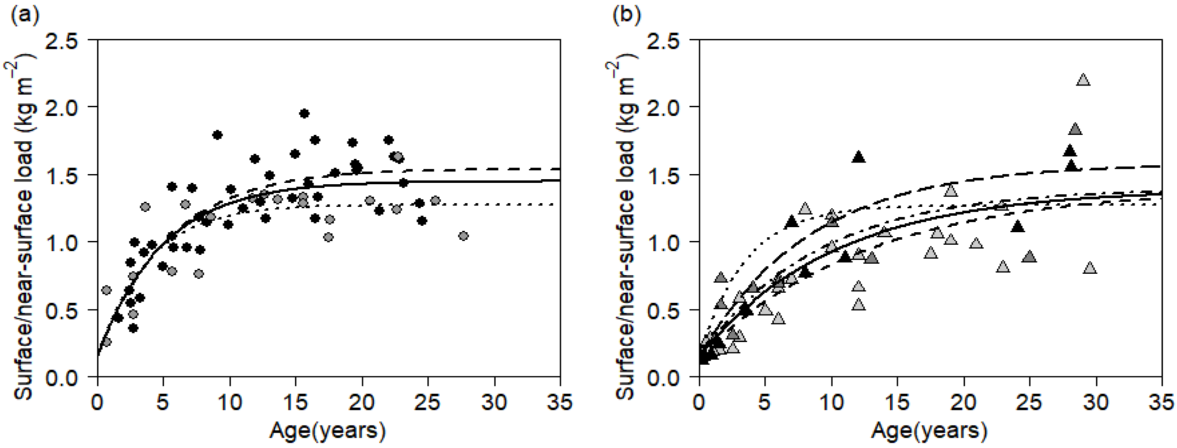

Figure 3. Modelled surface/near-surface fuel load accumulation curves and data for NE and SE sites. (**a**) NE sites: *E. amygdalina/E. sieberi*—black circles and dashed line, *E. obliqua*—grey circles and dotted line, NE combined model—solid line; (**b**) SE sites: *E. pulchella*—black triangles and long dashed line, *E. globulus*—dark grey triangles and dot dash line, *E. amygdalina/E. tenuiramus*—light grey triangles and dashed line, *A. verticillata*—open triangles and dotted line, SE combined eucalypt model—solid line.

Table 4. Parameters for surface/near-surface fuel load models. Standard errors are shown in parentheses.

Region	Species or Understorey	*n*	W_{ss} (kg m^{-2})	*k*
NE	*E. amygdalina* and *E. sieberi*	45	1.54 (0.06)	0.19 (0.03)
NE	*E. obliqua*	21	1.27 (0.07)	0.26 (0.07)
NE	All NE eucalyptus species combined	66	1.45 (0.05)	0.21 (0.03)
SE	*E. amygdalina* and *E. tenuiramis*	30	1.10 (0.09)	0.13 (0.02)
SE	*E. globulus/viminalis*	11	1.35 (0.14)	0.13 (0.02)
SE	*E. pulchella*	14	1.55 (0.12)	0.13 (0.02)
SE	*A. verticillata*	8	1.27 (0.18)	0.29 (0.14)
SE	All SE eucalypt species combined	59	1.25 (0.10)	0.12 (0.03)

Table 5. Goodness-of-fit statistics for surface/near-surface fuel load models.

Region	Species	RMSE	MAE	MBE
		(kg m^{-2})	(kg m^{-2})	(kg m^{-2})
NE	*E. amygdalina*/*E. sieberi* and *E. obliqua*	0.20	0.17	0.00
NE	All NE eucalypt species combined	0.22	0.18	0.00
SE	*E. globulus/viminalis*, *E. pulchella* and *E. amygdalina/tenuiramis*	0.22	0.17	−0.0 1
SE	*A. verticillata*	0.24	0.23	−0.03
SE	All SE eucalypt species combined	0.24	0.18	−0.01

Note: RMSE = root mean square error; MAE = mean absolute error; MBE = mean bias error.

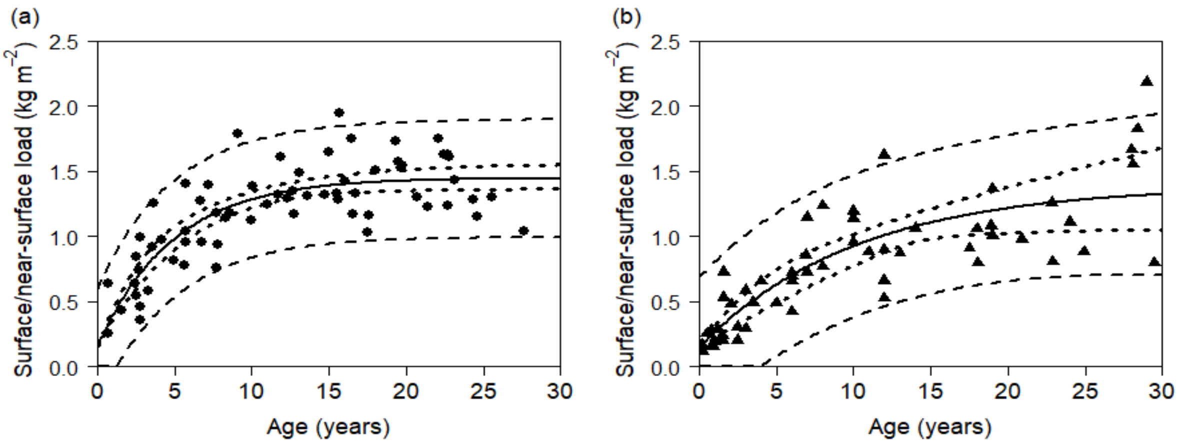

Figure 4. Modelled surface/near-surface fuel load accumulation curves (solid lines) with confidence bands (dotted lines) and prediction bands for new sites (dashed lines). (**a**) NE sites; (**b**) SE sites.

The SE data were also grouped by species. There was no significant difference in the models for *E. amygdalina* and *E. tenuiramis*. A model was created for *(i) E. globulus/viminalis*, *(ii) E. pulchella*, and *(iii) E. tenuiramis/amygdalina* with separate growth rates and equilibrium fuel loads, but the growth rates were not significantly different, so a model was fitted with the same growth rate and different equilibrium loads (Figure 3b, Tables 5 and 6). A separate model was made for *A. verticillata* as it had a very different grown rate (0.29 as opposed to 0.13). In addition, a model was made for eucalyptus in the whole SE region for operational use (Figure 3b). The four *E. obliqua* sites were only used in this model. The model for all eucalypt species was considerably worse than the NE model with wider prediction limits. The combined SE eucalypt model tended to under predict for larger loads, and the residuals showed some positive kurtosis indicative of large values at the tails. Confidence bands and prediction bands for a new site for the SE region combined model are shown in Figure 4b overlaid on the data.

Table 6. Parameters for step models. Standard errors are shown in parentheses. No standard errors are available for c from maximum likelihood. Model is m_1 when age less than or equal to c, otherwise m_2 and m is the mean when there is no critical value.

Component	Understorey	Metric	n	c	m_1	m_2	m
Elevated load	Litter/grassy	kg m^{-2}	39	9.0	0.02 (0.01)	0.05 (0.01)	
Elevated load	Heathy	kg m^{-2}	19	5.9	0.04 (0.01)	0.08 (0.01)	
Elevated load	Overall	kg m^{-2}	58	8.6	0.03 (0.01)	0.06 (0.01)	
Near surface height	Litter	m	18				0.26 (0.01)
Near surface height	Grassy/bracken/heathy	m	44				0.21 (0.01)
Near surface height	Overall	m	62				0.25 (0.01)
Elevated height	Litter/grassy	m	30				0.83 (0.08)
Elevated height	Bracken/heathy	m	27	8.8	0.97 (0.12)	1.29 (0.06)	
Elevated height	Overall	m	57	11.5	0.74 (0.11)	1.11 (0.06)	
Average height	Litter/grassy	m	30				0.15 (0.02)
Average height	Bracken/heathy	m	27	8.2	0.21 (0.10)	0.62 (0.06)	
Average height	Overall	m	57	11.1	0.15 (0.07)	0.39 (0.04)	

3.1.2. Elevated Fuel Load

Elevated load was measured only in the SE for 59 of the 68 sites, and there were no sites with a bracken understorey. One site with a very high elevated load from a south-facing slope was eliminated from the analysis as being atypical of the sample sites in *E. tenuiramis*. Elevated fuel load is highly dependent on the intensity of the previous burn, as low intensity fires may burn through surface and near-surface fuels beneath the elevated fuel. For fitting the model in Equation (1) the initial load was taken as the mean load under the age of 0.5 years, which was 0.013 kg m^{-2} (6 observations).

The *A. verticillata sites* had a grassy understory and for their age had a similar loading to the eucalyptus sites. As would be expected, heathy sites had a greater elevated loading than those with a litter or grassy understorey. Preliminary analysis showed the variance of the residuals from the heathy sites was large compared to those from the grassy and litter sites, and the growth parameter for the heathy sites was non-significant, so the heathy sites were analysed separately. There was no significant improvement in the model fit if grass and litter had separate parameters, so the grass and litter data were amalgamated. The model fit to the grassy/litter data was satisfactory although the standard error of the growth parameter was verging on non-significance. For the heath model, the growth parameter was non-significant. When an overall model (for use when the understorey is unknown) was attempted, no sensible parameters could be obtained from the minimization.

The step model, described above, was fitted to the litter/grassy and heathy data and a similar analysis was done on the combined data. The models are shown in Figure 5. Parameters and standard errors are given in Table 6 and goodness-of-fit statistics are in Table 7. In all cases, the parameters have low standard errors compared to the means.

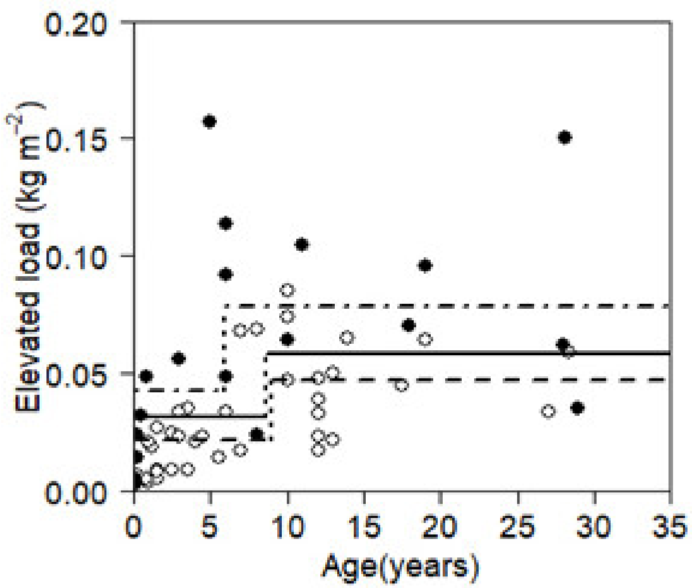

Figure 5. Step model for elevated fuel load for SE sites. Litter/grassy—empty circles, model—dashed line, heathy—black circles and dashed/dotted line, combined model—solid line.

