Quantifying fine fuel dynamics and structure in dry eucalypt forest (*Eucalyptus marginata*) in Western Australia for fire management

James S. Gould, W. Lachlan McCaw, N. Phillip Cheney

Research highlights

- Dynamics of fuel quantity and structure at different times after fire were assessed in two dry eucalypt forests with low and tall shrub understoreys.
- Accumulation and change were modelled and compared by fuel ages in each understorey type.
- Visual fuel hazard scores described the patterns of fuel dynamics over time in a similar fashion to models based on fuel load accumulation.

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Abstract

Techniques for rapid visual assessment of fuel characteristics have a broad range of applications in wildfire management and research. We developed and tested a technique for assessing forest fuels which provides hazard ratings for distinct layers within the overall fuel complex, including bark, elevated shrubs, near-surface and surface (forest litter) fuels. These layers are comprised predominantly of fine fuel particles <6 mm diameter. The technique was used to model fuel accumulation in dry eucalypt forest of *Eucalyptus marginata* at two locations with contrasting understorey structures. We found that visual fuel hazard ratings described patterns of fuel dynamics over time in a similar fashion to models based on fuel load accumulation. Visual hazard ratings can be related qualitatively to factors that reflect the difficulty of fire suppression by experienced fire fighters including visibility through the forest, access and difficulty of working machinery, flame height and spotting potential. The ability to relate hazard ratings to fire spread and fire behaviour would make them doubly useful.

Keywords: fuel, visual assessment, hazard rating, Project Vesta, fuel accumulation models, eucalypt forest

1. Introduction

Wildland fuelbed characteristics are temporally and spatially complex and can vary widely across the landscape (Burrows 1994, Riccardi *et al.* 2007). Fuels are often defined by the physical characteristics (e.g. loading, depth, height, bulk density, particle size) of live and dead vegetation that contribute to wildland fire behaviour (Davis 1959, Cheney 1981, Chandler *et al.* 1983, Pyne *et al.* 1996). Fuel characteristics can affect fire spread, flame structure, duration, and intensity of wildland fires. Describing and quantifying fuel is important for understanding fire behaviour and also provides information for fire management activities including prescribed burning, suppression difficulty, fuel hazard assessment and fuel treatment. Furthermore, fuel characteristics are increasingly of interest to ecologists, air quality managers and carbon accounting modellers. Techniques for reliable and rapid assessment of fuel characteristics are therefore essential for wildland fire management decisions.

Fuel load is the only fuel characteristic used in Australian forest fire danger rating systems to predict fire behaviour in a particular fuel type. Studies by McArthur (1962, 1967) and Peet (1965) suggested that the amount of fine fuel (<6 mm diameter) available on the forest floor (i.e. fuel consumed by the fire) was the most significant fuel variable affecting the behaviour of fires in eucalypt forests. These authors claimed that the rate of spread of the head fire is directly proportional to the load of fine fuel consumed. If the rate of spread is directly proportional to fuel load, it is argued that reducing the fuel load by half, halves the rate of spread and reduces the intensity of the fire four-fold. This relationship between fuel load, rate of spread and fire intensity has provided a simple but powerful argument to support fuel reduction burning in eucalypt forests for more than 50 years. However, the publications of McArthur (1962, 1967) and Peet (1965) contain no detailed description of analytical methods or confidence limits on the correlation between rates of spread and fuel load. Their relationships were obtained using data from low-intensity fires (<2500 kW m^{-1}) and evidence that this relationship holds true for fires of higher intensity is limited (Cheney 1990, Gould *et al.* 1996, Burrows 1994, 1999). McCaw *et al.* (2008) demonstrated that predictions of fire spread from the Forest Fire Danger Meter (FFDM) of McArthur (1967, 1973) and the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1985) were closest to observed values when winds were light (<12 km h^{-1}) and shrub fuels were sparse. The possibility that descriptors other than fine fuel load may better quantify the contribution of vegetation complex to the behaviour of moderate and high-intensity fires has been suggested by a number of authors (Gould *et al.* 1996, Burrows 1999, Gill and Zylstra 2005, McCaw *et al.* 2008).

Studies of fire spread in homogeneous fuel in a wind tunnel (Rothermel 1972) identified a number of fuel physical characteristics that affect spread including fuel load, bulk density, and fuel particle size . Individual parameters are difficult to define and impractical to measure in natural fuels, although this has been simplified by building artificial fuel models and adjusting parameters so that a reasonable fit to field data is achieved. The National Fire Danger Rating System (NFDRS; Deeming *et al.* 1977), BEHAVE fire behaviour prediction and fuel modelling system (Burgan and Rothermel 1984, Andrews *et al.* 2003), and FARSITE (Finney 1998) use Rothermel's fire spread model with 13 fuel models to predict fire behaviour. Scott and Burgan (2005) introduced additional fuel models for use with Rothermel's surface fire spread model. The use of fuel models to predict fire behaviour relies on the assumption that relationships established in the wind tunnel are directly transferrable to field fires, and multiple fuel models could be required to account for changes in fuel bed characteristics over time following fire. The fuel model approach has not been widely adopted in Australia, and field validation studies have shown that the Rothermel model does not predict well in relatively simple fuels of grass (Gould 1991) or eucalypt litter (Burrows 1999).

Eucalypt litter fuels are not homogeneous. They can be stratified into a relatively compacted horizontal surface fuel layer with an aerated, less compacted layer above; in some fuel types the strata are quite distinct, e.g. shrubs and grasses over litter. It is easy to observe how discontinuities in the surface litter layer (e.g. a narrow fire trail) can stop a low-intensity fire while a high-intensity fire may sweep across the same discontinuity, seemingly without impediment. There is increasing evidence that the characteristics of the aerated fuel layer including continuity, bulk-density, and fraction of green material have a significant influence on fire spread. For example, Cheney *et al.* (1992) found that the rate of spread of low-intensity fires in regrowth forest of silvertop ash (*Eucalyptus sieberi*) was directly related to the continuity of aerated fuels (the near-surface fuel layer) composed of shrubs, grasses and suspended litter above the surface litter layer. The apparent increase in fire rate of spread with increasing fuel load demonstrated by McArthur (1967) in fuels of different ages might not be due to the fuel load but rather to a range of structural factors such as height, composition, continuity and greenness which change as fuel re-accumulates after burning.

The quantity of fuel available for combustion cannot be known with certainty prior to a fire because consumption depends on environmental conditions and the intensity of the fire itself. Therefore, we have adopted a conceptual model whereby fire spreads by burning across the top of a fuel surface and then down into the fuel bed (Cheney 1990, Gould 2003). The fuel bed can then be sub-divided into fuels which:

- contribute to the flame height: primarily loosely compacted layers of surface, near-surface and elevated fuel;
- contribute to the depth of flame behind the fire front: the upper layer of the surface fuel bed and the larger twig components imbedded in it;
- contribute to smouldering combustion: the lower compacted layers of the surface fuel, duff and coarse down woody material;
- burn only when supported by the combustion of lower fuels: these are generally sparse elevated dead fuels, green fuels and some dead fuels >1 cm in diameter;
- do not burn because of their location, moisture content or size.

Accumulation of fine surface fuels after fire depends on the difference between the rate of accession and decomposition of litter, while the build up of the near-surface fuel and elevated fuel layers depends on the rate of net bio-mass production of the understorey vegetation. The pattern of the fuel re-accumulation after fire in Australia varies widely with forest types and environmental conditions (Birk and Simpson 1980, Walker 1981, Raison *et al* 1983, Raison *et al.* 1986, Burrows 1994). These authors developed models describing the pattern and rate build up of litter fuels after burning following the general form of an exponential function rising to a maximum or steady-state fuel load:

$$w_t = w_{ss}(1-e^{-kt}) \qquad (1)$$

where w_t is the weight (e.g. t ha^{-1}) of the litter accumulated at time t (years); w_{ss} is the steady-state quantity of accumulated fuel litter and k is the decay constant. This model has been adapted from the model proposed by Olson (1963) to describe the relationship between production and accumulation. The general pattern of fuel accumulation in dry eucalypt forests described by this model is one of relatively rapid and steady accumulation for a period following fire, commonly 5 to 8 years, after which time the rate of accumulation declines progressively and fuel loading stabilises at a level of equilibrium with the prevailing environmental conditions. Walker (1981) discussed this function and described a curve that flattens out to a plateau which tends to be greater in more productive forest, and is generally proportional to canopy cover within a particular forest type (Fox *et al.* 1979, Birk and Simpson 1980, Raison *et al.* 1983, O'Connell 1987, Burrows 1994),

There are numerous designs and procedures for inventory and continued monitoring of fuel characteristics for a range of wildland fire management decision support systems (Van Wagner 1968, Brown 1974, Catchpole and Wheeler 1992, Ottmar *et al.* 2000, Sandberg *et al.* 2001, Sikkink and Keane 2008). These procedures have ranged in scope from simple and rapid visual assessment to highly detailed measurement of complex fuel structures along transects or quadrats that take considerable time and effort. Recent developments in Australia using visual fuel hazard rating systems to assess the fuel factors affecting fire behaviour and suppression difficulty represent a new approach in fuel assessment (Wilson 1993, 1992, Tolhurst *et al.* 1996, McCarthy *et al.* 1999, DEH 2006, Gould *et al.* 2007 a & b, Hines *et al.* 2010). These techniques emphasise the whole fuel complex by combining a hazard rating for each of the different fuel layers i.e. bark, elevated (shrub fuels), and surface fuels (forest litter fuels) layers in dry eucalypt forest and shrub heath fuel types. Visual fuel hazard assessment guides were developed:

- to provide a simple and consistent method to assess the changes of fuel hazard in different vegetation or forest types,
- to quantify the changes in fire behaviour as fuel hazard changes since last fire,
- to quantify the fuel hazard for fire suppression operations,
- to assess fire fighter safety by recognising the fuel hazards and associated different fuel and fire behaviour, and
- to better estimate the potential fire threat.

This study examined the dynamics of fuel quantity and structure in two dry eucalypt forest communities with the objectives of characterising fuels of different age since fire, and comparing patterns of accumulation over time amongst different fuel layers using quantitative and qualitative descriptors.

2. Methods

The fuel assessment described in this paper was undertaken for Project Vesta (Cheney *et al.* 1998, Gould *et al.* 2007a), a comprehensive fire behaviour experiment conducted by CSIRO Forestry and Forest Products (now known as CSIRO Ecosystem Sciences) and Western Australia Department of Conservation and Land Management (now know as Department of Environment and Conservation). Project Vesta investigated the behaviour and spread of high-intensity bushfires in dry eucalypt forests with different fuel ages and understorey vegetation structures. Experimental studies were designed to quantify age-related changes in fuel attributes and fire behaviour in dry eucalypt forests typical of southern Australia.