Table 7. Goodness-of-fit statistics for step models. MBEs for all models are zero because of the type of fitted model.

Fuel Component	Understorey	RMSE	MAE	MBE
		(kg m^{-1})	(kg m^{-1})	(kg m^{-1})
Elevated load	Litter/grassy	0.02	0.01	0
Elevated load	Heathy	0.04	0.03	0
Elevated load	Overall	0.03	0.02	0
		(m)	(m)	(m)
Near surface height	Litter	0.06	0.05	0
Near surface height	Grassy/bracken/heathy	0.06	0.05	0
Near surface height	Overall	0.06	0.05	0
Elevated height	Litter/grassy	0.44	0.34	0
Elevated height	Bracken/heathy	0.30	0.24	0
Elevated height	Overall	0.40	0.33	0
Average height	Litter/grassy	0.13	0.09	0
Average height	Bracken/heathy	0.26	0.20	0
Average height	Overall	0.28	0.23	0

Note: RMSE = root mean square error; MAE = mean absolute error; MBE = mean bias error.

3.2. Fuel Hazard Rating Results

3.2.1. Fuel Hazard Rating Models

The eucalypt over-storey group in the NE was *E. amygdalina*. In the SE, there was *E. amygdalina*, *E. tenuiramis*, *E. globulus*, *E. viminalis*, and SE *E. pulchella* (as well as a single *E. obliqua* site). Since the level of FHR in the SE sites was lower than in the NE sites (Table 2), a regional split was used. The number of data points for eucalypt fuel hazard (62 points) was much lower than those for fuel load (126 points), so grouping by species was not done.

There were only eight sampled points for *A. verticillata* dominated vegetation, and only one of these sites was older than 13 years (and this site also had low levels of hazard rating). It was therefore considered that there were insufficient data to develop an FHR model for *A. verticillata*, and sites for this species were removed from the analysis.

3.2.2. Surface Fuel Hazard Rating

There was considerable scatter in the data around the fitted curves, particularly for the SE data. In addition, k and H_0 were poorly determined for the SE sites with large standard errors compared to the mean. The model was refitted with H_0 set at 0. Figure 6a shows the resulting surface FHR accumulation curves with the data points from the two regions. The surface FHR for the SE sites had a slower growth rate constant (k = 0.14) than the NE sites (k = 0.24) and a lower asymptote (3.4 as opposed to 4.2). Estimated parameters for the fitted models and their standard errors are given in Table 8, and goodness-of-fit statistics are in Table 9 (and for all other models).

Table 8. Estimated parameters with standard errors (in parentheses) for hazard rating models.

Group	Fuel Hazard Stratum	n	H_{ss}	k	H_0
NE sites	Surface	32	4.2 (0.2)	0.24 (0.09)	1.5 (0.6)
SE sites	Surface	30	3.4 (0.3)	0.14 (0.04)	0
NE/SE sites	Near-surface	62	3.6 (0.1)	0.25 (0.05)	0
Litter	Near-surface	18	3.2 (0.3)	0.16 (0.06)	0
Grass	Near-surface	17	3.5 (0.2)	0.28 (0.07)	0
Heath/bracken	Near-surface	27	4.1 (0.1)	0.20 (0.05)	1.0 (0.4)
NE sites	Combined surface and near-surface	32	4.9 (0.1)	0.36 (0.08)	1.7 (0.4)
SE sites	Combined surface and near-surface	30	4.6 (0.2)	0.21 (0.04)	0
NE sites	Bark	32	3.9 (0.4)	0.10 (0.05)	1.6 (0.4)
SE sites	Bark	30	5	0.02 (0.00)	1.0 (0.3)
NE sites	Overall	32	4.7 (0.2)	0.17 (0.05)	1.6 (0.5)
SE sites	Overall	30	3.5 (0.1)	0.22 (0.04)	0

Table 9. Goodness-of-fit statistics for hazard rating models.

Fuel Hazard Stratum	RMSE	MAE	MBE
NE surface	0.57	0.45	0.00
SE surface	0.61	0.51	0.01
NE/SE near-surface	0.70	0.55	0.01
Litter near-surface	0.65	0.55	−0.01
Grass near-surface	0.57	0.50	−0.01
Heath/bracken near-surface	0.40	0.34	0.00
NE combined surface and near-surface	0.37	0.24	0.00
SE combined surface and near-surface	0.60	0.53	0.00
NE bark	0.52	0.42	0.00
SE bark	0.54	0.45	0.00
NE overall	0.49	0.39	0.00
SE overall	0.42	0.35	0.00

RMSE = root mean square error; MAE = mean absolute error; MBE = mean bias error.

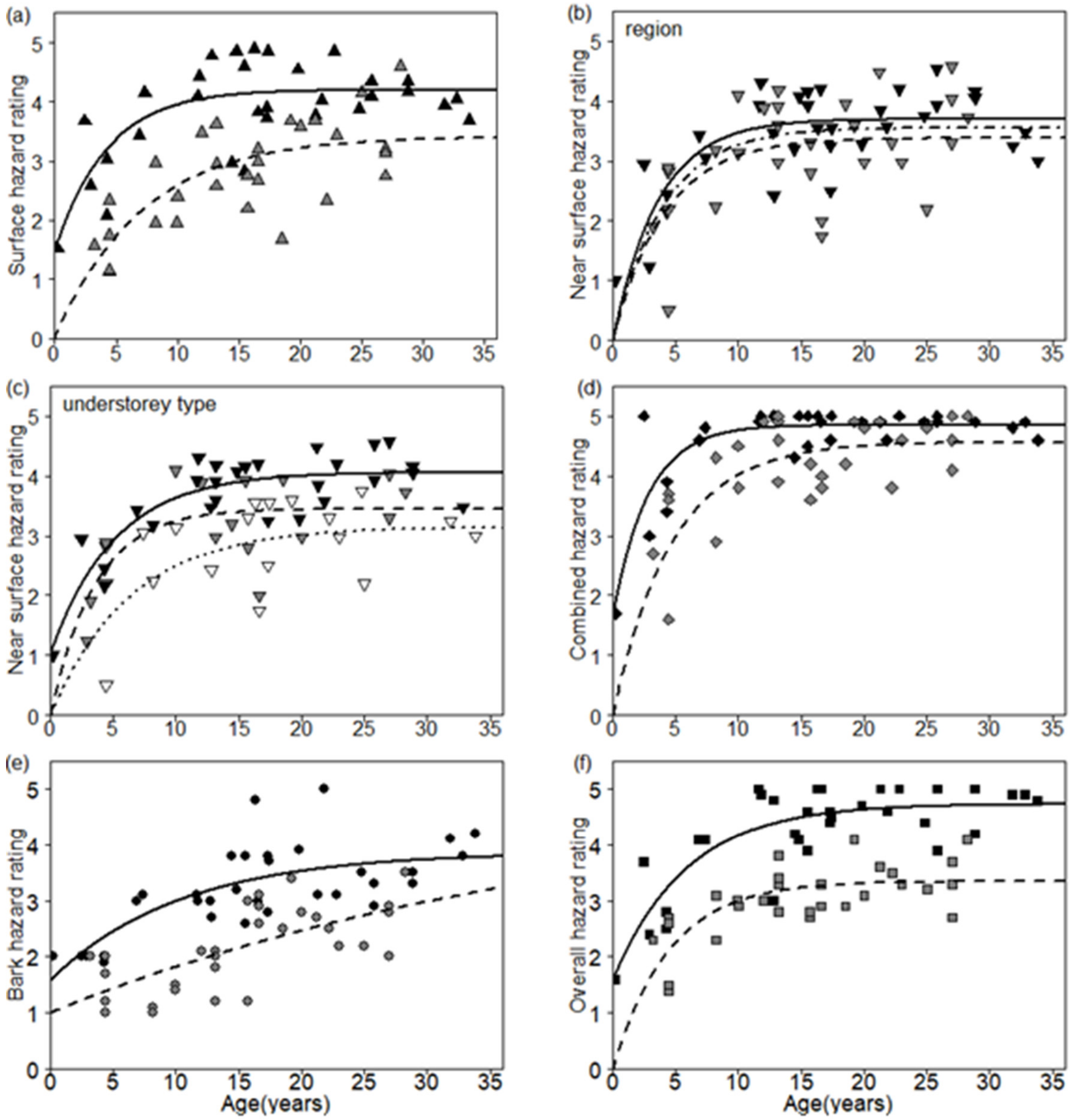

Figure 6. Fuel hazard accumulation curves and data split by region (and understory type for near-surface fuel): (**a**) surface FHR: NE—black triangles and solid line, SE—grey triangles and dash line; (**b**) near-surface FHR by region: NE—black triangles and solid line, SE—grey triangles and dash line, combined region—dot-dash line; (**c**) near-surface FHR by understorey type: litter: open triangles and dotted line, grass: grey triangles and dashed line, heath/bracken: black triangles and solid line; (**d**) combined surface and near-surface FHR: NE—black diamonds and solid line, SE—grey diamonds and dash line; (**e**) bark FHR: NE—black circles and solid line, SE—grey circles and dash line; (**f**) overall FHR: NE sites: black squares and solid line, SE sites: grey squares and dashed line.

3.2.3. Near-Surface Fuel Hazard Rating and Height

The near-surface FHR accumulation curves for the NE and SE sites were very similar, so a single curve was fitted to the data (Figure 6b; note that model fits for the NE and SE sites are also shown in Figure 6b). However, the goodness-of-fit statistics were considerably worse than for surface FHR (Table 9). An alternative model split by understorey type was considered. Examination of the curves and a rough likelihood analysis showed that the heath and bracken understorey types could be combined. The growth and initial hazards rates were poorly estimated for both grass and litter and the initial hazards were set to 0 (Table 8). Figure 6c shows the accumulation curves for the near-surface FHR by understorey type overlayed with the data. The asymptote was lowest for grass (3.5) and highest for heath/bracken (4.1). The model for heath/bracken had among the best model goodness-of-fit statistics (Table 9).

There was no significant difference in near-surface height between the NE and SE sites. For understorey type, a grouping of litter versus grassy/heathy/bracken was used. For the litter, grassy/heathy/bracken, and overall asymptotic models, the growth parameters were either non-significant or verging on non-significance. The maximum height was quickly achieved after fire, so the best estimates are the means of the groups, 0.21 m and 0.26 cm for litter and grassy/bracken, respectively. If understorey type is unknown, the data mean of 0.25 cm is the best estimate. There is a lot of scatter about these estimates, as can be seen from Figure 7a. Table 6 contains the estimates and standard errors, and Table 7 contains the goodness-of fit statistics for all the height and cover models.