2.1. Study sites

Two experimental sites were located at Dee Vee Road (33º 06' S, 116º 24' E) 40 km east of Harvey and at McCorkhill forest block (34º 54' S, 115º 46' E) 25 km west of Nannup in south-west Western Australia (see Fig. 1). The Dee Vee site is in open forest of Jarrah (*E. marginata*) with a sparse low shrub understorey (*LS*). Average annual rainfall at Dee Vee is slightly less than 900 mm with potential summer (December to February) evaporation of about 650 mm. The dominant understorey shrub (*Bossiaea ornata*) grows to around 50 cm in height after 36 months post-fire, then slowly senesces so that older fuels are comprised predominantly of leaf litter, bark and twigs with only a small proportion of live shrubs. Vegetation and fuels at the McCorkhill site is representative of dry eucalypt forest with a tall understorey shrub layer (*TS*). Average annual rainfall at the site is 1100-1200 mm with potential summer evaporation of about 500 mm. Jarrah and Marri (*Corymbia calophylla*) form an overstorey with 30-50 % canopy cover and a top height of 25-30 m. Intermediate canopy trees consist primarily of *Allocasuarina fraseriana, Xylomelum occidentale, Banksia grandis* and Jarrah/Marri saplings. The *TS* understorey is dominated by *Taxandria parviceps* which ranges in height from 20 cm to 300 cm and in cover from sparse to near continuous depending on the time since last fire. McCorkhill was the site of previous high-intensity fire experiments conducted during Project Aquarius and Project Narrik in the summer of 1983

(Burrows 1983, Gould *et al.* 1996). Hereafter, the Dee Vee and McCorkhill study sites are referred to as low shrub (*LS*) and tall shrub (*TS*) respectively.

(Insert Figure 1)

2.2. Fuel layers

We defined five visually obvious fuel layers that could be associated with observed fire behaviour. These layers can be broadly identified by a change in bulk density and are illustrated in Fig. 2.

1. *Overstorey tree and canopy layer* - dominant and co-dominant trees forming the uppermost canopy layer of the forest. Trees are pole size (dbhob 15-45 cm) or greater. The flammable fuel is the bark, which depends on the tree species and the height and density of the forest. The bark type of different species can have a large impact on the rate of surface fuel accretion, transfer of a surface fire into the canopy and on the generation of firebrands.
2. *Intermediate tree and canopy layer* – shorter trees with crowns either below or extending into lower part of the forest canopy. These may be immature individuals of overstorey species or species of intermediate stature that form a distinct layer beneath the co-dominants of the overstorey (e.g. *Allocasuarina* spp., *Banksia* spp.). Patches of eucalypt regrowth in the open or around scattered dominants may be classed as intermediate until they reach pole size. The intermediate tree layer can add a significant amount of bark fuel, and act as ladder fuel that carries fire into the overstorey canopy.
3. *Elevated fuel layer* – tall shrubs and other understorey plants without significant suspended material. This layer may include regeneration of the overstorey species intermixed with shrubs. Individual fuel components generally have an upright orientation, and include live and dead material.
4. *Near-surface fuel layer* – grasses, low shrubs, creepers, and collapsed understorey usually containing suspended leaf, twig and bark material from the overstorey vegetation. The height of this layer can vary from just centimetres to over a metre above the ground. Fuel layer components typically have a mixed orientation ranging from horizontal to vertical, and the layer is capable of suspending leaves, twigs and bark above the ground.

5. *Surface fuel layer* **–** leaves, twigs and bark of overstorey and understorey plants. Fuel components are generally horizontally layered. This layer usually makes up the bulk of the fuel consumed and provides most of the energy released by a fire. Surface fuel burns by both flaming and smouldering combustion, and determines the flame depth of a surface fire.

(Insert Figure 2)

2.3. Visual fuel assessment

Fuel hazard was rated using a categorical score from 0 to 4 based on visual assessment of the percent cover score (*PCS*) and the fuel hazard score (*FHS*) for each of the five fuel layers, following the concept of Cheney *et al.* (1992), Wilson (1992, 1993), and Tolhurst *et al.* (1996). The *PCS* rates the cover of each layer into five scores described in Table 1, and *FHS* represents a subjective assessment of the flammability of each layer based on the type of bark, the density and morphological development of the vegetation and the accumulation of litter as described in Table 2.

Prior to conducting the full scale fuel survey the authors conducted half day training sessions for the fuel assessors during which they were instructed on the identification of different fuel layers and shown examples of the full range of potential conditions and scores in each layer. The objective of training was to standardise assessments so that individuals consistently rated a given fuel condition to within one score of each other.

2.4. Destructive sampling

Fine fuel (<6 mm diameter) in the surface and near-surface layers was measured using systematic stratified ranked sampling procedure (McIntyre 1952, Cheney *et al.* 1992). The layers of surface and near-surface fuel were visually identified using the rules above, and within a 5-m radius of the sample point the ranked sample removed the operator bias (McIntyre 1952) by visually ranking both layers in order of light, medium and heavy fuel loads. The medium ranked sample was collected using circular quadrats of 0.05 m^2 for surface fuel and 0.2 m^2 for near-surface fuels. All samples collected were taken back to a laboratory and oven dried at 103 °C for 24 hours. Fuel loading was expressed as the quantity per unit area in units of t ha^{-1}. Separating the near-surface fuel from the underlying surface fuel in the 0.2 m^2 samples proved impractical and so the near-surface loading was determined as the difference between the total load of the 0.2 m^2 sample and the surface fuel load from the 0.05 m^2 sample.

2.5. Field Procedures

Fuel sample plots were located along two transect lines parallel to the proposed direction of the head fire spread and placed 50 m from the burning plot edge to minimise potential edge effects and trampling of the fuel in the centre of the plot where the head fire was expected to burn. The number of sample in each age class depended upon the variability of the fuels based on sample variances from a pilot survey, which ranged from 5 samples per line in the youngest and most uniform fuel to 16 samples per line in the oldest and clumpiest fuel (Gould *et al.* 2007a). The spacing of the plots for each fuel was varied so that they systematically sampled the full length of the 200 m transect line.

At each location the presence or absence of near-surface fuel at the centre point was noted. The *PCS* and *FHS* for the five fuel layers was scored according to Table 1 and 2 (overstorey and intermediate layers within 10 m of the centre point and elevated, near-surface and surface layers within 5 m of the centre point). The position of the average top height of the elevated and near-surface fuel layers was visually located and measured.

Destructive ranked samples of the surface and near-surface fine fuels <6 mm in size were taken from their respective quadrats within a 5 m radius of centre point. The surface fuel depth to mineral soil and near-surface height of the medium ranked samples were recorded.

Fuel samples were taken from all experimental burnt plots in four sampling stages:

Stage I: (February March 1997) Description of fuel quantity, structure, continuity, fuel hazard rating and fuel height with 735 samples in the *LS* site, and 1077 samples in the *TS* site.

Stage II: (November 1997) Additional surface fuel samples (396 samples in *LS* and 614 samples in *TS*) together with 66 plots to sample elevated fuel. Elevated fuel was ranked by height-class and destructively sampled to determine the live-to-dead ratio of elevated fuel, by fuel age.

Stage III: (November 1998) The time lag between Stage I and Stage II sampling and the fire experiments required further sampling closer to the time of the experiments in order to allow for any additional changes that may have taken place in fuel characteristics (*LS* 116 samples and *TS* 541 samples).

Stage IV: (January 2001) The opportunity arose to burn some additional plots under stronger winds and to collect data on spot fire behaviour at the *LS* site. Therefore, an additional 168 samples were take in three age classes to measure the rate of change in the surface, near-surface and elevated fuels since 1998 in the plots to be burnt in 2001 (Gould *et al.* 2007a).

We initially sought to estimate mean fuel loading in each fire plot with a sampling error of ±10 percent. Stage I sampling provided estimates of the combined surface and near-surface fuel loads with standard errors <10 percent of the mean for each fire plot. However, surface fuel load samples had much greater dispersion and variation, with standard error for most plots being >10 percent of the mean. Achieving the objective of ±10 percent would have required a substantial increase in the number of samples, and been both costly and time consuming. The practical compromise adopted for the Stage II sampling of surface fuels was to improve the estimate of surface fuel quantity to a sampling error of ± 15 percent.

Combining data from Stage I and Stage II gave surface fuel load estimates with standard errors <15 percent for all fire plots. In over 80 percent of the fire plots, surface fuel load estimates had standard errors <10 percent of the mean. Despite the detailed site selection, and vegetation mapping (Gould *et al.* 2007a) the fuel survey from Stage I and II, there were high degree of spatial variation and dispersion of surface and near-surface fuel load both within individual 200 x 200 m plot and between plots of the same fuel age.

2.6. Analysis

Fuel data included continuous (fuel load, depth, height) and scored (*FHS, PCS*) variables and a variety of statistical methods were used to compare and model fuel dynamics in different fuel ages and sites. Symbols for fuel variables are listed in Table 3. Results were analysed in S-PLUS (S-PLUS 2006) using correlation, box and whisker plots and non-linear regression. A multi comparison of all pairwise differences in fuel parameter means based on fuel age groupings was performed using the multi comparison function in S-PLUS (Bechhofer *et al.* 1995, Hue 1996, S-PLUS 2006). Mean values of fuel variables were plotted against time (in months) since the last fire. Fitting a nonlinear regression model to the data has specific advantages:

- nonlinear models are often derived on the basis of physical or biological considerations (e.g. Olsen 1963, O'Connell 1987), and
- parameters of a nonlinear model usually have direct interpretation in terms of the process under investigation (e.g. Walker 1981, Raison *et al.* 1983, Burrows 1994).

Two nonlinear models were used to describe the fuel characteristics changes since last fire:

$$f_p = ss(1 - \exp(k*\text{age}) \quad (1)$$ (Olsen 1963)

$$f_p = (a*\text{age})/(b+\text{age}) \quad (2)$$

where f_p is the fuel parameter value at a given fuel age; and *ss*, *k*, *a*, and *b* are regression constants. Regression variables *ss*, *k*, *a*, and *b* estimates were solved by nonlinear regression modelling (SPLUS 2006) for the two fuel types.

3. Results

Fuel ages since last fire ranged from 16 to 255 months at the *LS* site and 3 to 185 months at the *TS* site. Median surface fuel loads (L_s) generally increased with time since fire, and the variability of L_s increased notably in fuels >120 months with individual samples ranging from 5.5 to 45.2 t ha^{-1} and 1.3 to 73.5 t ha^{-1} at *LS* and *TS* forest types respectively (Fig. 3). Changes in fuel characteristic with time were examined using the mean characteristic for each of four age classes: 1= < 36 months, 2= 37 to 72 months, 3= 73 to 120 months, and 4 > 120 months. Means and standard deviations of fuel variables are given in Table 4. Table 5 presents the results of multiple comparisons of pairwise means of fuel variables within and between fuel types for different fuel age classes based on Turkey's HSD (honestly significant difference) methods (SPLUS 2006).

(Insert Figure 3)

All fuel characteristics and hazard scores increased with increasing fuel age. Parameters for the fitted equations are listed in Table 6 and 7 and curves for selected fuel variables (L_s, FHS_{ns}, H_e, *and* FHS_{ob}) are shown in Fig. 4. Equation 2 provided a fit similar to that of equation 1 but did not limit fuel accumulation to a steady-state condition. In particular, we consider equation 2 better represented the changes in near-surface fuel load (L_{ns}) and *FHS* that take place from 180 months after fire (Gould *et al.* 2007a , McCaw *et al*. 2008).

(Insert Figure 4)

3.1. Surface fuel layer

On both sites PCS_s built up rapidly reaching 50 – 75 percent by 36 months and >95 percent cover within 72 months after burning. PCS_s was significantly higher at the *LS* site than at the TS site for fuel ages < 120 months but this difference did not persist into the oldest fuel age class.