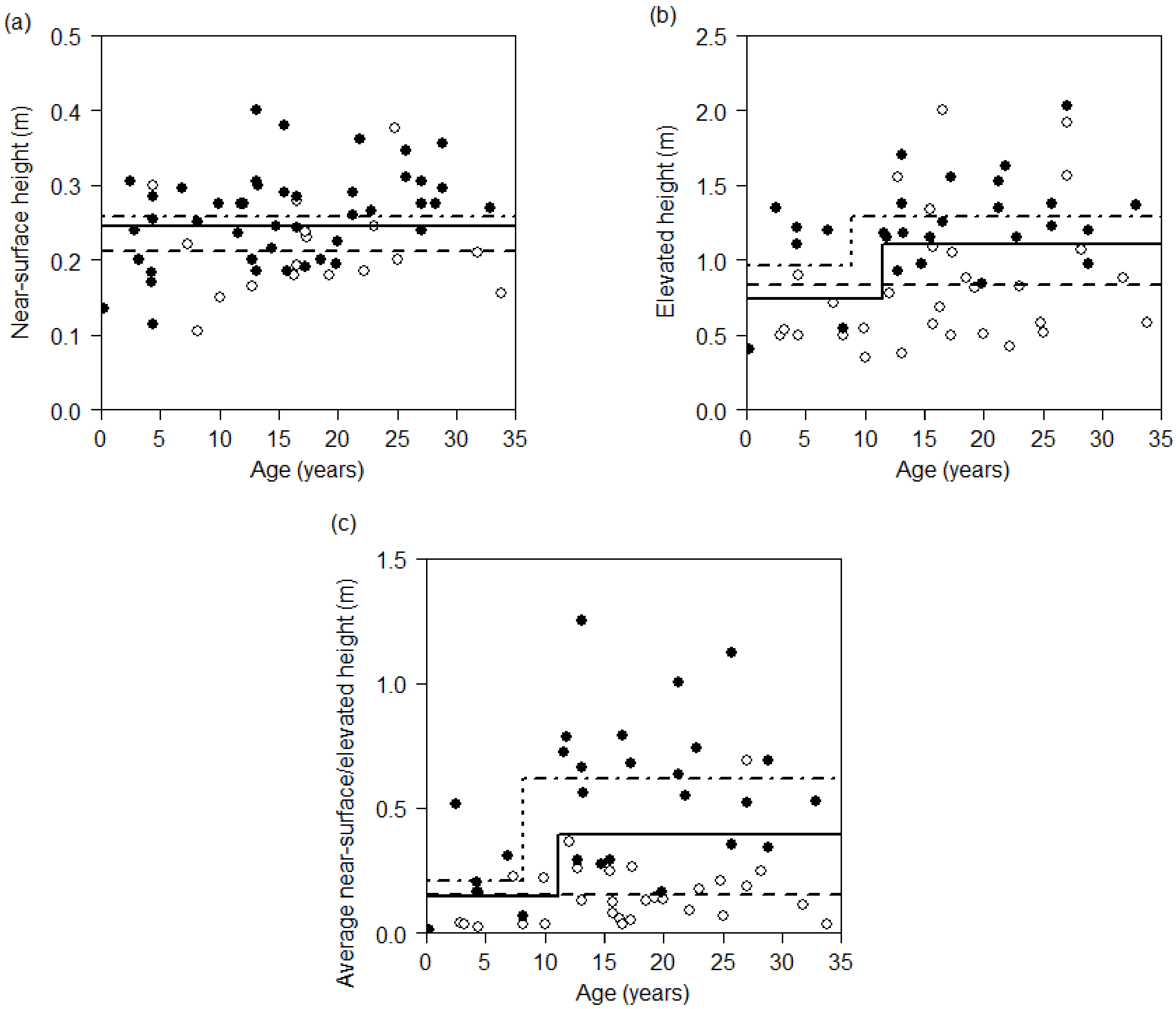

Figure 7. Step models for near-surface, elevated fuel height, and average near-surface/elevated height overlaying the data and split by understorey. (**a**) Near-surface height: litter—white circles and dashed line; grassy/bracken/heathy—black circles and dotted-dashed line, overall model—solid line. (**b**) Elevated height: litter/grassy—white circles and dashed line; bracken/heathy—black circles and dotted-dashed line, overall model—solid line. (**c**) Average near-surface/elevated height: litter/grassy—white circles and dashed line; bracken/heathy—black circles and dotted-dashed line, overall model—solid line.

3.2.4. Combined Surface and Near-Surface Fuel Hazard Rating

The combined surface and near-surface fuel hazard increased quickly for the NE region (k = 0.36) and more slowly (k = 0.20) in the SE region to maximums of 4.9 for the NE and 4.6 for the SE. Indeed, the NE data were close to the maximum by 7 years. Again, the SE region data were more scattered about the accumulation curve. Figure 6d shows the resulting accumulation curves by region overlaying the data. The goodness-of-fit statistics are generally better than for surface FHR and near-surface FHR (Table 9).

3.2.5. Elevated Fuel Hazard Rating and Height

The correlation between elevated hazard and age was poor (r = 0.23), and the asymptotic model was not appropriate. The step model was not significantly better than using the mean of the data as a best estimate. There was a highly significant difference between the mean elevated FHR in the NE and SE sites ($p < 0.001$) with mean elevated FHR in NE and SE sites, respectively, of 2.2 and 1.0.

There was no significant difference elevated height between the NE and SE sites. For the understorey type, a grouping of heathy/bracken versus litter/grassy was used. For the litter/grassy, heathy/bracken, and overall models, the growth parameters in the asymptotic model were non-significant. For the litter/grassy data, the step model was not significantly better than constant height with age, and the overall mean of 0.83 m was the best estimate. In the litter/grassy group, the mean height under about 9 years (0.97 m) was significantly less than the mean height over 11 years (1.29 m), and the step function shown in Figure 7b best fitted the data. A step function was also appropriate for the overall model. Estimates of the parameters, standard errors, and goodness-of fit statistics are in Tables 6 and 7.

3.2.6. Average Near-Surface/Elevated Height

Average near-surface/elevated height is an input into the Vesta II fire behaviour model [20]. It is defined as the average of the near-surface and elevated heights weighted by their respective covers. To avoid using four separate models, step models were created for the average height. As with near-surface and elevated heights, there was no significant difference in average height between the NE and SE sites. A grouping of litter/grassy versus heathy/bracken was used. The maximum average height for the litter/grassy sites was quickly achieved after fire, so the best estimate is the mean of 0.15 m. The bracken/heathy sites had an average height of 0.21 m up to eight years when it rose to 0.62 m. The overall model was similar to the bracken/heathy model, but the change point was about 11 years, where the mean rose from 0.14 m to 0.39 m (see Figure 7c and Table 6). Table 7 contains the goodness-of fit statistics. The standard errors are high for the heathy/bracken and overall models below the critical points.

3.2.7. Bark Fuel Hazard Rating

The increase in bark FHR with age was slow, particularly for the SE sites where it was almost linear. The asymptote for the SE sites was poorly determined and was set at 5. More data at less than 5 years and greater than 30 years are needed to make the model more robust. The bark fuel hazard is obviously species-dependent, and the regional split indicates partly the difference in species. The starting level, H_0, was 1.6 for the NE and 1 for the SE. This parameter is highly dependent on the intensity of the previous fire [54] and the species. Figure 6e shows the resulting accumulation curves by region overlaying the data.

3.2.8. Overall Fuel Hazard Rating

The regional separation in overall FHR was more pronounced than in the strata models (Figure 6f). Growth rates were fairly similar (0.17 for the NE and 0.22 for the SE). The main difference between regions is the asymptote (4.7 for the NE and 3.5 for the SE). The goodness-of-fit statistics are generally better than for the separate strata models. Figure 8a,b show the data, models, and confidence and prediction bands for the two regions.

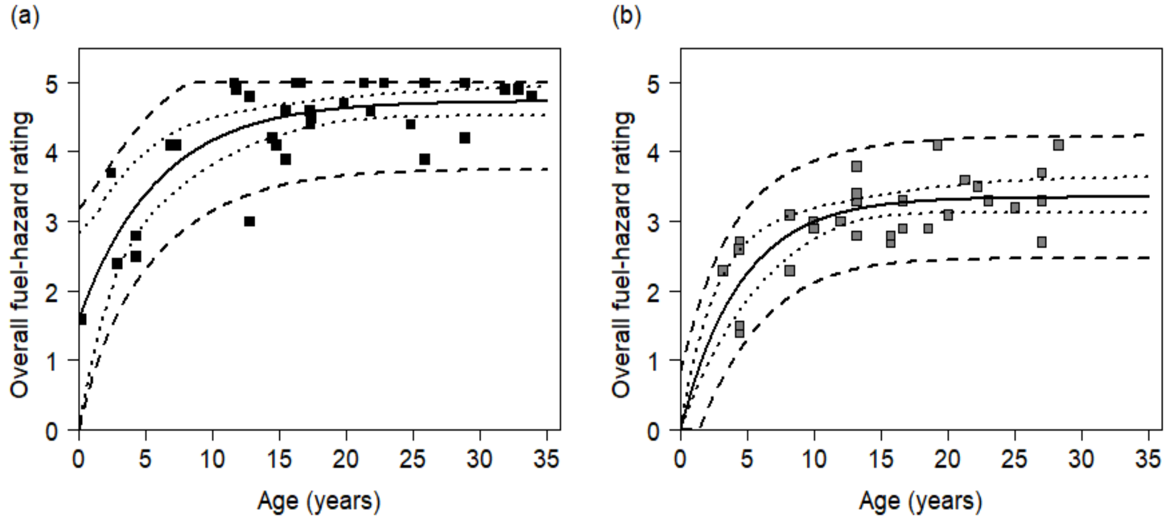

Figure 8. Modelled overall fuel hazard accumulation curves (solid lines) with confidence bands (dotted lines) and prediction bands for new sites (dashed lines). (**a**) NE sites—black squares; (**b**) SE sites—grey squares.

4. Discussion

4.1. Fuel Load

The fuel load assessment part of this study developed fuel load prediction models for use in Tasmanian dry eucalypt forests. The surface/near-surface model developed in this paper for *E. amygdalina*/*E. sieberi* is very similar to the previously published Tasmanian *E. sieberi* model [41] while the NSW model for *E. sieberi* regrowth with no wire-grass understorey [8] has a similar accumulation in the first 5 years following fire but then asymptotes to about 0.3 kg m^{-2} less than our model (i.e., to 0.12 kg m^{-2} rather than 0.15 kg m^{-2}).

Fuel load models for *A. verticillata*, *E. pulchella* (heathy), *E. tenuiramus* (heathy) and *E. amygdalina* (heathy) in SE Tasmania have been previously published [40]. The *A. verticillata* fuel load model has a lower asymptote than our model (0.98 kg m^{-2} compared to 0.127 kg m^{-2}), but it was based on only five sites with the oldest being 17.5 years, while ours was based on eight sites with the oldest being 27 years, so ours should be more reliable. The heathy *E. amygdalina* model asymptotes to 0.6 kg m^{-2} less than our *E. amygdalina/E. tenuiramus* model. For *E. tenuiramus*, the model has faster initial growth initially but a similar asymptote to our model. Finally, the *E. pulchella* model has a much lower asymptote than ours, but the data correspond to a maximum age of only 11 years.