L_s increased steadily reaching a mean value of 10 – 11 t ha^{-1} 120 months after burning. Thereafter the rate of accumulation reduced, but fuel load was still increasing slowly up to 13 – 14 t ha^{-1} at 300 months (Fig. 5a). There was no significant difference in mean L_s between LS and TS sites for the youngest and oldest fuel age classes (1 and 4) (Table 5). Pairwise comparisons of means indicated that L_s was significantly different between all fuel age classes at the *TS* site, but not significantly different between fuel age classes 2 and 3 at the *LS* site.

Surface fuel depth (D_s) increased in a similar manner on both sites. The Turkey's HSD analysis indicated that there was no significant difference in mean D_s up to 120 months old fuels between the two sites. The mean D_s was significantly higher in the old fuel age class (4) at the *TS* compared to the *LS* site. A linear regression was fitted to L_s with D_s as a predictor resulted in R^2 of 0.22 and 0.50 for the *LS* and *TS* respectively. Thus, D_s is not a good predictor for L_s where fuel depth can vary under different atmospheric conditions e.g. drier fuels "fluffing up" under hot dry conditions. When D_s combined with L_s to give bulk density, both sites had reached the maximum bulk density after 60 months, and remained more or less constant thereafter. Mean surface fuel bulk density (*BD_s)* at *TS* was lower (42.4 kg m^{-3}) than at *LS* (49.3 kg m^{-3}), and were significantly lower in all age classes indicating perhaps the greater presence of sedges and low ground plants in the *TS* fuels.

The FHS_s increased in a similar way on both sites (Fig. 5b). The FHS_s reached 3 by 84 months (7 years) after burning, and is described as 'established litter cover with decomposition present and a litter depth of 15-25 mm'. Eighty four months after burning the mean litter depth was around 20 mm. FHS_s was significantly different only the 72 – 120 month fuel age class (3) between the two sites.

(Insert Figure 5)

3.2. Near-surface layer

The PCS_{ns} increased for 120 months on both sites to a score of 2 described as 'scattered well separated clumps of near-surface fuel occupying 25 –50 percent of the site'. After 72 months the mean PSC_{ns} was significantly higher at the *TS* site. The PSC_{ns} continued to increase on the *TS*, and was projected to reach a score of 3 at 300 months after burning (Fig. 6a), indicating that the material suspended in the tall shrubs continued to increase as the shrubs grew, and was likely to continue as the shrubs senesced and collapsed.

Fuel load in the near-surface layer (total of both surface and near-surface fuel- F_{sns}) increased to 14 t ha^{-1} by 120 months after burning, and was projected to reach 16 to 18 t ha^{-1} 240 months after burning. The estimated additional fine fuel suspended only from L_{ns} ranged from 2 to 9 t ha^{-1} (by subtracting F_s from F_{sns}) (Fig. 6a). Results of the Tukey's HSD method with 95 percent confidence suggests similar L_{ns} means between the two sites by fuel age classes. Mean L_{ns} was not significantly different between age class 1 and 2, and 2 and 3 in the *TS* and *LS* respectively.

(Insert Figure 6)

Mean near-surface fuel height (H_{ns}) reached 15 cm 36 months after burning (Fig. 7a). The H_{ns} is strongly influenced by the species composition, and the bracken in fuel age class 2 at the *LS* site produced H_{ns} over 27 cm where it was present. Overall, H_{ns} at *LS* stabilised at around 20 cm 120 months after burning. At the *TS* site the near-surface fuel continued to increase in height beneath the tall shrubs, and levelled out at 25 cm 180 months after burning (Fig. 7a). The BD_{ns} was on average 7 and 9 kg m^{-3} at the *TS* and *LS* sites respectively. After 36 months the H_{ns} and BD_{ns} were significantly different between the two sites by fuel age classes with the *LS* site having lower H_{ns} and higher BD_{ns} than the *TS* site.

Near-surface fuel hazard score (FHS_{ns}) was significantly different between the two sites by fuel age classes and within each site the FHS_{ns} was also significantly different between age classes. The trajectory of change in FHS_{ns} at the two sites diverged after 36 months (Fig. 7b). The projected hazard score approached a value of 3 at the *LS* site 300 months (i.e. 25 years) after burning with suspended leaves, twigs and bark starting to obscure rocks and logs, and the proportion of dead material in the near-surface layer was estimated to be between 25 and 50 percent. At the *TS* site the hazard score rose more rapidly and was projected to reach a value of 3.7 after 300 months (Fig. 7b). At this value the large amount of suspended leaves, twig and bark obscured logs, rocks and holes. Shrub vegetation was senescent with >50 percent dead material in the layer.

(Insert Figure 7)

3.3. Elevated fuel

The elevated fuel layer re-established rapidly after fire and at *LS* site occupied 25 – 50 percent from 72 months onwards, declining slightly as shrubs senesced with age. PCS_e followed a similar pattern at *TS* site reaching a maximum score 48 months after burning and did not change further with age (Fig. 8a). At both sites the majority of shrubs were respouters that largely made up the elevated fuel fully occupied the site and did not increase in abundance as a result of burning. Visually, the density of shrubs at the *TS* site appeared much greater than at the *LS* site, but this impression was not supported by actual cover estimates.

Height of the elevated fuels was clearly different between sites (Fig. 4 e & f). At the *LS* site shrubs reached a maximum height of around 75 cm 60 months after burning, and then declined and maintained a stable height of 50 cm after 72 months as the shrubs senesced. The accepted relationship describing the change with age (equation 2) was not fitted to the *LS* data.

At the *TS* site the H_e rose steadily to 150 cm after 144 months. There was no significant difference of the mean H_e between age class 2 and 3 while between age 3 and 4 the mean H_e was significantly different. Although dead material was starting to increase, the shrubs had not reached the stage where they were starting to senesce and collapse, and the height of the elevated layer was projected to increase slowly to 150 cm at 300 months (i.e. 25 years).

Mean FHS_e was similar at the two sites for the first 36 months after fires but became significantly different thereafter. Mean FHS_e at *TS* tended to be about ½ point higher than the score at the *LS* site after 120 months by which time there values had stabilised (Fig. 8b).

(Insert Figure 8)

3.4. Intermediate canopy and bark

Percent cover score of the intermediate tree canopy was not affected by previous fires, and was independent of time since fire. The FHS_{ib} shows a steady increase with time since fire, and the pattern of change was similar at both sites with no significant difference in mean FHS_{ib} by age classes between sites (Fig. 9a). This indicates that the burning regime at both *LS* and *TS* burnt the bark to the height of the intermediate tree crowns regardless of intensity and season of burning.

3.5. Overstorey canopy and bark

The PCS_{oc} was also independent of time since fire. Mean PCS_{oc} at *LS* site was significantly higher by ½ score compared to the *TS* site. The FHS_{ob} on the overstorey trees increased with time since fire (Fig. 4 g & h, Fig. 9b), and is expected to continue to increase beyond 240 months, particularly if the trees have been burnt by a high-intensity fire that consumed bark from ground level to upper branchlets. The FHS_{ob} tended to be slightly higher at *LS* site than at *TS* site. This is probably because previous burning at *LS* site has been conducted under a low soil dryness index in spring and at lower intensity than the predominantly autumn burning at *TS* site. For this reason flames would not carry as far up the tree stem. The *TS* site was burnt by experimental fires in the summer of 1983 which consumed the bark to the upper branchlets of most of the trees, whereas there is no record of high-intensity wildfire at *LS* site since before 1960. The time since the upper bark was burnt at *LS* site is therefore considerably longer than the 240 months since the oldest surface fuels were burnt. In the continued absence of fire we would expect the FHS_{ob} to continue increasing until it approached the maximum value of 4.

(Insert Figure 9)

4. Discussion

The process of subdividing fuels into clearly identifiable layers and employing a sampling procedure that avoided bias provided robust estimates of fuel hazard and cover. This was reflected by the ability of different observers to consistently score the same fuel condition to within one class of each other. The key to consistent results was to ensure observers were familiar with fuels that scored the maximum value (4) for each identifiable layer. A number of field guides have been developed to provide a systematic method for assessing fuel hazard and potential fire behaviour in dry eucalypt forest (Wilson, 1992, 1993, Tolhurst *et al*. 1996, McCarthy *et al*. 1999, DEH 2006, Gould *et al.* 2007b, Hines *et al.* 2010). These guides provide a description for each fuel stratum and attributes to assess the fuel hazard rating, including photographs that illustrate the range of fuel hazard ratings for each fuel stratum. Practitioners can apply these guides to make rapid and consistent assessments of fuel hazard ratings in a range of dry eucalypt forest without the need for time consuming destructive sampling.

Although the scoring system is subjective, hazard scores can be related qualitatively to factors that relate to difficulty of fire suppression, (e.g. visibility through the forest, access and difficulty of working machinery, flame height and spotting potential) by experienced fire fighters (McCarthy *et al.* 1999, Hines *et al.* 2010), and so can be doubly useful if they can be related to fire spread and fire behaviour (Gould *et al.* 2007b).

All of the fuel characteristics were correlated with one another, and so it is not surprising that the patterns of increase with age are similar. The time taken for fuel to build up to its maximum level will depend on the degree of change to vegetation structure caused by the last fire, which will be strongly influenced by fire intensity. Climatic conditions may also affect the time taken for each fuel layer to attain its maximum expression of growth habit. In jarrah forest repeated burns of low to moderate intensity appear to cause little change in understorey species composition and, over 180 to 240 months, no change to intermediate or overstorey tree composition (Burrows and Wardell-Johnson 2003, Wittkuhn *et al.* in press). In some forest types, high-intensity fires may temporarily alter the height and density, and hence the hazard score of the elevated and near-surface fuel layers by stimulating germination of understorey plants with abundant soil-stored seed (Shea *et al.* 1979, Christensen and Maisey 1987). However, we would expect the change in hazard with time to follow the patterns illustrated by these sites.

Hazard ratings for some fuel layers approached a steady state in the older age classes, but there was no indication that the over-all hazard rating was starting to decrease in the 240 months after burning. In some cases it was apparent that the collapse of the elevated layer was contributing to the structure of the near-surface layer, and larger fuel elements of twigs and fine branches from the elevated, intermediate and overstorey layers were supporting the finer fuels of leaf bark and twig material in the near-surface layer. Larger fuel elements decay more slowly than leaf litter (O'Connell 1987), and not only contribute to increased height and cover of the near-surface layer but also to reduced decomposition of fine litter elements by supporting them above the ground in a generally drier environment than the surface litter.

The change in the hazard of different layers is manifest by examining the differences in the hazard rating of the two fuel types, where the most obvious difference between the two sites was in the potential hazard of the elevated fuel.

Fuel loading is influenced by the time since last fire and also by a variety of scale dependent factors including site productivity, stand structure and density, species composition, and localised patterns of understorey vegetation structure. These finer scale influences introduce considerable variability in fuel characteristics and cannot be readily mapped at a scale useful for fire management. The destructive sampling presented here provided an estimate of fuel loading and can adequately describe the pattern of fine fuel re-accumulation after fire (Equations 1 and 2, Table 6 and 7). Modelled estimates of fuel loading may give better estimates of fuel loading for fire managers than a destructive sampling design. Developing sampling designs for fuel loading that accurately captures the variability is difficult, costly, and timely. The older fuels have the greatest variation in fuel loading (Fig. 3), thus a more intense sampling is required. The markedly greater variability of fuel loading in older fuels also has important implications for fire behaviour as localised patches of very heavy fuel accumulation can contribute to extreme fire behaviour including tall flames, canopy flaring and spotting. Maximum firebrand densities downwind of experimental fires conducted during Project Vesta were found to be proportional to fuel age (Gould *et al*. 2007a).