Many of the studies in the mainland literature only measured litter load and/or the species were different to the ones in this study. Fuel studies performed in NSW and adjoining states were summarised [39] with the aim of producing accumulation curves for NSW vegetation types [64]. These predictions were weighted according to the study's reliability, and curves produced for litter, litter plus near-surface, and elevated fuel load. For litter plus near surface fuel, their coastal/hinterland model has k = 0.17 and W_{ss} = 1.64 kg m^2, which is similar to our NE *E. amygdalina/sieberi* model which has k = 0.19 and W_{ss} = 1.54 kg m^2.

Models for different species in our data were based on different numbers of data points, for example, the NE *E. tenuiramis/amygdalina* group is based on 30 data points and the parameters are reasonably well estimated, but the other groups in the NE have fewer data points, particularly in older fuel, and the model for these groups should be used with caution. The *A. verticillata* group had only 8 data points, and the model needs improvement. The model used is particularly sensitive to fuel load in older sites and needs several data points in older for the fuel to be robust.

Elevated load could be modelled by a step function, although there was a lot of variability. It is needed to estimate total fuel loading and hence intensity, or for input into Phoenix Rapidfire [21,22], but is only a small component of total loading. If more information is needed on elevated loading, more sampling should be done in the SE Tasmanian and in bracken-dominated sites.

Bark loading was not measured during the data collection performed for this study and is again a component of total loading. It could be estimated from bark hazard rating using [14].

4.2. Near-Surface and Elevated Fuel Height

To our knowledge, little has been published on the height and cover of near-surface and elevated fuel, a notable exception being in Western Australian jarrah forests [35]. Near-surface height is an input into the Vesta model [9,11]. An asymptotic model was fitted to the jarrah data in [35], but it appears fairly constant after 6 years. Elevated fuel height is used to predict flame height [9,11]. In the jarrah low shrub site, the elevated fuel height was fairly constant with age, while in the tall shrub site, the height increased with age and as asymptotic model was appropriate.

In our data, these height variables, as well as the average height, were either fairly constant with age or could be fitted by a step function in which the increase occurred at about 10 years. This probably reflects that some elevated fuel is left after the last fire and by 10 years growth of new elevated fuel has stabilised.

4.3. Fuel Hazard Rating

The FHR assessment part of this study developed FHR prediction models for use in Tasmanian dry eucalypt forests. The vegetation types covered comprise most of the forest area in NE and SE Tasmania [48], so these models will have wide applicability.

The FHR models use the site age to predict surface, near-surface, combined surface and near-surface, bark and overall FHR. Due to the high degree of variability within the FHR data collected during this project, it was not possible to develop reliable models for predicting elevated FHR. The high degree of variability in the data for elevated FHR relates at least in part to the intensity of the last fire. For example, most fires, including low intensity fires, are effective at removing surface and near-surface fuel, but moderate to high intensity fires are required to remove elevated and bark fuel [54]. There was insufficient data on the intensity of the last fire which burnt the sites to include this as a factor in the analysis. Remotely recording fire severity is now possible e.g., [65,66] and could be used to improve prediction models.

Eight FHR accumulation curves have been developed in NSW [39]. The model form used in Equation (1) was a poor fit to the elevated fuel data, and a linear model provided a better fit. When the models for overall FHR in [39] were compared to our models, the best fit to our NE Tasmanian model (k = 0.17, H_{ss} = 4.7, H_0 = 1.6) was their Sydney coastal model (k = 0.16, H_{ss} = 4.6, H_0 = 1). For overall FHR in SE Tasmania (k = 0.22 and H_{ss} = 3.5, H_0 = 0), nothing matched well, the closest match being the Hunter–Macleay NSW model (k = 0.14 and H_{ss} = 4.2, H_0 = 1.3).

The Victorian overall fuel hazard assessment guide does not provide detailed guidance as to how to incorporate the relative importance of different fuel strata, and how to determine the level of FHR when there is divergence between the levels of these components (as there frequently is). For example, in our study we found that in most of the plots sampled for FHR, the percentage of dead fuel, vegetation cover, continuity and/or height were poorly correlated. This finding is closely mirrored by results from Tasmanian heathlands [67].

We propose, as a modification of the Victorian overall fuel hazard assessment guide, a weighting of fuel strata as presented in Table 3. This modification is not required when assessing bark fuels because of the small number of fuel characteristics that need to be considered. However, the fuel stratum weightings in Table 3 are subjective, and more research is needed for validation. Using the modified guide, experienced assessors should be able to reliably and consistently assess the level of surface, near-surface, elevated, and bark FHR present at a site in less than 15 min. This ability to perform rapid and robust assessments is a major advantage over the collection of fuel load data which typically takes about two person days per site to collect the field data followed by about two days lab work drying and processing the fuel in order to determine its dry weight.

As an example of the use to which these FHR prediction models will be put to, the FHR models were used to test the Project Vesta's Equation (10) model [11] using fire behaviour information collected during the January 2013 Tasmanian bushfires. The fire spread rates in this assessment ranged between 0.1 and 0.9 m s^{-1} (mean 0.6 m s^{-1}), and the Project Vesta model under-predicted the fire spread rate of these fires by an average of only 9.3% [68].

5. Conclusions

This paper presents fuel load, height, and FHR accumulation models for use in NE and SE Tasmanian dry eucalypt forests. The paper has also tested the Victorian fuel hazard assessment guide under Tasmanian conditions and found that, provided the relative importance of the different fuel strata components are weighted according to their influence on fire behaviour, the guide provides for a rapid and robust methodology for estimating FHR. The equations in this paper will be used for planning prescribed burning, fire risk assessments, bushfire behaviour prediction, the Australian bushfire fuel classification system, for use in the Australian Fire Danger Rating System and in the Australian Standard for building in bushfire prone areas.

Author Contributions: The project was initiated and supervised by A.F.P., the field work assessing fuel hazard assessment and majority of the write-up was performed by J.B.M.-S., the statistical analysis and remaining write-up was performed by W.R.A. and all three authors performed editing on the work. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Site Data.

Site	Vegetation Type		Bark	Alt	Asp	Slope	Geo	Site	Vegetation Type		Bark	Alt	Asp	Slope	Geo
1-NE	E.amyg	Gr	F	130	100	8	Dg	69-SE	A.vert	Gr	O	155	1	3	Jd
2-NE	E.amyg	Bk	F	120	180	8	Dg	70-SE	E.glob	Lt	C	80	1	1	Ts
3-NE	E.amyg	Hh	F	120	85	1	Dg	71-SE	E.glob	Gr	C	300	2	3	Jd
4-NE	E.amyg	Bk	F	70	140	2	Dg	72-SE	E.glob	Gr	C	430	1	2	Jd
5-NE	E.amyg	Lt	F	80	350	1	Dg	73-SE	E.glob	Hh	C	110	4	3	Ts

Table A1. *Cont.*

Site	Vegetation Type		Bark	Alt	Asp	Slope	Geo	Site	Vegetation Type		Bark	Alt	Asp	Slope	Geo
6-NE	E.amyg	Hh	F	100	200	7	Dg	74-SE	E.glob	Lt	C	430	2	1	Jd
7-NE	E.amyg	Bk	F	110	330	3	Dg	75-SE	E.glob	Gr	C	395	1	3	Jd
8-NE	E.amyg	Gr	F	60	270	1	Dg	76-SE	E.glob	Gr	C	150	3	1	Ts
9-NE	E.amyg	Lt	F	80	65	3	Dg	77-SE	E.glob	Lt	C	120	3	3	Ts
10-NE	E.amyg	Hh	F	80	95	1	Dg	78-SE	E.glob	Gr	C	235	3	3	Jd
11-NE	E.amyg	Bk	F	30	120	5	Dg	79-SE	E.glob	Gr	C	210	3	3	Jd
12-NE	E.amyg	Bk	F	150	270	5	Dg	80-SE	E.amyg	Gr	F	180	4	3	Ts
13-NE	E.amyg	Hh	F	120	125	8	Dg	81-SE	E.amyg	Gr	F	110	4	1	Ts
14-NE	E.amyg	Bk	F	100	295	10	Dg	82-SE	E.amyg	Gr	F	215	3	3	Ts
15-NE	E.amyg	Bk	F	110	280	5	Dg	83-SE	E.amyg	Gr	F	310	2	3	Ts
16-NE	E.amyg	Lt	F	140	10	8	Dg	84-SE	E.amyg	Gr	F	60	4	2	Ts
17-NE	E.amyg	Lt	F	370	95	5	Jd	85-SE	E.amyg	Gr	F	210	1	1	Ts
18-NE	E.amyg	Lt	F	350	100	7	Jd	86-SE	E.amyg	Gr	F	210	1	1	Ts
19-NE	E.amyg	Lt	F	480	40	9	Pm	87-SE	E.amyg	Gr	F	210	1	1	Ts
20-NE	E.amyg	Gr	F	440	20	7	Pm	88-SE	E.amyg	Gr	F	230	2	0	Ts
21-NE	E.amyg	Hh	F	0	150	8	Jd	89-SE	E.amyg	Hh	F	135	4	0	Ts
22-NE	E.amyg	Hh	F	450	205	4	Pm	90-SE	E.amyg	Hh	F	120	2	1	Ts
23-NE	E.amyg	Hh	F	480	330	14	Pm	91-SE	E.amyg	Hh	F	245	1	1	Ts
24-NE	E.amyg	Hh	F	40	160	2	Pm	92-SE	E.amyg	Hh	F	130	4	2	Ts
25-NE	E.amyg	Hh	F	20	310	2	Pm	93-SE	E.amyg	Hh	F	90	4	2	Ts
26-NE	E.amyg	Bk	F	60	180	1	Pm	94-SE	E.amyg	Hh	F	195	3	1	Ts
27-NE	E.amyg	Hh	F	390	30	4	Jd	95-SE	E.amyg	Hh	F	20	2	1	Ts
28-NE	E.amyg	Hh	F	390	310	7	Jd	96-SE	E.amyg	Hh	F	40	1	0	Ts
29-NE	E.amyg	Hh	F	590	315	7	Jd	97-SE	E.amyg	Hh	F	40	2	0	Ts
30-NE	E.amyg	Hh	F	370	285	10	Jd	98-SE	E.amyg	Hh	F	150	1	1	Ts
31-NE	E.amyg	Bk	F	50	170	4	Pm	140-NE	E.obli	Bk	F	144	225	3	Dg
32-NE	E.amyg	Bk	F	70	330	4	Pm	141-NE	E.obli	Bk	F	110	180	4	Pm
33-NE	E.amyg	Lt	F	70	260	2	Pm	142-NE	E.obli	Hh	F	180	45	5	Dg
34-NE	E.amyg	Bk	F	70	70	1	Pm	143-NE	E.obli	Bk	F	160	45	3	Dg
35-NE	E.amyg	Bk	F	50	140	1	Pm	144-NE	E.obli	Bk	F	206	270	2	Dg
36-NE	E.amyg	Lt	F	40	355	8	Pm	145-NE	E.obli	Hh	F	200	0	4	Dg
37-NE	E.amyg	Bk	F	70	175	9	Pm	146-NE	E.obli	Bk	F	198	90	8	Dg
38-NE	E.amyg	Hh	F	50	0	17	Pm	147-NE	E.obli	Bk	F	190	135	3	Dg
39-NE	E.amyg	Bk	F	60	340	4	Pm	148-NE	E.obli	Bk	F	142	0	2	Pm
40-SE	E.tenu	Lt	C	80	2	3	Pm	149-NE	E.obli	Bk	F	141	180	11	Dg
41-SE	E.tenu	Lt	C	100	1	3	Pm	150-NE	E.obli	Bk	F	70	180	2	Pm
42-SE	E.tenu	Lt	C	300	1	2	Pm	151-NE	E.obli	Bk	F	127	180	4	Dg
43-SE	E.tenu	Lt	C	170	1	3	Pm	152-NE	E.obli	Hh	F	410	270	12	Pm
44-SE	E.tenu	Lt	C	110	2	3	Pm	153-NE	E.obli	Bk	F	98	200	2	Dg
45-SE	E.tenu	Hh	C	220	2	3	Pm	154-NE	E.obli	Hh	F	104	0	4	Pm
46-SE	E.tenu	Lt	C	90	1	3	Pm	155-NE	E.obli	Bk	F	92	315	3	Dg
47-SE	E.tenu	Lt	C	250	2	3	Pm	156-NE	E.obli	Bk	F	150	270	6	Pm
48-SE	E.tenu	Lt	C	230	4	3	Pm	157-NE	E.obli	Bk	F	116	180	4	Pm

Table A1. *Cont.*

Site	Vegetation Type		Bark	Alt	Asp	Slope	Geo	Site	Vegetation Type		Bark	Alt	Asp	Slope	Geo
49-SE	E.pulc	Hh	C	330	5	1	Jd	158-NE	E.obli	Bk	F	59	90	5	Jd
50-SE	E.pulc	Hh	C	260	2	1	Jd	159-NE	E.sieb	Hh	F	211	22.5	6	Dg
51-SE	E.pulc	Gr	C	240	2	2	Jd	160-NE	E.obli	Bk	F	211	180	16	Jd
52-SE	E.pulc	Gr	C	270	3	2	Jd	161-NE	E.obli	Bk	F	196	0	12	Jd
53-SE	E.pulc	Hh	C	310	3	1	Jd	162-NE	E.sieb	Hh	F	145	310	12	Dg
54-SE	E.pulc	Lt	C	310	4	1	Jd	163-NE	E.sieb	Bk	F	70	0	4	Pm
55-SE	E.pulc	Gr	C	300	1	2	Jd	164-NE	E.sieb	Bk	F	62	45	10	Pm
56-SE	E.pulc	Gr	C	80	3	1	Jd	165-NE	E.sieb	Hh	F	66	45	30	Pm
57-SE	E.pulc	Gr	C	120	1	3	Jd	166-NE	E.amyg	Bk	F	147	0	3	Pm
58-SE	E.pulc	Gr	C	120	1	3	Jd	167-SE	E.pulc	Hh	C	171	45	12	Jd
59-SE	E.pulc	Hh	C	90	2	3	Jd	168-SE	E.amyg	Hh	F	75	90	5	Ts
60-SE	E.pulc	Hh	C	210	3	1	Jd	169-SE	E.pulc	Gr	C	313	60	14	Jd
61-SE	E.pulc	Hh	C	190	2	2	Jd	170-SE	E.amyg	Lt	F	114	270	14	Pm
62-SE	A.vert	Gr	O	40	5	3	Jd	171-SE	E.amyg	Lt	F	273	45	18	Pm
63-SE	A.vert	Gr	O	55	3	1	Jd	172-SE	E.obli	Bk	F	413	180	4	Pm
64-SE	A.vert	Gr	O	150	1	2	Jd	173-SE	E.vimi	Gr	C	220	110	14	Jd
65-SE	A.vert	Gr	O	30	2	2	Jd	174-SE	E.obli	Hh	F	357	0	14	Pm
66-SE	A.vert	Gr	O	105	2	2	Jd	175-SE	E.obli	Hh	F	154	200	16	Pm
67-SE	A.vert	Gr	O	100	3	1	Jd	176-SE	E.obli	Hh	F	157	180	14	Pm
68-SE	A.vert	Gr	O	155	1	3	Jd								

Site: NE = northeast Tasmania, SE = southeast Tasmania; vegetation type—over storey: E.amyg = *Eucalyptus amygdalina*, E.obli = *Eucalyptus obliqua*, E.sieb = *Eucalyptus sieberi*, E.vimi = *Eucalyptus viminalis*, E.pulc = *Eucalyptus pulchella*, E.glob = *Eucalyptus globulus*, E.tenu = *Eucalyptus tenuiramis* A.vert = *Allocasuarina verticillata*; understorey: Gr = grassy, Bk = bracken, Hh = heathy, Lt = litter; m = metres; deg = degrees; geology: Jd = Jurassic dolerite; Dg = Devonian granite, Pm = Permian mudstone, Ts = Triassic sandstone.

Appendix B

Table A2. Fuel Load Data.

	Veg Type		Age	Surface			Near-Surface				Elevated				Total
Site	Over	Under		cvr	hgt	load	cvr	hgt	live	dead	cvr	hgt	live	dead	Load
				%	m	kg m^{-1}	%	m	kg m^{-1}	kg m^{-1}	%	m	kg m^{-1}	kg m^{-1}	kg m^{-1}
1-NE	E.amyg	Gr	5.7	94	0.02	0.65	40	0.48	0.17	0.22	0		-	-	1.04
2-NE	E.amyg	Bk	15	87	0.02	0.97	45	0.33	0.18	0.49	0		-	-	1.64
3-NE	E.amyg	Hh	18	97	0.02	1.00	55	0.46	0.08	0.43	2	2.30	-	-	1.51
4-NE	E.amyg	Bk	16	87	0.02	0.77	48	0.39	0.13	0.53	7	1.27	-	-	1.42
5-NE	E.amyg	Lt	11	94	0.01	0.81	45	0.32	0.11	0.33	0	0.85	-	-	1.24
6-NE	E.amyg	Hh	10	85	0.02	0.93	30	0.24	0.05	0.15	0	0.00	-	-	1.12
7-NE	E.amyg	Bk	13	86	0.02	0.85	54	0.48	0.12	0.51	6	1.31	-	-	1.48
8-NE	E.amyg	Gr	2.8	74	0.01	0.59	55	0.35	0.25	0.15	0	0.00	-	-	0.99
9-NE	E.amyg	Lt	22.1	88	0.02	0.97	54	0.33	0.32	0.47	1	1.80	-	-	1.75
10-NE	E.amyg	Hh	23.1	86	0.02	0.83	59	0.35	0.20	0.41	6	2.60	-	-	1.44
11-NE	E.amyg	Bk	9.1	88	0.01	1.06	66	0.33	0.21	0.51	1	2.00	-	-	1.79
12-NE	E.amyg	Bk	4.2	80	0.01	0.73	35	0.29	0.08	0.16	0	0.00	-	-	0.97
13-NE	E.amyg	Hh	7.7	95	0.01	0.55	60	0.45	0.14	0.49	0	0.00	-	-	1.18
14-NE	E.amyg	Bk	1.6	52	0.01	0.29	32	0.26	0.06	0.09	0	2.00	-	-	0.43
15-NE	E.amyg	Bk	14.7	76	0.01	0.60	60	0.32	0.21	0.51	1	2.00	-	-	1.32