4.1. Dry eucalypt forest – litter dominated fuel with low shrubs (LS)

The low shrubs of the elevated fuel layer peaked in height by age 60 months after burning, and then declined slightly as the shrubs senesced. The fraction of shrub cover reached a maximum by 48 months, and remained constant thereafter. Elevated fuel hazard, however, rose steadily to age 120 months as dead material in the senescing shrubs contributed to the hazard rating, and remained more or less constant to at least 240 months after fire.

Near-surface fuel height rose rapidly in the first 48 months after burning and then remained relatively constant thereafter. The near-surface fuel cover continued to increase up to age 120 months before it appeared to level off at around a score of 2, or 25 – 50 percent cover. The fuel load in the near-surface layer followed a similar pattern. By comparison, the hazard score for the near-surface layer rose quite rapidly in the first 120 months, and then continued to rise steadily so that the highest scores were observed in the oldest fuel.

Percent cover score of the surface fuel had obtained a maximum score of around 3.7 after 72 months. However the bulk density of the surface layer remained constant, indicating that both fuel load and litter depth continued to increase up to 240 months. Although the rate of increase was slow at 240 months, the trend of the data indicated that both fuel depth and fuel load would continue to increase with time since burning. The hazard score for the near-surface layer had practically levelled off at 240 months, but the slowly increasing fuel load will result in higher fire intensity at any given burning conditions as the fuel continues to age.

4.2. Dry eucalypt forest – tall shrub-dominated fuel type (TS)

The height of the elevated fuel layer continued to increase up to 192 months. At this age the shrubs were still growing and had not begun to senesce. There is little evidence to suggest that in this forest the shrubs will be suppressed and die within the foreseeable future, and if the elevated fuel hazard follows the pattern shown in the *LS* site we would expect the hazard to continue to increase for at least another 240 months after the shrubs reach their maximum height, and probably reach scores between 3 and 3.5.

Near-surface fuel height was quite variable but appeared to be levelling off by 192 months. This trend may change if the tall shrubs do collapse at a later age. However, the cover score was still increasing steadily at 192 months, as was the fuel load in this layer (including surface fuel). As a result, the near-surface hazard score was over 3 at 192 months and still increasing, and if this trend continues we would expect the hazard score to approach the maximum value of 4 by age 360+ months after burning. As discussed above, slower decay rates of the larger fuel elements will provide the structure to support leaf, bark and twig litter for many years, and if the elevated layer does senesce and collapse this will only serve to maintain the near-surface layer which will then become the dominant fuel structure in an older fuel type.

Surface fuel load was still increasing at 192 months but appeared to be levelling out, and may reach a steady-state load of around 14 t ha^{-1}. The hazard score of the surface fuel was levelling out towards a maximum value of 3.7. This score was slightly higher than the surface fuel in the *LS* site even though the fuel load was slightly lower, reflecting the lower bulk density surface fuel layer. Measurements of surface fuel characteristics were made between the clumps of near-surface fuel. However, as the near-surface fuels increase in cover as the fuels age, they become progressively more important in determining the fire behaviour.

The relationship between fire behaviour and fuel characteristics, including hazard scores, will be examined in a future manuscript. Fuel load estimates will still be required for calculation of fire intensity. In most forests, generalised fuel build-up curves provide an estimate of fuel load that is sufficiently accurate to characterise the fire in terms of line-fire intensity when combined with an accurate measure of rate of spread.

Future fire behaviour models seeking to characterise the thermal environment of bushfires will need to incorporate information about the amount, arrangement and condition of fuels across a broad range of size classes. Coarse woody fuels make an important contribution to fire behaviour and heat release from fires in open eucalypt forest (Sullivan *et al*. 2002), but were outside the scope of the Project Vesta experiments. Coarse woody fuels have been characterised at a range of sites in the jarrah forest (McCaw in press), and experiments have been conducted to identify factors affecting the combustion of woody fuels, including quantity, particle size, arrangement and condition (Hollis *et al*. 2010, Hollis *et al*. in press).

5. Conclusion

The visual fuel hazard rating system presented here is subjective; the process of stratifying the fuels into layers that are clearly identifiable and setting out a sampling procedure that avoids bias meant that the system was robust, and can quantify the rate of change of different fuel strata since the time of last fire. Visual fuel hazard ratings described patterns of fuel accumulation over time in a similar fashion to models based on fuel load accumulation. In dry eucalypt forests, generalised fuel accumulation curves provide an estimate of fuel load that is sufficiently accurate to characterise the fire in terms of line-fire intensity when combined with an accurate measure of rate of spread. Visual hazard ratings can be related qualitatively to factors that reflect the difficulty of suppression, (e.g. visibility through the forest, access and difficulty of working machinery, flame height and spotting potential) by experienced fire fighters, and so can be doubly useful if it can be related to fire spread and fire behaviour. This study contributes to a broader investigation of the relationship between visual fuel assessment scores, other fuel characteristics, fire weather and behaviour of moderate to high-intensity fires in dry eucalypt forest.

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Tables

Table 1

Percent Cover Score (*PSC*) - visual estimate of the percent cover for the five fuel layers to five score classes (0-4).

Table 2

Fuel Hazard Score *(FHS*) - visual estimate of the potential fuel hazards for the five fuel layers to five score classes (0-4).

Table 3

Symbols for variable used in analysis.

Table 4

Mean and standard deviation (brackets) of fuel variables by fuel age class for low shrub (*LS*) and tall shrub (*TS*) fuel types in dry eucalypt forests.

Table 5

Asterisk (*) identified the pairwise fuel variable means not significantly different at 95 percent confidence by Tukey’s HSD method by fuel age classes between and within fuel types.

Table 6

Regression equations developed for equation (1) $\{f_p = ss\,(1\text{-}\exp(-k*\text{age})\}$ and equation (2) $\{f_p = (a*\text{age})/(b+\text{age})\}$ where: *ss*, *k*, *a*, and *b* are estimated regression parameters (std er= standard error) for the low shrub site (*LS*).

Table 7

Regression equations developed for equation (1) $\{f_p = ss\,(1\text{-}\exp(-k*\text{age})\}$ and equation (2) $\{f_p = (a*\text{age})/(b+\text{age})\}$ where: *ss*, *k*, *a*, and *b* are estimated regression parameters (std er= standard error) for tall shrub site (*TS*).

Table 1

Percent Cover Score (*PSC*) - visual estimate of the percent cover for the five fuel layers to five score classes (0-4).

Overstorey Tree Canopy- Percent Cover Score; *(Estimate canopy cover within 10 m radius from the sample point)*				
0	**1**	**2**	**3**	**4**
0	**1-25%**	**25-50%**	**50-75%**	**75%+**
- overstorey tree canopy cover absent - no vertical projection of live overstorey canopy onto the ground within 10 m radius from the sample point	- very sparse / isolated crowns - <25% of skylight is intercepted by crown foliage, i.e. >75% gaps in the overstorey canopy	- open forest with well separated crowns - 25–50% of skylight is intercepted by crown foliage i.e. >50% gaps in the overstorey canopy	- open forest with clear to slight separation of crowns - 50–75% of skylight foliage is intercepted by crown foliage, i.e. <50% gaps in the overstorey canopy	- closed or dense live canopy - all overstorey canopy trees within 10 m radius from sample point are touching or overlapping - > 75% of skylight is intercepted by crown foliage, i.e. <25% gaps in the canopy.

Intermediate Canopy Trees- Percent Cover Score; *(Estimate canopy cover within 10 m radius from the sample point)*				
0	**1**	**2**	**3**	**4**
0	**1-25%**	**25-50%**	**50-75%**	**75%+**
- intermediate tree canopy cover absent - no vertical projection of live intermediate canopy onto the ground within 10 m radius from the sample point	-very sparse / isolated intermediate trees -<25% of skylight is intercepted by crown foliage, i.e. >75% gaps in the intermediate canopy	- intermediate trees with well separated crowns - 25–50% of skylight is intercepted by crown foliage, i.e. >50% gaps in the intermediate canopy	- intermediate trees with clear to slight separation of crowns - 50–75% of skylight foliage is intercepted by crown foliage, i.e. <50% gaps in the intermediate canopy	- closed or dense live intermediate tree canopy - all intermediate canopy trees within 10 m radius from sample point are touching or overlapping - > 75% of skylight is intercepted by crown foliage, i.e. <25% gaps in the intermediate canopy

Elevated Fuel Layer Percent Cover Score: *(Estimate canopy cover within 5 m radius from the sample point)*				
0	**1**	**2**	**3**	**4**
0	**1-25%**	**25-50%**	**50-75%**	**75%+**
- elevated fuel is absent within 5 m plot radius	- shrubs are very sparse or in small isolated clumps within 5 m plot radius	- scattered shrubs or well separated clumps, - gaps or openings >50% of the 5 m plot radius	- discontinuous shrub cover or clumps - gaps or openings <50% of the 5 m plot radius	- continuous cover of shrubs within 5 m plot radius - shrub crowns are touching or overlapping
Near-Surface Layer Percent Cover Score *(Estimate canopy cover within 5 m radius from the sample point)*				
0	**1**	**2**	**3**	**4**
0	**1-25%**	**25-50%**	**50-75%**	**75%+**
- near-surface fuel layer is absent within 5 m plot radius	- very sparse or small isolated clumps of near-surface fuel within 5 m radius	- scattered well separated clumps of near-surface fuels - gaps or opening >50% of the 5 m plot radius	- discontinuous cover or large clumps or near-surface fuel covering between 50 and 75% of the plot areas - gaps or openings <50% of the 5 m plot radius	- continuous cover of shrubs within 5 m plot radius - gaps are very small (<25 % of plot area) or touching between clumps of near-surface fuels
Surface Fuel Layer Percent Cover Score *(Estimate canopy cover within 5 m radius from the sample point)*				
0	**1**	**2**	**3**	**4**
>0-25%	**25-75%**	**75-90%**	**90-95%**	**95%+**
- litter is very sparse or in small isolated patches within 5 m plot radius - >75% of the 5 m plot radius is bare soil or rock outcrops	- scattered patches of litter between bare soil or rock outcrops - over 25% of the 5 m plot radius is bare soil or rock	- scattered, discontinuous and light cover of litter - <10% of the 5 m radius plot is bare soil or rock outcrops, i.e. >8 m^2 of bare soil or rock within the plot	- large patches of continuous cover of litter - <10% of the 5 m plot is bare soil or rock outcrop, i.e. between 4 and 8 m^2 of bare soil or rock outcrop within 5 m plot radius	- continuous cover of litter fuel within 5 m plot radius - <5% of the plot area is bare soil or rock outcrop i.e. <4 m^2 of bare soil or rock outcrops within 5-m plot radius

Table 2

Fuel Hazard Score *(FHS)* - visual estimate of the potential fuel hazards for the five fuel layers to five score classes (0-4).