Table A2. *Cont.*

	Veg Type		Age	Surface			Near-Surface				Elevated				Total
Site	**Over**	**Under**		**cvr**	**hgt**	**load**	**cvr**	**hgt**	**live**	**dead**	**cvr**	**hgt**	**live**	**dead**	**Load**
				%	**m**	**kg m^{-1}**	**%**	**m**	**kg m^{-1}**	**kg m^{-1}**	**%**	**m**	**kg m^{-1}**	**kg m^{-1}**	**kg m^{-1}**
16-NE	E.amyg	Lt	7.8	91	0.01	0.69	33	0.22	0.04	0.20	1	3.00	-	-	0.93
17-NE	E.amyg	Lt	3.3	70	0.01	0.45	26	0.21	0.03	0.10	3	2.33	-	-	0.58
18-NE	E.amyg	Lt	6.8	76	0.01	0.79	27	0.20	0.05	0.12	2	2.50	-	-	0.95
19-NE	E.amyg	Lt	8.3	74	0.02	0.95	31	0.27	0.05	0.14	1	2.00	-	-	1.14
20-NE	E.amyg	Gr	5	61	0.01	0.60	42	0.27	0.09	0.13	2	1.75	-	-	0.81
21-NE	E.amyg	Hh	12.3	74	0.02	0.83	45	0.45	0.13	0.33	2	2.67	-	-	1.29
22-NE	E.amyg	Hh	24.3	87	0.02	1.01	37	0.30	0.07	0.20	5	2.75	-	-	1.28
23-NE	E.amyg	Hh	21.4	62	0.02	0.69	43	0.30	0.14	0.39	0	0.00	-	-	1.22
24-NE	E.amyg	Hh	11.9	92	0.02	0.98	48	0.48	0.17	0.46	0	0.00	-	-	1.61
25-NE	E.amyg	Hh	7.2	91	0.01	0.88	44	0.35	0.18	0.33	4	2.29	-	-	1.40
26-NE	E.amyg	Bk	16.4	92	0.02	0.99	55	0.43	0.10	0.66	0	2.00	-	-	1.75
27-NE	E.amyg	Hh	2.5	61	0.01	0.62	24	0.24	0.03	0.20	2	3.50	-	-	0.85
28-NE	E.amyg	Hh	22.5	85	0.02	1.01	48	0.30	0.19	0.43	1	2.00	-	-	1.62
29-NE	E.amyg	Hh	19.5	73	0.02	0.89	48	0.38	0.27	0.40	3	3.75	-	-	1.57
30-NE	E.amyg	Hh	16.5	73	0.02	0.79	28	0.25	0.09	0.29	0	3.00	-	-	1.17
31-NE	E.amyg	Bk	2.5	31	0.00	0.16	52	0.39	0.20	0.18	0	3.00	-	-	0.54
32-NE	E.amyg	Bk	3.6	81	0.01	0.74	23	0.28	0.05	0.12	0	3.00	-	-	0.91
33-NE	E.amyg	Lt	24.6	86	0.01	0.91	31	0.23	0.02	0.22	1	2.00	-	-	1.15
34-NE	E.amyg	Bk	2.4	57	0.01	0.36	48	0.30	0.14	0.14	1	4.00	-	-	0.63
35-NE	E.amyg	Bk	19.6	86	0.02	0.81	65	0.40	0.25	0.46	5	2.63	-	-	1.52
36-NE	E.amyg	Lt	15.7	91	0.02	1.05	65	0.50	0.29	0.60	0	0.00	-	-	1.95
37-NE	E.amyg	Bk	5.7	86	0.01	1.12	41	0.33	0.06	0.22	1	2.00	-	-	1.40
38-NE	E.amyg	Hh	16.7	84	0.02	0.87	53	0.31	0.11	0.36	0	0.00	-	-	1.33
39-NE	E.amyg	Bk	19.7	94	0.02	0.95	65	0.53	0.19	0.40	1	3.00	-	-	1.54
40-SE	E.tenu	Lt	29.5	100	0.02	0.66	20	0.09	0.11	0.02	80	2.20	0.37	0.12	1.28
41-SE	E.tenu	Lt	17.5	60	0.02	0.86	30	0.12	0.03	0.01	30	2.55	0.04	0.01	0.95
42-SE	E.tenu	Lt	14	90	0.02	1.01	60	0.15	0.05	0.00	40	2.64	0.05	0.01	1.13
43-SE	E.tenu	Lt	12	60	0.03	0.87	40	0.21	0.02	0.01	40	2.79	0.02	0.01	0.92
44-SE	E.tenu	Lt	12	60	0.03	0.62	20	0.24	0.03	0.01	20	1.26	0.02	0.00	0.68
45-SE	E.tenu	Hh	8	70	0.02	1.20	50	0.18	0.03	0.00	20	1.46	0.02	0.00	1.26
46-SE	E.tenu	Lt	6	80	0.03	0.64	60	0.40	0.04	0.04	50	1.72	0.02	0.01	0.75
47-SE	E.tenu	Lt	3.5	70	0.02	0.44	20	0.37	0.05	0.00	30	1.74	0.01	0.00	0.50
48-SE	E.tenu	Lt	2.5	70	0.03	0.18	60	0.33	0.01	0.01	40	1.91	0.00	0.02	0.23
49-SE	E.pulc	Hh	28.1	90	0.03	1.11	100	0.34	0.19	0.26	30	1.66	0.15	0.00	1.70
50-SE	E.pulc	Hh	28	90	0.03	1.39	70	0.14	0.24	0.04	30	1.36	0.05	0.01	1.72
51-SE	E.pulc	Gr	12	80	0.03	1.46	70	0.12	0.12	0.04	30	1.39	0.03	0.00	1.65
52-SE	E.pulc	Gr	12	100	0.03	1.45	70	0.12	0.13	0.04	50	2.16	0.03	0.01	1.66
53-SE	E.pulc	Hh	11	80	0.02	0.68	80	0.15	0.12	0.08	10	2.66	0.10	0.00	0.98
54-SE	E.pulc	Lt	8	100	0.02	0.54	50	0.16	0.20	0.02	20	2.50	0.07	0.00	0.83
55-SE	E.pulc	Gr	7	100	0.02	0.77	60	0.19	0.36	0.02	10	4.06	0.02	0.00	1.16
56-SE	E.pulc	Gr	3.5	90	0.01	0.41	50	0.20	0.07	0.01	40	3.14	0.00	0.03	0.52
57-SE	E.pulc	Gr	1.5	60	0.01	0.12	70	0.15	0.10	0.01	20	3.87	0.00	0.00	0.24
58-SE	E.pulc	Gr	0.9	50	0.01	0.08	60	0.16	0.06	0.01	30	4.72	0.00	0.00	0.16
59-SE	E.pulc	Hh	0.3	60	0.03	0.15	20	0.12	0.00	0.00	20	1.33	0.00	0.01	0.16
60-SE	E.pulc	Hh	0.1	40	0.03	0.12	20	0.13	0.00	0.01	0	5.80	0.00	0.01	0.13
61-SE	E.pulc	Hh	0.1	60	0.03	0.12	30	0.19	0.00	0.02	0	4.24	0.00	0.00	0.14

Table A2. *Cont.*

	Veg Type		Age	Surface			Near-Surface				Elevated				Total
Site	**Over**	**Under**		**cvr**	**hgt**	**load**	**cvr**	**hgt**	**live**	**dead**	**cvr**	**hgt**	**live**	**dead**	**Load**
				%	**m**	**kg m^{-1}**	**%**	**m**	**kg m^{-1}**	**kg m^{-1}**	**%**	**m**	**kg m^{-1}**	**kg m^{-1}**	**kg m^{-1}**
62-SE	A.vert	Gr	27	100	0.04	1.27	90	0.21	0.13	0.02	20	3.75	0.03	0.00	1.46
63-SE	A.vert	Gr	13	100	0.03	1.10	100	0.23	0.09	0.00	10	3.65	0.02	0.00	1.21
64-SE	A.vert	Gr	10	80	0.03	0.92	60	0.25	0.08	0.01	20	1.53	0.03	0.01	1.05
65-SE	A.vert	Gr	5.5	100	0.03	0.72	80	0.19	0.04	0.01	10	1.50	0.01	0.00	0.78
66-SE	A.vert	Gr	4.5	90	0.02	1.05	90	0.19	0.11	0.16	20	1.79	0.02	0.00	1.34
67-SE	A.vert	Gr	3	80	0.02	1.02	60	0.17	0.09	0.01	20	2.07	0.03	0.00	1.16
68-SE	A.vert	Gr	1.5	80	0.02	0.17	80	0.17	0.11	0.01	10	3.64	0.00	0.01	0.30
69-SE	A.vert	Gr	0.8	40	0.02	0.09	60	0.18	0.02	0.01	20	6.05	0.00	0.01	0.13
70-SE	E.glob	Lt	28.4	100	0.02	1.67	30	0.17	0.09	0.06	10	5.33	0.06	0.00	1.88
71-SE	E.glob	Gr	13	100	0.02	0.81	80	0.17	0.05	0.01	30	4.85	0.04	0.01	0.92
72-SE	E.glob	Gr	10	100	0.02	1.05	100	0.16	0.07	0.02	60	5.35	0.08	0.01	1.22
73-SE	E.glob	Hh	6	70	0.02	0.57	60	0.13	0.05	0.07	50	3.87	0.09	0.01	0.78
74-SE	E.glob	Lt	4	100	0.02	0.40	60	0.10	0.22	0.03	40	4.13	0.02	0.00	0.67
75-SE	E.glob	Gr	2.5	80	0.01	0.26	60	0.13	0.04	0.00	40	6.27	0.00	0.01	0.31
76-SE	E.glob	Gr	1.6	60	0.01	0.49	50	0.12	0.03	0.00	10	4.52	0.00	0.01	0.54
77-SE	E.glob	Lt	1.6	70	0.02	0.37	50	0.16	0.34	0.01	20	3.96	0.00	0.01	0.73
78-SE	E.glob	Gr	1.2	50	0.02	0.12	90	0.20	0.12	0.03	20	4.06	0.00	0.02	0.30
79-SE	E.glob	Gr	0.2	40	0.02	0.10	30	0.21	0.00	0.02	10	1.53	0.00	0.01	0.13
80-SE	E.amyg	Gr	19	90	0.02	0.74	100	0.26	0.14	0.12	2	3.12	0.03	0.03	1.07
81-SE	E.amyg	Gr	12	80	0.02	0.44	70	0.24	0.08	0.00	20	3.05	0.05	0.00	0.57
82-SE	E.amyg	Gr	10	100	0.02	0.54	70	0.20	0.35	0.07	40	3.05	0.05	0.03	1.03
83-SE	E.amyg	Gr	7	100	0.02	0.43	90	0.16	0.23	0.06	40	3.51	0.06	0.01	0.79
84-SE	E.amyg	Gr	3	80	0.02	0.15	80	0.09	0.11	0.02	30	3.66	0.00	0.02	0.31
85-SE	E.amyg	Gr	1.5	50	0.03	0.06	70	0.15	0.13	0.01	20	3.64	0.01	0.01	0.23
86-SE	E.amyg	Gr	1	30	0.03	0.04	60	0.21	0.13	0.02	10	5.80	0.00	0.02	0.21
87-SE	E.amyg	Gr	0.2	50	0.03	0.12	40	0.20	0.00	0.04	10	5.01	0.00	0.02	0.19
88-SE	E.amyg	Gr	29	90	0.03	1.86	50	0.20	0.11	0.22	30	4.47	0.03	0.00	2.22
89-SE	E.amyg	Hh	19	100	0.02	0.78	50	0.16	0.34	0.24	40	4.46	0.07	0.03	1.46
90-SE	E.amyg	Hh	18	90	0.02	0.47	90	0.17	0.35	0.24	30	2.70	0.07	0.00	1.13
91-SE	E.amyg	Hh	10	90	0.02	0.86	90	0.20	0.20	0.13	50	2.36	0.06	0.01	1.26
92-SE	E.amyg	Hh	6	90	0.02	0.40	90	0.21	0.23	0.02	30	1.49	0.08	0.03	0.77
93-SE	E.amyg	Hh	6	80	0.02	0.29	60	0.21	0.12	0.01	50	1.62	0.04	0.01	0.47
94-SE	E.amyg	Hh	5	100	0.01	0.31	100	0.17	0.12	0.06	80	1.81	0.15	0.00	0.64
95-SE	E.amyg	Hh	3	50	0.01	0.30	70	0.14	0.28	0.01	20	4.33	0.00	0.06	0.64
96-SE	E.amyg	Hh	0.8	40	0.01	0.08	60	0.15	0.19	0.01	20	5.08	0.00	0.05	0.33
97-SE	E.amyg	Hh	0.5	50	0.02	0.11	0	0.12	0.14	0.01	20	6.80	0.00	0.03	0.28
98-SE	E.amyg	Hh	0.2	50	0.03	0.12	20	0.05	0.00	0.04	10	1.55	0.00	0.02	0.19