Fuel Layer	**Fuel Hazard Score (FHS):** ***Description of the overstorey trees bark type and bark fuel***				
	0	1	2	3	4
Overstorey Tree Canopy Bark	Absent	- stringybark (*E. marginata, E. obliqua, E, baxteri*) where bark is well charred and tightly held on whole trunk - ironbarks (*E. tricarpa, E. paniculata*) with very tight, platy or fibrous bark -smooth barks (*E. rossi*) which do not produce long ribbons of bark	- stringybark where most of bark is black on the lower trunk - few pieces of bark are loosely attached to trunks - bloodwood with tight fibrous bark which has not been burnt for many years - smooth / candle bark (*E. rubida, E. globus, E. regnans*) which shed long ribbons of bark but have smooth bark down to ground level	- stringybark where <50% of surface area of the trees is black - upper parts of trunk may not be charred - smooth / candle barks with long ribbons of bark which are loose - fibrous or platy bark on lower trunk, which have not been burnt for many years	- stringybark with large flakes of bark that can be easily dislodged - huge amounts of bark are available for spotting - outer bark on the trees is attached weakly - minimal evidence of charring (complete grey appearance on trunks)
Fuel Layer	**Fuel Hazard Score (FHS):** ***Description of the intermediate trees bark type and bark fuel.***				
	0	1	2	3	4
Intermediate Tree Canopy Bark	Absent	- stringybark where bark is well charred and tightly held on whole trunk - ironbarks with very tight, platy or fibrous bark -smooth barks, which do not produce long ribbons of bark	- stringybark where most of bark is black on the lower trunk - few pieces of bark are loosely attached to trunks - bloodwood with tight fibrous bark which has not been burnt for many years - smooth / candle bark which shed long ribbons of bark but have smooth bark down to ground level	- stringybark where <50% of surface area of the trees is black - upper parts of trunk may not be charred - smooth / candle barks with long ribbons of bark which are loose - fibrous or platy bark on lower trunk, which have not been burnt for many years	- stringybark with large flakes of bark can be easily dislodged - huge amounts of bark are available for spotting - outer bark on the trees is attached weakly - minimal evidence of charring (complete grey appearance on trunks)

Fuel Layer	**Fuel Hazard Score (FHS):** ***Description of fuel density and morphological development of plants.***				
	0	1	2	3	4
Elevated Fuel Layer (*record height*)	Absent	- easy to walk through, but vegetation does brush against legs occasionally - elevated material is sparse/dispersed - dead material is virtually absent - sparse shrub vegetation	- moderate easy to walk through, but brush against or step over vegetation most of the time - proportion of dead material is <20% - not much fine fuel present at base of shrubs	- difficult to walk through, need to carefully select path or step high - proportion of dead material is 20-50%	- very difficult to see where you are walking, need to use arm to push through vegetation up to 3 m tall - plants are senescent - high proportion of dead material >50% - very fine fuel present from top to bottom of the vegetation
Fuel Layer	**Fuel Hazard Score (FHS):** ***Description of accumulation and bulk density changes of the near-surface fuel layer.***				
	0	1	2	3	4
Near-surface Fuel Layer (*record height*)	Absent	- near-surface fuel material is sparse/dispersed - dead material is virtually absent - sparse vegetation less than 0.2 mm	- scattered suspended leaves, twigs and bark - proportion of dead material is <20%	- scattered suspend leaves, twigs and bark - proportion of dead material is 20–50%	- large amounts of leaves, twigs and bark suspended in the layer - high proportion of dead material >50% - vegetation is senescent
Fuel Layer	**Fuel Development Score (FDS):** ***Description of stages of accession and decomposition of litter fuels.***				
	0	1	2	3	4
Surface Fuel Layer	Absent	- very thin layer of litter on forest floor - litter depth <10 mm	- established litter cover with no signs of decomposition - litter depth 10-20 mm	- established litter cover with decomposition present - litter depth 15-25 mm	- very thick layer of litter on forest floor with a duff layer underneath litter layer - litter depth >25 mm

Table 3

Symbols for variable used in analysis.

Symbol	**Variable**
Nomenclature	
n	Number of samples or observations
LS	Low shrub
TS	Tall shrub
FHS	Fuel hazard score
PCS	Percent cover score
L	Fuel load < 6mm (t ha^{-1}
D	Fuel depth (mm)
H	Fuel height (cm)
BD	Bulk density (kg m^{-3})
subscripts	
s	Surface fuel
sp	Surface fuel profile
ns	Near-surface fuel
sns	Surface and near-surface fuel
e	Elevated fuel
ib	Intermediate trees bark
ic	Intermediate tree canopy
ob	Overstorey trees bark
oc	Overstorey tree canopy

Table 4

Mean and standard deviation (brackets) of fuel variables by fuel age class for low shrub (*LS*) and tall shrub (*TS*) fuel types in dry eucalypt forests.

Fuel type	*LS*				*TS*			
Age Class	1	2	3	4	1	2	3	4
Age (months)	<36	37 – 72	73 – 120	>120	<36	37 – 72	73 – 120	>120
Surface fuel layer								
L_s	4.5	8.3	7.9	11.9	4.6	7.2	9.3	11.4
	(1.8)	(3.5)	(4.1)	(5.8)	(1.9)	(4.0)	(3.9)	(6.9)
D_s	12.0	20.2	18.5	24.4	13.5	19.6	20.2	27.1
	(5.5)	(7.3)	(7.9)	(9.5)	(6.1)	(8.2)	(7.1)	(11.6)
BD_s	44.0	44.4	47.6	54.6	37.3	38.4	48.0	42.9
	(22.6)	(20.1)	(2.76)	(33.6)	(18.6)	(15.8)	(17.7)	(17.6)
FHS_s	1.9	3.0	2.8	3.5	1.7	3.0	3.0	3.4
	(0.8)	(0.5)	(0.6)	(0.5)	(0.6)	(0.5)	(0.5)	(0.6)
PCS_s	2.2	3.4	3.2	3.7	2.7	3.5	3.5	3.8
	(0.8)	(0.7)	(0.8)	(0.5)	(0.8)	(0.6)	(0.7)	(0.6)
Near-surface layer								
L_{ns}	2.8	5.3	6.1	7.3	3.4	4.7	6.1	7.8
	(1.8)	(3.6)	(4.7)	(5.1)	(2.1)	(3.4)	(4.2)	(5.5)
H_{ns}	9.4	15.8	15.2	16.2	14.2	17.7	21.2	22.8
	(3.7)	(6.0)	(5.9)	(5.5)	(4.7)	(5.9)	(6.9)	(6.5)
BD_{ns}	6.5	7.1	9.4	9.2	5.6	5.9	6.6	7.5
	(3.3)	(3.2)	(4.5)	(4.4)	(1.9)	(2.5)	(2.5)	(3.2)
L_{sns}	5.2	10.0	13.0	13.8	7.6	10.0	13.4	10.4
	(1.9)	(3.3)	(5.0)	(5.3)	(2.2)	(3.9)	(4.9)	(6.6)
BD_{sns}	6.5	7.1	9.4	9.2	5.6	5.9	5.5	7.5
	(3.3)	(3.2)	(4.5)	(4.4)	(1.9)	(2.5)	(2.5)	(3.2)
FHS_{ns}	0.7	1.9	2.2	2.6	0.9	2.3	2.8	3.1
	(0.7)	(0.7)	(0.5)	(0.7)	(0.9)	(0.6)	(0.6)	(0.5)
PCS_{ns}	0.6	1.4	1.8	1.8	0.7	1.7	2.1	2.3
	(0.6)	(0.7)	(0.6)	(0.6)	(0.8)	(0.8)	(0.7)	(0.7)
Elevated fuel layer								
H_e	47.3	62.0	57.3	47.7	71.4	109.3	124.0	145.5
	(22.5)	(28.1)	(25.5)	(15.4)	(20.2)	(32.9)	(43.8)	(47.9)
FHS_e	1.3	2.0	2.1	2.2	1.4	2.3	2.4	2.7
	(0.4)	(0.6)	(0.4)	(0.4)	(0.5)	(0.5)	(0.6)	(0.6)
PCS_e	1.6	1.9	2.1	1.8	2.0	2.4	2.2	2.2
	(0.6)	(0.6)	(0.6)	(0.5)	(0.6)	(0.7)	(0.7)	(0.7)
Intermediate canopy layer								
FHS_{ib}	1.5	2.0	2.2	2.7	1.3	2.2	2.3	2.6
	(0.5)	(0.6)	(0.8)	(0.8)	(0.5)	(0.4)	(0.7)	(0.6)
PCS_{ic}	1.4	1.5	1.6	1.6	1.7	1.8	1.5	1.8
	(0.6)	(0.6)	(0.7)	(0.7)	(0.6)	(0.7)	(0.7)	(0.7)
Overstorey canopy layer								
FHS_{ob}	1.6	2.2	2.0	3.1	1.3	1.9	2.2	2.3
	(0.5)	(0.6)	(0.4)	(0.5)	(0.6)	(0.6)	(0.7)	(0.8)
PCS_{oc}	1.8	1.7	1.6	1.8	1.4	1.2	1.3	1.3
	(0.6)	(0.6)	(0.6)	(0.7)	(0.6)	(0.6)	(0.6)	(0.7)

Table 5

Asterisk (*) identified the pairwise fuel variable means not significantly different at 95 percent confidence by Tukey's HSD method by fuel age classes between and within fuel types.

	L_s	D_s	BD_s	FHS_s	PCS_s	L_{ns}	H_{ns}	BD_{ns}	FHS_{ns}	PCS_{ns}	H_e	FHS_e	PCS_e	FHS_{ib}	PCS_{ic}	FHS_{ob}	PCS_{oc}
1(*LS*) - 1(*TS*)	*	*		*		*		*		*		*		*			
1(*LS*) - 2(*LS*)			*					*							*		*
1(*LS*) - 2(*TS*)						*		*									
1(*LS*) - 3(*LS*)			*								*				*		*
1(*LS*) -3(*TS*)			*					*							*		
1(*LS*) - 4(*LS*)											*				*		*
1(*LS*) - 4(*TS*)			*					*									
1(*TS*) - 2(*LS*)							*				*		*				
1(*TS*) - 2(*TS*)			*			*		*							*		
1(*TS*) - 3(*LS*)							*						*		*		
1(*TS*) - 3(*TS*)								*					*		*		*
1(*TS*) - 4(*LS*)															*		
1(*TS*) - 4(*TS*)															*		*
2(*LS*) - 2(*TS*)		*		*		*								*			
2(*LS*) - 3(*LS*)	*	*	*		*	*	*				*	*		*	*	*	*
2(*LS*) - 3(*TS*)	*	*	*	*		*		*							*	*	
2(*LS*) - 4(*LS*)							*						*		*		*
2(*LS*) - 4(*TS*)			*					*								*	
2(*TS*) - 3(*LS*)	*	*							*	*				*	*	*	
2(*TS*) - 3(*TS*)		*		*	*			*				*					
2(*TS*) - 4(*LS*)												*					
2(*TS*) - 4(*TS*)															*		*
3(*LS*) - 3(*TS*)		*	*			*							*	*	*	*	
3(*LS*) - 4(*LS*)						*		*			*	*			*		*
3(*LS*) - 4(*TS*)													*				
3(*TS*) - 4(*LS*)															*		
3(*TS*) - 4(*TS*)													*			*	*
4(*LS*) - 4(*TS*)	*			*	*	*								*			

[1] The samples sizes were unequal; thus theTukey method used was equivalent to what is commonly known as Tukey-Kramer (Kramer 1956) multiple comparison method (SPLUS 2006).