Table A2. *Cont.*

Veg Type			Age	Surface			Near-Surface				Elevated				Total
Site	**Over**	**Under**		**cvr**	**hgt**	**load**	**cvr**	**hgt**	**live**	**dead**	**cvr**	**hgt**	**live**	**dead**	**Load**
				%	**m**	**kg m^{-1}**	**%**	**m**	**kg m^{-1}**	**kg m^{-1}**	**%**	**m**	**kg m^{-1}**	**kg m^{-1}**	**kg m^{-1}**
140-NE	E.obli	Bk	15.5	95	0.03	1.03	30	0.41	0.11	0.18	4	1.51	-	-	1.33
141-NE	E.obli	Bk	17.6	94	0.03	0.96	27	0.33	0.10	0.10	4	1.38	-	-	1.16
142-NE	E.obli	Hh	8.6	88	0.03	1.07	25	0.31	0.05	0.05	2	1.56	-	-	1.18
143-NE	E.obli	Bk	0.7	29	0.02	0.23	11	0.22	0.01	0.01	1	1.20	-	-	0.25
144-NE	E.obli	Bk	0.7	67	0.03	0.52	27	0.26	0.09	0.02	4	1.25	-	-	0.64
145-NE	E.obli	Hh	25.6	93	0.03	1.00	35	0.32	0.11	0.19	3	0.97	-	-	1.30
146-NE	E.obli	Bk	17.5	89	0.02	0.79	24	0.25	0.09	0.16	1	1.45	-	-	1.03
147-NE	E.obli	Bk	2.8	43	0.02	0.30	24	0.31	0.07	0.09	0	1.00	-	-	0.46
148-NE	E.obli	Bk	3.7	97	0.03	0.95	29	0.30	0.08	0.22	1	1.03	-	-	1.25
149-NE	E.obli	Bk	15.6	90	0.03	1.15	16	0.20	0.03	0.10	2	0.90	-	-	1.28
150-NE	E.obli	Bk	13.6	97	0.03	1.00	31	0.30	0.07	0.23	6	1.29	-	-	1.31
151-NE	E.obli	Bk	27.6	85	0.03	0.85	19	0.25	0.06	0.13	0	1.10	-	-	1.04
152-NE	E.obli	Hh	22.7	89	0.03	0.95	19	0.28	0.12	0.16	1	1.14	-	-	1.23
153-NE	E.obli	Bk	12.7	98	0.03	0.84	28	0.43	0.17	0.34	0	0.00	-	-	1.35
154-NE	E.obli	Hh	20.7	93	0.03	1.09	26	0.28	0.11	0.11	4	1.24	-	-	1.30
155-NE	E.obli	Bk	5.7	72	0.01	0.52	22	0.26	0.15	0.11	1	1.33	-	-	0.78
156-NE	E.obli	Bk	11.7	97	0.02	0.94	26	0.31	0.16	0.23	0	0.95	-	-	1.32
157-NE	E.obli	Bk	6.7	91	0.02	0.86	27	0.33	0.11	0.30	3	1.42	-	-	1.27
158-NE	E.obli	Bk	2.7	87	0.02	0.49	29	0.34	0.11	0.14	1	1.17	-	-	0.74
159-NE	E.sieb	Hh	12.7	93	0.03	0.93	18	0.19	0.16	0.09	2	1.46	-	-	1.17
160-NE	E.obli	Bk	22.7	94	0.04	1.47	20	0.27	0.02	0.14	1	1.05	-	-	1.63
161-NE	E.obli	Bk	7.7	88	0.02	0.66	23	0.34	0.05	0.05	0	1.40	-	-	0.76
162-NE	E.sieb	Hh	2.7	39	0.02	0.33	8	0.17	0.01	0.02	1	1.52	-	-	0.36
163-NE	E.sieb	Bk	10.1	95	0.02	1.26	23	0.23	0.05	0.07	2	1.45	-	-	1.38
164-NE	E.sieb	Bk	19.3	94	0.03	1.66	9	0.15	0.01	0.06	3	1.30	-	-	1.73
165-NE	E.sieb	Hh	5.8	75	0.02	0.88	8	0.17	0.00	0.07	1	1.00	-	-	0.96
166-NE	E.amyg	Bk	22.8	98	0.03	1.00	41	0.49	0.24	0.37	1	1.33	-	-	1.61
167-SE	E.pulc	Hh	24	83	0.02	0.53	75	0.40	0.28	0.30	16	1.44	-	-	1.11
168-SE	E.amyg	Hh	22.8	93	0.03	0.95	48	0.42	0.23	0.08	3	1.38	-	-	1.26
169-SE	E.pulc	Gr	23.7	72	0.03	0.84	24	0.19	0.06	0.23	0	0.00	-	-	1.14
170-SE	E.amyg	Lt	20.9	75	0.02	0.56	47	0.15	0.17	0.25	4	1.06	-	-	0.98
171-SE	E.amyg	Lt	22.9	58	0.01	0.62	41	0.10	0.02	0.17	4	1.33	-	-	0.80
172-SE	E.obli	Bk	2.1	55	0.01	0.42	19	0.23	0.05	0.01	2	1.52	-	-	0.48
173-SE	E.vimi	Gr	24.9	56	0.02	0.76	68	0.16	0.07	0.05	3	1.15	-	-	0.88
174-SE	E.obli	Hh	6.9	90	0.02	0.72	20	0.17	0.12	0.02	0	0.00	-	-	0.86
175-SE	E.obli	Hh	18.9	87	0.02	0.85	21	0.29	0.13	0.10	4	1.42	-	-	1.08
176-SE	E.obli	Hh	18	70	0.02	0.65	11	0.19	0.08	0.06	6	1.31	-	-	0.79

Site: NE = northeast Tasmania, SE = southeast Tasmania; veg type over = over storey-dominant species: E.amyg = *Eucalyptus amygdalina*, E.obli = *Eucalyptus obliqua*, E.sieb = *Eucalyptus sieberi*, E.vimi = *Eucalyptus viminalis*, E.pulc = *Eucalyptus pulchella*, E.glob = *Eucalyptus globulus*, E.tenu = *Eucalyptus tenuiramis* A.vert = *Allocasuarina verticillata*; under = understorey type: Gr = grassy, Bk = bracken, Hh = heathy, Lt = litter; yrs = years; cvr = cover, %; hgt = height, m; live = live fuel load, kg m^{-2}; dead = dead fuel load, kg m^{-2}; total load: kg m^{-2}.

Appendix C

Table A3. Fuel Hazard Rating Data from Tasmanian Dry Forests.

	Over-	Under		Surface				Near-Surface					Elevated						Bark	Overall
Site	Storey	Storey	Age	horiz	cvr	hgt	FHR	horiz	cvr	hgt	dead	FHR	horiz	vert	cvr	hgt	dead	FHR	FHR	FHR
1-NE	E.amyg	Gr	15.5	3.2	44	0.04	2.8	3.1	53	0.38	56	3.9	0.4	0.4	4	1.33	10	0.4	2.6	3.9
2-NE	E.amyg	Bk	15.5	4.8	86	0.10	4.6	4.1	66	0.29	54	4.2	0.8	1	9	1.15	61	1.7	3.8	4.6
4-NE	E.amyg	Bk	25.8	4.6	82	0.07	4.4	4.1	70	0.35	59	4.5	3.9	5	64	1.38	50	4.6	3.3	5
5-NE	E.amyg	Lt	7.3	4.5	84	0.04	4.2	1.8	21	0.22	51	3.1	1.7	3.3	26	0.71	39	2.7	3.1	4.1
6-NE	E.amyg	Hh	19.8	4.5	91	0.06	4.6	1.6	18	0.20	76	3.3	1.4	1.9	15	0.84	31	2.2	3.9	4.7
7-NE	E.amyg	Bk	22.8	5	92	0.08	4.9	3.2	50	0.27	69	4.2	3.4	4.2	53	1.15	62	4.3	3.1	5
8-NE	E.amyg	Gr	2.9	3.5	61	0.02	2.6	1.3	15	0.24	5	1.2	0.1	0.1	1	0.50	5	0.2	2	2.4
10-NE	E.amyg	Hh	32.8	4.3	79	0.06	4.1	2.5	32	0.27	53	3.5	2.4	3	33	1.36	41	3.4	3.8	4.9
11-NE	E.amyg	Bk	18.8	5	92	0.14	4.8	4.9	87	0.34	90	5	4.7	5	78	1.50	59	4.9	3.9	5
13-NE	E.amyg	Hh	17.3	3.7	63	0.05	3.7	1.4	15	0.19	83	3.3	2.7	3.3	42	1.55	25	3.1	2.8	4.4
14-NE	E.amyg	Bk	0.2	2	31	0.01	1.5	1	5	0.14	5	1	0.1	0.1	1	0.40	5	0.1	2	1.6
15-NE	E.amyg	Bk	6.9	3.2	75	0.05	3.4	2.7	33	0.30	44	3.4	1.5	1.3	18	1.20	35	2.7	3	4.1
16-NE	E.amyg	Lt	17.4	5	92	0.06	4.9	2.2	29	0.23	70	3.6	1.8	1.8	19	1.05	41	3.1	3.7	4.5
17-NE	E.amyg	Lt	12.8	5	90	0.07	4.8	1.8	16	0.17	38	2.4	1.7	1.1	15	1.55	5	1.2	2.7	3
18-NE	E.amyg	Lt	16.3	5	95	0.11	4.9	2.2	17	0.18	97	3.6	0.7	0.7	4	0.68	5	0.7	4.8	5
19-NE	E.amyg	Lt	17.3	4.5	67	0.06	3.9	1.4	16	0.24	60	2.5	0.5	1	3	0.50	24	1	3.8	4.6
20-NE	E.amyg	Gr	14.5	3.2	55	0.05	3	2.7	41	0.22	36	3.2	0	0	0		NA	0	3.8	4.2
21-NE	E.amyg	Hh	21.8	4.2	77	0.10	4	3.3	49	0.36	51	3.6	1.9	1.9	23	1.63	11	1.4	5	4.6
22-NE	E.amyg	Hh	4.3	3.3	51	0.04	3	1.5	17	0.17	29	2.2	1.6	1.6	16	1.10	3	1.3	1.9	2.8
23-NE	E.amyg	Hh	4.3	2.3	30	0.03	2.1	2.3	28	0.18	28	2.5	1.1	0.8	9	1.21	1	0.8	2	2.5
24-NE	E.amyg	Hh	21.3	4	70	0.06	3.8	2.9	39	0.26	62	3.9	4.2	4.5	67	1.35	50	4.5	3.1	5
25-NE	E.amyg	Hh	16.5	4	73	0.08	3.8	4	67	0.29	45	4.2	3.4	3.8	48	1.25	49	4.2	3	5
26-NE	E.amyg	Bk	2.5	4	61	0.10	3.7	3	28	0.31	30	3	3.2	3.6	32	1.35	13	2.3	2	3.7
31-NE	E.amyg	Bk	11.8	4.7	84	0.08	4.4	3.9	61	0.28	53	4.3	3.6	4.8	54	1.15	26	3.8	3	4.9
32-NE	E.amyg	Bk	12.8	4.9	93	0.05	4.8	1.9	25	0.20	69	3.5	1.9	3	27	0.93	35	3.2	3	4.8
33-NE	E.amyg	Lt	33.8	4.5	79	0.03	3.7	1.4	13	0.16	75	3	0.3	0.7	2	0.58	38	0.8	4.2	4.8
34-NE	E.amyg	Bk	11.6	4.4	76	0.06	4.1	2.6	37	0.24	69	3.9	3.8	3.9	55	1.18	25	3.9	3.1	5
35-NE	E.amyg	Bk	28.8	4.4	81	0.08	4.4	3.5	54	0.36	54	4.1	1.1	1.4	13	1.20	37	1.5	3.5	4.2
36-NE	E.amyg	Lt	24.8	4.1	69	0.07	3.9	3.1	50	0.38	46	3.8	0.5	0.8	4	0.58	18	0.7	3.5	4.4