Table 6

Regression equations developed for equation (1) {$f_p = ss$ (1-exp(-k*age)} and equation (2) {f_p= (a*age)/(b+age)} where: *ss*, *k*, *a*, and *b* are estimated regression parameters (std er= standard error) for the low shrub site (*LS*).

	$f_p = ss$ (1-exp(-k*age)								**f_p= (a*age)/(b+age)**							
Fuel parameter (f_p)	**ss**	**s.e.**[a]	**k**	**s.e.**	***R_c^2***[b]	***MBE***[c]	***MAE***[d]	***RSME***[e]	**a**	**s.e.**	**b**	**s.e.**	***R_c^2***	***MBE***	***MAE***	***RSME***
Surface fuel load (t ha^{-1})	13.16	1.25	0.017	0.004	*0.70*	*0.10*	*1.31*	*1.67*	16.11	2.09	53.56	18.79	*0.74*	*0.03*	*1.18*	*1.57*
Surface fuel depth (mm)	24.08	1.35	0.025	0.004	*0.70*	*0.17*	*2.16*	*2.61*	27.86	1.89	30.69	7.43	*0.78*	*0.04*	*1.74*	*2.25*
Surface fuel bulk density (kg m^{-3})	52.95	3.00	0.089	0.040	*0.10*	*0.04*	*6.91*	*8.53*	57.89	4.75	7.81	5.06	*0.24*	*0.31*	*6.68*	*7.87*
Surface fuel hazard score	3.33	0.12	0.035	0.005	*0.79*	*0.01*	*0.23*	*0.27*	3.78	0.19	20.69	4.46	*0.81*	*0.00*	*0.22*	*0.26*
Surface fuel percent cover score	3.69	0.11	0.042	0.005	*0.82*	*0.00*	*0.16*	*0.25*	4.10	0.18	15.62	3.51	*0.78*	*0.00*	*0.22*	*0.28*
Near-surface fuel load (t ha^{-1})	6.20	0.78	0.025	0.009	*0.57*	*0.01*	*0.79*	*1.02*	10.47	1.84	44.35	22.88	*0.66*	*0.01*	*1.02*	*1.21*
Near-surface fuel height (cm)	20.02	2.53	0.035	0.017	*0.32*	*0.01*	*3.82*	*4.65*	22.22	3.92	18.55	15.35	*0.30*	*-0.02*	*3.79*	*4.75*
Near-surface bulk density (kg m^{-3})	4.62	0.35	0.058	0.026	*0.23*	*0.02*	*0.56*	*0.70*	5.30	0.52	13.78	7.50	*0.47*	*0.01*	*0.47*	*0.58*
Surface + near-surface fuel load (t ha^{-1})	16.04	1.2	0.022	0.004	*0.82*	*0.03*	*1.33*	*1.50*	19.14	2.17	39.02	13.82	*0.81*	*-0.02*	*1.29*	*1.52*
Surface + near-surface bulk density (kg m^{-3})	9.09	0.65	0.042	0.014	*0.38*	*0.07*	*0.86*	*1.10*	9.97	0.83	13.48	6.28	*0.55*	*0.01*	*0.73*	*0.93*
Near-surface fuel hazard score	2.81	0.22	0.018	0.004	*0.81*	*-0.01*	*0.27*	*0.31*	3.44	0.40	50.73	16.92	*0.81*	*-0.01*	*0.28*	*0.31*
Near-surface fuel percent cover score	2.01	0.16	0.024	0.005	*0.75*	*-0.01*	*0.22*	*0.25*	2.36	0.29	35.20	14.53	*0.71*	*-0.01*	*0.24*	*0.27*
Elevated fuel height (cm)	--	--	--	--					--	--	--	--				
Elevated fuel hazard score	2.18	0.14	0.038	0.010	*0.53*	*0.01*	*0.23*	*0.27*	2.42	0.21	16.95	7.19	*0.58*	*0.00*	*0.22*	*0.26*
Elevated fuel percent cover score	1.96	0.09	0.103	0.047	*0.09*	*0.00*	*0.17*	*0.25*	2.05	0.14	3.89	3.64	*0.14*	*0.00*	*0.17*	*0.24*
Intermediate bark hazard score	2.97	0.25	0.021	0.004	*0.62*	*0.04*	*0.29*	*0.37*	3.44	0.35	36.85	12.48	*0.72*	*0.01*	*0.25*	*0.32*
Intermediate canopy percent cover score	1.59	0.05	0.182	0.117	*0.02*	*0.00*	*0.10*	*0.14*	1.64	0.07	2.15	2.11	*0.11*	*0.00*	*0.10*	*0.13*
Overstorey bark hazard score	3.15	0.28	0.019	0.005	*0.58*	*0.05*	*0.34*	*0.41*	3.63	0.39	39.58	13.51	*0.71*	*0.02*	*0.28*	*0.34*

[a]s.e.= standard error, [b]R_c^2= conditional R^2 (Haung *et al.* 2009), [c]MBE= mean bias error, [d]MAE= Absolute error, [e]RMSE- root mean squared error (Willmott (1982)

Table 7

Regression equations developed for equation (1) {f_p = *ss* (1-exp(-*k**age)} and equation (2) {f_p= (*a**age)/(*b*+age)} where: *ss*, *k*, *a*, and *b* are estimated regression parameters (std er= standard error) for tall shrub site (*TS*).

	f_p = *ss* (1-exp(-*k**age)								f_p= (*a**age)/(*b*+age)							
Fuel parameter (f_p)	**ss**	**s.e.**[a]	**k**	**s.e.**	R_c^2 [b]	*MBE*[c]	*MAE*[d]	*RSME*[e]	**a**	**s.e.**	**b**	**s.e.**	R_c^2	*MBE*	*MAE*	*RSME*
Surface fuel load (t ha^{-1})	12.36	0.83	0.014	0.002	*0.92*	*0.03*	*0.64*	*0.72*	16.90	1.65	86.36	18.41	*0.92*	*0.01*	*0.61*	*0.71*
Surface fuel depth (mm)	26.40	1.89	0.020	0.004	*0.74*	*0.11*	*2.26*	*2.53*	32.91	3.27	47.92	13.70	*0.79*	*0.05*	*1.92*	*2.27*
Surface fuel bulk density (kg m^{-3})	34.53	1.69	0.056	0.014	*0.27*	*0.05*	*3.12*	*4.34*	46.62	2.83	8.38	4.37	*0.33*	*0.00*	*3.11*	*4.17*
Surface fuel hazard score	3.39	0.11	0.030	0.004	*0.86*	*0.00*	*0.18*	*0.21*	4.03	0.23	27.93	6.22	*0.84*	*-0.01*	*0.19*	*0.23*
Surface fuel percent cover score	3.67	0.06	0.051	0.005	*0.81*	*0.00*	*0.14*	*0.16*	4.01	0.13	10.79	2.55	*0.88*	*0.00*	*0.14*	*0.18*
Near-surface fuel load (t ha^{-1})	9.08	1.48	0.012	0.004	*0.81*	*0.08*	*0.71*	*0.80*	12.42	2.62	102.84	43.99	*0.83*	*0.05*	*0.66*	*0.76*
Near-surface fuel height (cm)	23.33	1.48	0.025	0.005	*0.77*	*0.09*	*1.66*	*1.98*	28.11	2.52	33.84	10.29	*0.82*	*0.03*	*1.33*	*1.78*
Near-surface bulk density (kg m^{-3})	3.34	0.22	0.046	0.015	*0.29*	*0.01*	*0.32*	*0.42*	3.80	0.35	15.53	7.59	*0.50*	*0.01*	*0.28*	*0.35*
Surface + near-surface fuel load (t ha^{-1})	17.66	2.31	0.014	0.004	*0.80*	*0.16*	*1.44*	*1.60*	23.47	4.12	81.08	31.87	*0.82*	*0.09*	*1.34*	*1.50*
Surface + near-surface bulk density (kg m^{-3})	9.92	0.31	0.057	0.016	*0.32*	*0.01*	*0.54*	*0.65*	7.72	0.43	11.58	4.22	*0.62*	*0.00*	*0.39*	*0.48*
Near-surface fuel hazard score	2.95	0.31	0.022	0.007	*0.72*	*-0.29*	*0.33*	*0.42*	3.77	0.72	48.93	27.74	*0.67*	*-0.02*	*0.35*	*0.45*
Near-surface fuel percent cover score	2.67	0.27	0.014	0.003	*0.90*	*-0.02*	*0.15*	*0.20*	3.71	0.62	85.34	31.31	*0.89*	*-0.02*	*0.16*	*0.21*
Elevated fuel height (cm)	148.1	6.87	0.022	0.003	*0.91*	*0.44*	*6.30*	*8.06*	184.4	11.07	43.67	7.82	*0.94*	*0.07*	*5.15*	*6.66*
Elevated fuel hazard score	2.62	0.12	0.028	0.004	*0.88*	*-0.01*	*0.14*	*0.17*	3.17	0.24	31.57	8.53	*0.86*	*0.00*	*0.16*	*0.17*
Elevated fuel percent cover score	2.26	0.53	0.092	0.022	*0.31*	*0.00*	*0.11*	*0.12*	2.33	0.09	3.10	2.20	*0.26*	*0.00*	*0.11*	*0.12*
Intermediate bark hazard score	2.80	0.13	0.023	0.003	*0.91*	*0.00*	*0.14*	*0.16*	3.50	0.23	42.48	8.41	*0.93*	*0.00*	*0.13*	*0.14*
Intermediate canopy percent cover score	1.78	0.07	0.142	0.136	*0.01*	*0.00*	*0.13*	*0.18*	1.80	0.12	0.945	3.45	*0.01*	*0.00*	*0.12*	*0.18*
Overstorey bark hazard score	2.41	0.13	0.026	0.005	*0.85*	*0.00*	*0.12*	*0.17*	2.93	0.24	34.18	9.42	*0.86*	*0.00*	*0.12*	*0.17*

[a]s.e.= standard error, [b]R_c^2= conditional R^2 (Haung *et al.* 2009), [c]MBE= mean bias error, [d]MAE= Absolute error, [e]RMSE- root mean squared error (Willmott (1982)

Figures

Fig. 1. Location of Dee Vee (Low Shrub- *LS*) and McCorkhill (Tall Shrub- *TS*) study sites in southwest forest regions of Western Australia.

Fig. 2. Different fuel layers within a dry eucalypt forest that can be identified visually. The grey scale on the left side indicates the relative bulk density of each layer.

Fig 3. Box-and whisker plots of the surface fuel load distribution by fuel ages and fuel type a) *LS* and b) *TS* sites. The boxes are the fuel age groupings into four fuel age classes The box-and-whisker plot shows the median value, 75^{th} and 25^{th} quartiles (i.e., 50% of the cases have values within the box), outer fences indicate the extend of the data beyond quartiles, and outlines (solid dots with line).

Fig. 4. Comparison of the two nonlinear models (Tables 6 & 7) for surface fuel load (a & b), near-surface fuel hazard score (c & d), elevated fuel height (e & f) and overstorey bark hazard score (g & h) for the *LS* and *TS* sites. Error bars indicate 1 standard error of the mean. Fig 4e at the *LS* site equations was not fitted.