Table A3. *Cont.*

	Over-	Under		Surface				Near-Surface					Elevated						Bark	Overall
Site	**Storey**	**Storey**	**Age**	**horiz**	**cvr**	**hgt**	**FHR**	**horiz**	**cvr**	**hgt**	**dead**	**FHR**	**horiz**	**vert**	**cvr**	**hgt**	**dead**	**FHR**	**FHR**	**FHR**
37-NE	E.amyg	Bk	14.8	4.9	94	0.10	4.9	3	39	0.25	77	4.1	2.2	3.4	19	0.98	20	2.5	3.2	4.1
38-NE	E.amyg	Hh	25.8	4.4	76	0.06	4.1	3.4	53	0.31	48	3.9	1.5	2	16	1.22	23	2.1	2.9	3.9
39-NE	E.amyg	Bk	28.8	4.7	84	0.04	4.2	3.2	46	0.30	64	4.2	3.8	4.6	57	0.98	35	4.2	3.3	5
41-SE	E.tenu	Bk	8.2	2.7	50	0.07	3	1.3	12	0.25	92	3.2	0.6	0.7	7	0.54	8	0.7	1.1	3.1
43-SE	E.tenu	Lt	27	1.4	13	0.03	1.7	1.2	16	0.11	43	2.6	0.8	0.8	9	0.59	6	0.8	1.2	2.3
44-SE	E.tenu	Lt	4.4	1	11	0.04	1.1	0.5	2	0.30	5	0.5	0	0	0	0	NA	0	1	1.4
45-SE	E.tenu	Hh	13.2	3.5	72	0.08	3.6	2.5	42	0.31	62	3.6	2.5	2.3	39	1.37	6	1.7	2.1	3.3
48-SE	E.tenu	Lt	15.7	2.7	60	0.06	2.8	1.6	22	0.19	59	3.3	0.4	0.4	4	1.09	5	0.4	1.2	2.7
49-SE	E.pulc	Hh	13.2	3.6	74	0.08	3.6	3.3	60	0.40	47	3.9	3.4	3.6	60	1.70	10	2.3	1.2	3.8
51-SE	E.pulc	Gr	27	3.2	49	0.03	2.8	2.3	31	0.24	62	3.3	1.1	0.8	6	1.92	3	0.8	2	2.7
52-SE	E.pulc	Gr	27	3.4	52	0.06	3.2	4	71	0.31	51	4	2.2	2.6	31	1.56	3	1.5	2.8	3.3
53-SE	E.pulc	Hh	13.2	3	37	0.08	3	3.9	62	0.30	49	4.2	2.5	3.2	32	1.18	14	2.2	2	3.4
54-SE	E.pulc	Lt	23	3.4	65	0.09	3.4	2.7	39	0.25	31	3	0.9	1.7	10	0.83	8	1.1	2.2	3.3
55-SE	E.pulc	Gr	13.2	2.1	35	0.06	2.6	2.3	43	0.19	29	3	1.3	1.4	13	0.38	5	1.2	1.8	2.8
56-SE	E.pulc	Gr	18.5	2	22	0.02	1.7	3.1	48	0.20	56	4	0.4	0.5	4	0.88	5	0.3	2.5	2.9
58-SE	E.pulc	Lt	13.2	3.2	57	0.02	2.5	2.1	29	0.38	72	2.5	0	0	0	0	NA	0	2	2.5
60-SE	E.pulc	Hh	27	3.3	54	0.04	3.1	4	68	0.28	65	4.6	2	1.4	17	2.03	3	1.3	2.9	3.7
62-SE	A.vert	Gr	9	3.3	57	0.05	3.3	4	69	0.28	67	4.6	1.1	0.9	12	1.28	5	1	2.1	3.2
63-SE	A.vert	Gr	6.3	2.4	34	0.06	2.7	4	77	0.30	57	4.5	2.2	1.5	23	1.78	6	1.5	2	3.2
64-SE	A.vert	Gr	25	2.3	31	0.03	2.1	3.5	58	0.24	48	3.8	0.7	1.1	4	0.93	2	0.7	1.9	2.9
65-SE	A.vert	Gr	5.2	3.9	70	0.03	3.1	2.1	33	0.18	40	2.8	0.2	0.2	1	1.13	53	0.4	2.1	3.1
66-SE	A.vert	Gr	10	2.9	49	0.03	2.5	2.9	46	0.29	68	4.1	3	3	39	1.93	28	3.1	2	3.7
67-SE	A.vert	Gr	5	1.8	20	0.04	2	3.7	67	0.29	62	4.5	3.3	3.2	44	1.80	13	2.5	2	3.5
69-SE	A.vert	Gr	4.4	2.6	29	0.03	2.3	3	43	0.29	23	2.8	0.6	0.7	5	0.90	4	0.5	1.7	2.7
70-SE	E.glob	Lt	16.6	3.3	52	0.05	3	0.9	13	0.28	56	2	0	0	0	0	NA	0	2.9	3.3
71-SE	E.glob	Gr	28.2	4.9	87	0.08	4.6	2.9	43	0.28	53	3.7	1.3	2.4	13	1.06	9	1.2	3.5	4.1
72-SE	E.glob	Gr	9.9	2	30	0.03	2	3.9	70	0.28	44	4.1	0.7	1.5	5	0.54	5	0.7	1.5	3
73-SE	E.glob	Gr	21.2	3.9	63	0.12	3.7	3.8	57	0.29	80	4.5	2.6	2.7	31	1.53	10	1.8	2.7	3.6
74-SE	E.glob	Lt	19.2	3.5	74	0.08	3.7	2.5	26	0.18	73	3.6	1.7	2	12	0.82	12	1.6	3.4	4.1

Table A3. *Cont.*

	Over-	Under		Surface				Near-Surface					Elevated						Bark	Overall
Site	**Storey**	**Storey**	**Age**	**horiz**	**cvr**	**hgt**	**FHR**	**horiz**	**cvr**	**hgt**	**dead**	**FHR**	**horiz**	**vert**	**cvr**	**hgt**	**dead**	**FHR**	**FHR**	**FHR**
75-SE	E.glob	Gr	15.7	2.7	47	0.03	2.2	2	22	0.19	34	2.8	2.6	2.8	15	0.57	5	1.5	3	2.8
76-SE	E.glob	Gr	16.6	2.7	51	0.04	2.7	1.9	33	0.24	26	2	0	0	0	0	NA	0	2.6	3.3
77-SE	E.glob	Lt	16.6	3.3	61	0.05	3.2	1.5	13	0.19	29	1.8	0.1	0	1	2.00	5	0.1	3.1	2.9
78-SE	E.glob	Gr	4.4	1.9	19	0.03	1.8	2.4	51	0.26	25	2.9	1.7	1.4	27	0.01	5	1.3	1.2	2.6
79-SE	E.glob	Gr	4.4	2.3	29	0.06	2.7	2.8	49	0.25	33	3.3	2.8	2.4	48	0.01	5	1.9	2.5	3.4
82-SE	E.amyg	Gr	25	2.6	39	0.08	2.9	3.7	71	0.18	21	3.1	0.4	0.4	4	1.63	50	0.5	2.2	2.9
83-SE	E.amyg	Lt	22.2	2.5	51	0.03	2.3	1.9	22	0.19	64	3.3	1.5	3	12	0.42	19	2.1	2.5	3.5
87-SE	E.amyg	Gr	3.2	1.4	14	0.03	1.6	0.9	8	0.20	68	1.9	0.5	0.5	4	0.53	15	0.7	2	2.3
88-SE	E.amyg	Gr	12	3.5	63	0.08	3.5	3.4	55	0.28	43	3.9	2	2.1	28	0.78	6	1.5	2.1	3
90-SE	E.amyg	Bk	3.2	1.4	17	0.03	1.7	0.2	2	0.23	28	0.4	4.8	4.5	90	1.50	25	4.4	2	4.8
91-SE	E.amyg	Lt	25	4.5	76	0.06	4.2	1.8	25	0.20	24	2.2	0.5	0.4	4	0.52	5	0.4	2.2	3.2
94-SE	E.amyg	Gr	20	3.5	73	0.08	3.6	1.8	24	0.23	48	3	1.2	1.4	17	0.51	6	1.2	2.8	3.1
101-SE	E.amyg	Gr	4.4	1.2	10	1	1.2	1.1	7	12	33	2.2	0.7	0.7	4	49	5	0.7	2	1.5
102-SE	E.tenu	Lt	8.2	2	22	3	2	2.4	28	11	22	2.2	0.1	0.2	1	50	5	0.1	1	2.3
103-SE	E.tenu	Lt	10	1.8	25	5	2.4	1.1	12	15	98	3.1	0.7	0.7	5	35	5	0.7	1.4	2.9

Site: NE = northeast Tasmania, SE = southeast Tasmania; over storey: E.amyg = *Eucalyptus amygdalina*, E.pulc = *Eucalyptus pulchella*, E.glob = *Eucalyptus globulus*, E.tenu = *Eucalyptus tenuiramis* A.vert = *Allocasuarina verticillata*; understorey: Gr = grassy, Bk = bracken, Hh = heathy, Lt = litter; Hgt = height, metres; Cvr = cover, %; Horiz = horizontal continuity; Vert = vertical continuity; FHR = fuel hazard rating. Note that FHR between 0 and 1.0 are assumed to be low, 1.1 to 2.0 moderate, 2.1 to 3.0 high, 3.1 to 4.0 very high and 4.1 to 5.0 extreme.

Appendix D

Table A4. Field Data Collected. Site data collected.

Site Identifier	Number
Date	
Easting	6 figure grid reference
Northing	7 figure grid reference
Datum	Fuel load sites: AGD66/55; FHR sites: GDA94/55
Location	GPS or map, accuracy in metres
Altitude	Metres
Aspect	Degrees magnetic
Slope	Degrees
Geology	Geology map followed by field inspection
Fire age	Year (month if known), fire history map, oral record, aging using nodes and/or ring counts
Tree cover and height	Visual estimate to the nearest 10% and metre
vegetation type	Species and cover (Braun-Blanquet index [69]):
	1 = <1%, 2 = 1 to 5%, 3 = 5 to 25%, 4 = 25 to 50%, 5 = 50 to 75%, 6 = 75 to 100%

Table A5. Field Data Collected. Fuel load and fuel hazard rating data collected.

Project	Stratum	Variable	Data Recorded	Data Range
Fuel load	Surface	cover depth	projective cover centimetres	0 to 100
	Near-surface	cover height	projective cover centimetres	0 to 100
	Elevated	cover height	projective cover centimetres	0 to 100
Fuel hazard rating	Surface	cover depth horizontal continuity decomposition state	projective cover centimetres category category	0 to 100 L, M, H, VH, E L to VH
	Near-surface	cover dead height horizontal continuity	projective cover visual estimate, percent centimetres category	0 to 100 0 to 100 L, M, H, VH, E
	Elevated	cover dead height horizontal continuity vertical continuity	projective cover visual estimate, percent centimetres category category	0 to 100 0 to 100 L, M, H, VH, E L, M, H, VH, E
	Bark	bark type attachment amount	category category category	fibrous, candle or other L, M, H, VH, E L, M, H, VH, E

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