Fig 5. Accumulation of mean load (<6mm) (5a) and change in fuel hazard scores of the surface fuel layer in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

Fig. 6. Change in fuel percent cover score (a) and accumulation of mean fuel load (<6mm) (b) of the near-surface fuel layer in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

Fig. 7. Accumulation of height (a) and changes in fuel hazard score (b) of the near-surface layer in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

Fig. 8. Changes in elevated fuel (a) percent cover score and (b) fuel hazard score in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

Fig. 9. Change in (a) intermediate trees and (b) overstorey trees bark hazard in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

Figures

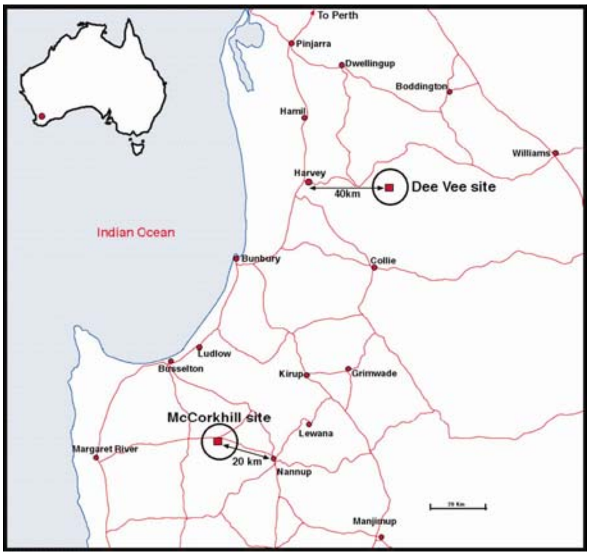


Fig. 1. Location of Dee Vee (Low Shrub- *LS*) and McCorkhill (Tall Shrub- *TS*) study sites in southwest forest regions of Western Australia.

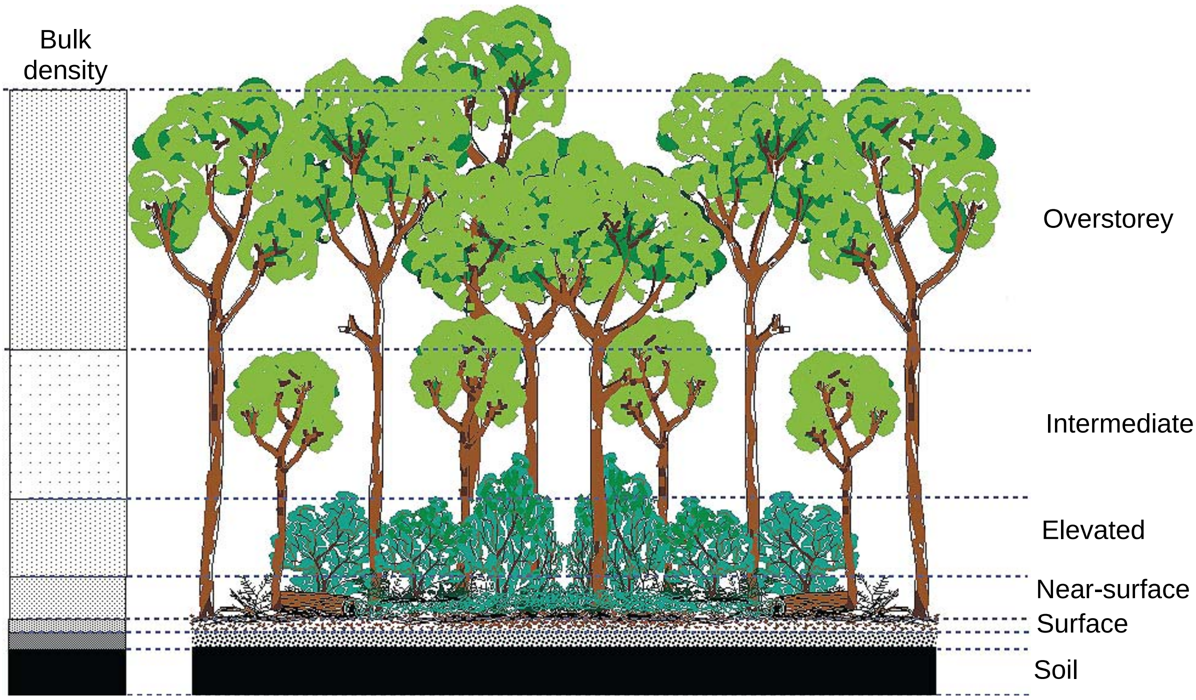
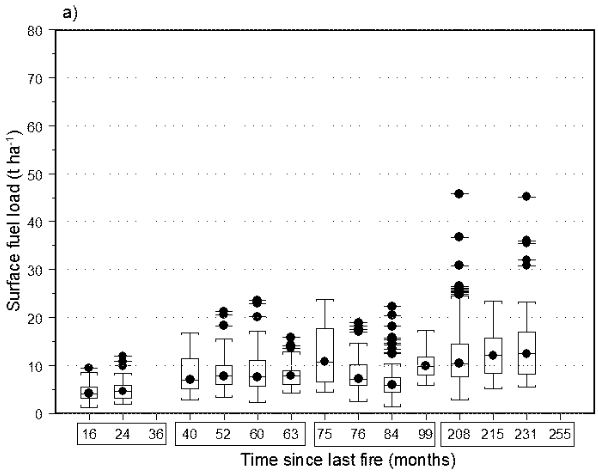


Fig. 2. Different fuel layers within a dry eucalypt forest that can be identified visually. The grey scale on the left side indicates the relative bulk density of each layer.



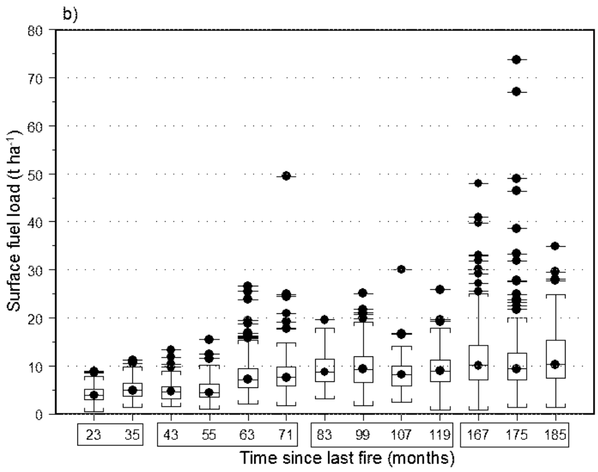


Fig 3. Box-and-whisker plots of the surface fuel load distribution by fuel ages and fuel type a) *LS* and b) *TS* sites. The boxes are the fuel age groupings into four fuel age classes The box-and-whisker plot shows the median value, 75th and 25th quartiles (i.e., 50% of the cases have values within the box), outer fences indicate the extend of the data beyond quartiles, and outlines (solid dots with horizontal bar).

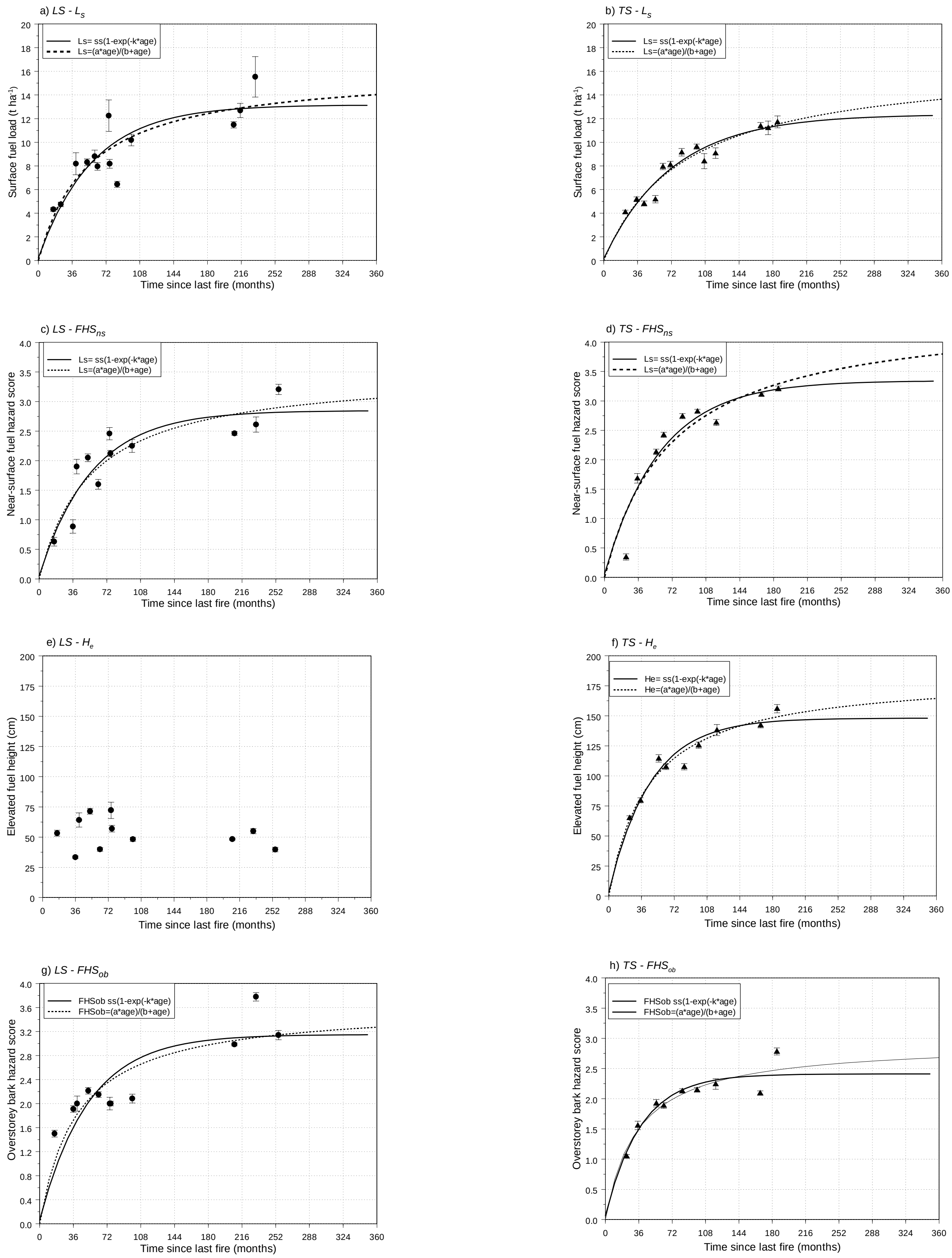


Fig. 4. Comparison of the two nonlinear models (Tables 6 & 7) for surface fuel load (a & b), near-surface fuel hazard score (c & d), elevated fuel height (e & f) and overstorey bark hazard score (g & h) for the *LS* and *TS* sites. Error bars indicate ±1 standard error of the mean. Fig 4e at the *LS* site equations was not fitted.

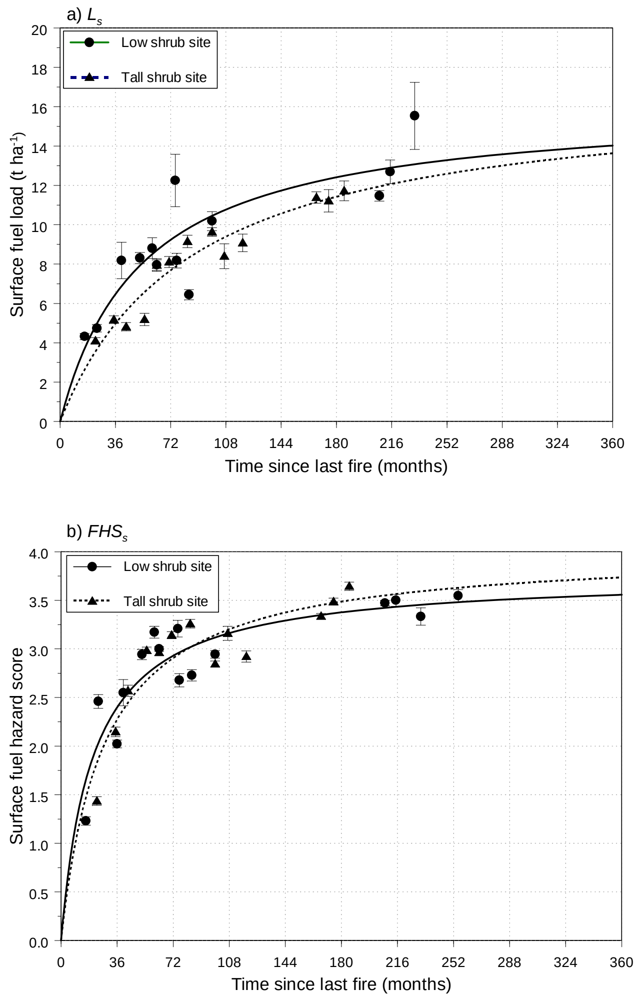


Fig 5. Accumulation of mean load (<6mm) (a) and change in fuel hazard scores (b) of the surface fuel layer in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

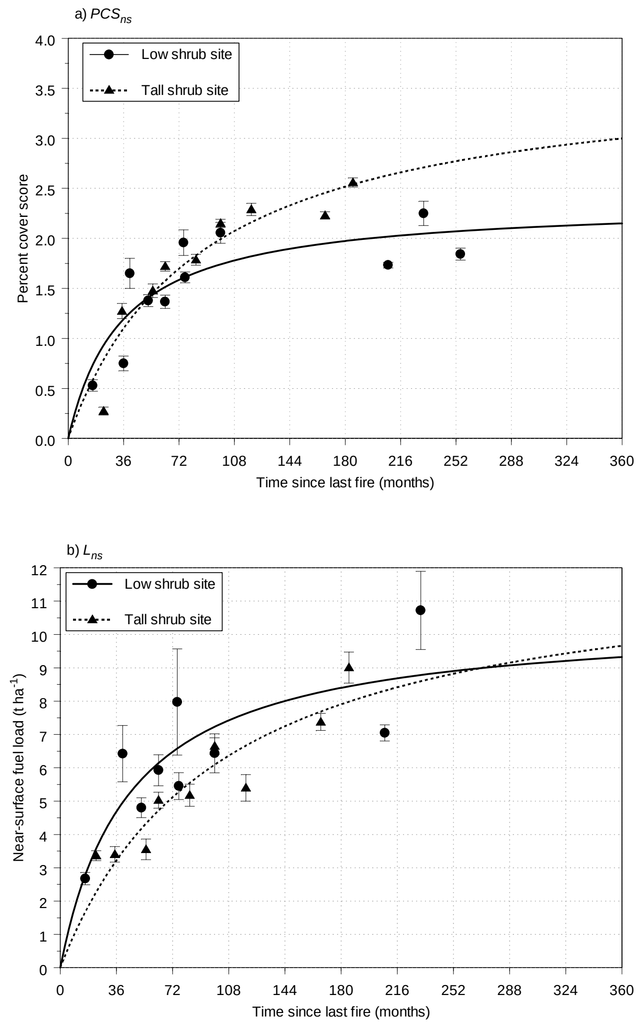


Fig. 6. Change in fuel percent cover score (a) and accumulation of mean fuel load (<6mm) (b) of the near-surface fuel layer in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

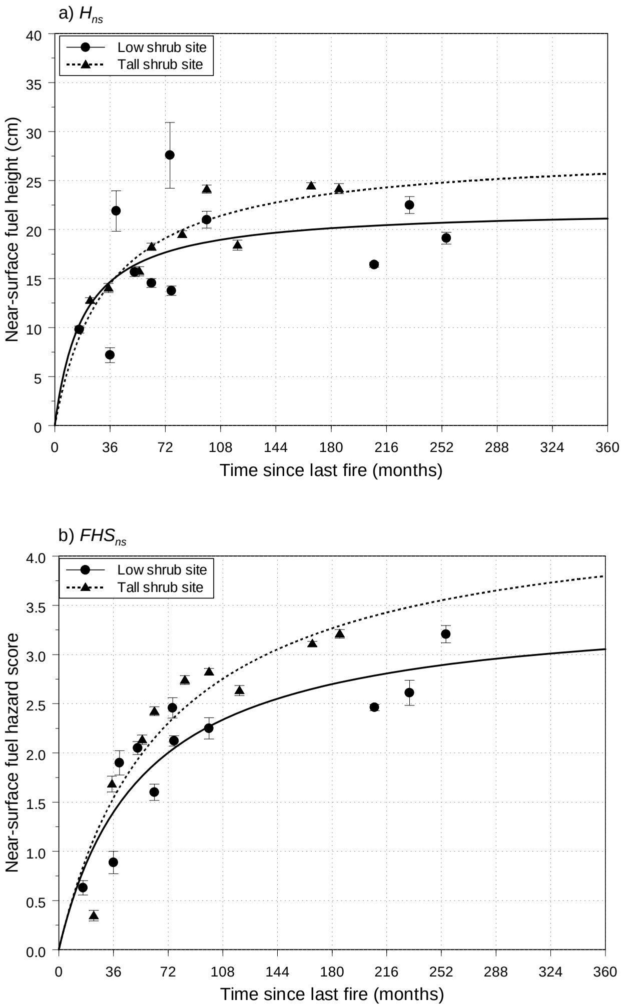


Fig. 7. Accumulation of height (a) and changes in fuel hazard score (b) of the near-surface layer in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

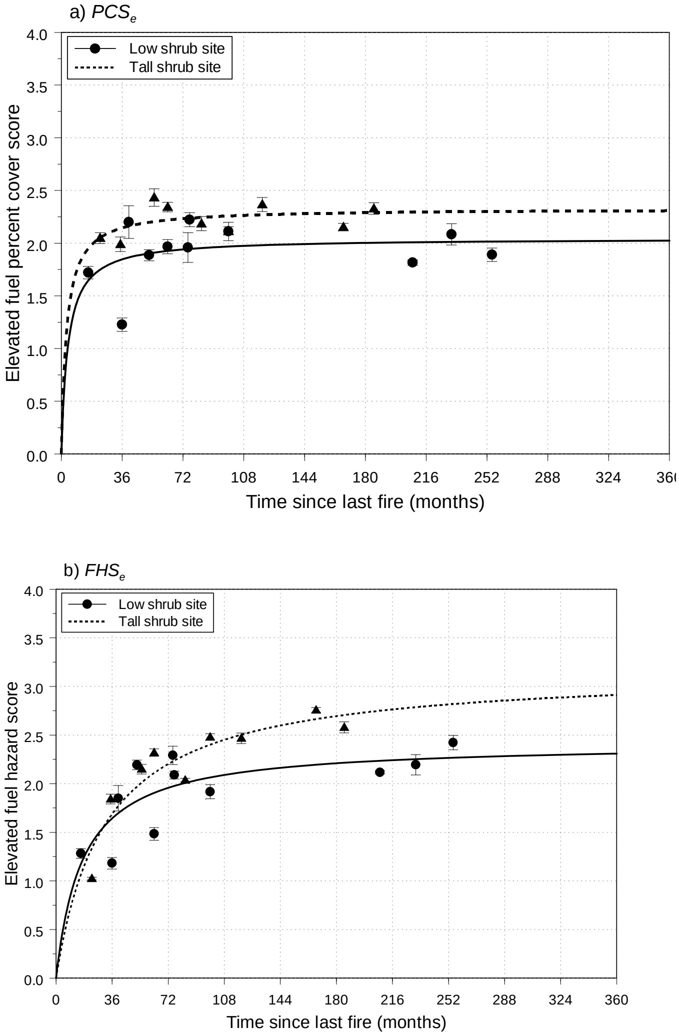


Fig. 8. Changes in elevated fuel (a) percent cover score and (b) fuel hazard score in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).

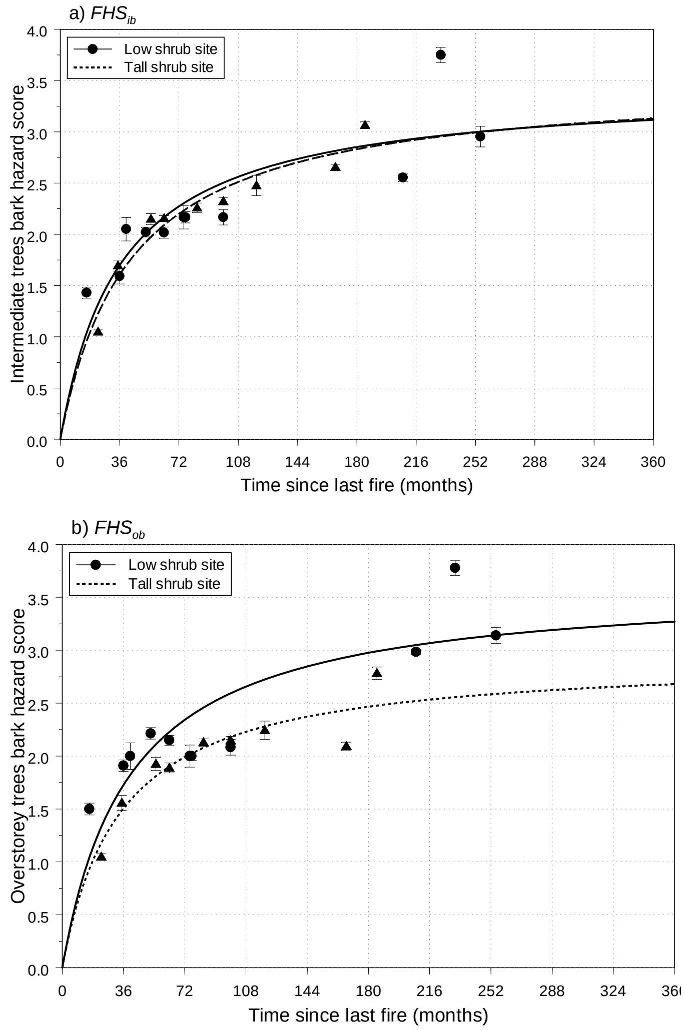


Fig. 9. Change in (a) intermediate trees and (b) overstorey trees bark hazard in areas of different age fuel after burning at *LS* and *TS* sites (Curves for equation (2) f_p = (a*age)/(b+age) in Tables 6 & 7 and error bars indicate 1 standard error of the mean).