A NEW FUEL LOAD MODEL FOR EUCALYPT FORESTS IN SOUTHEAST QUEENSLAND

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Abstract
Fires, whether wild or prescribed, exhibit a dominating influence on the Australian landscape. Land managers are required to develop and implement fire management plans in order to contend with the complex requirements of life and property protection as well the ecological needs of the fire-adapted landscape. Land managers in southeast Queensland rely upon fuel growth models and hazard assessment guides developed in other regions of Australia and the reliability of these guides has not been thoroughly tested. Fuel Accumulation models are to estimate and predict fuel quantities worldwide. Linear models were developed for *Eucalyptus racemosa* open woodland and *Eucalyptus major/Corymbia citriodora* open forest types. The linear regression model suggests that time since fire, fuel depth and foliage projective cover are reliable predictors of surface fuel quantity and they can independently explain a total of 68% of the variation within the data set. The most reliable model for *E. racemosa* open woodland was y = (0.286) Fuel Depth + (0.321) Time Since Fire + (0.100) Foliage Projective Cover. The variation in the data also suggests that fuel is related to other factors other than those measured here. Overall, this model provides useful guidance on the development of fine fuels in eucalypt forests of southeast Queensland, but more extensive testing of the model is needed.

Additional Keywords: Fuel load, ecological fire, land management, southeast Queensland.

Introduction
Fuel accumulation models are used to estimate and predict fuel quantities worldwide (Anderson 1982, Conroy 1993). They are now considered to be an essential part of the decision making process and are widely used by land management agencies (McCarthy *et al.* 1999). Fuel accumulation is a result of many separate and related influencing factors and as such, are complex systems that are difficult to completely explain (Gill 1997). The total fuel load will depend on the rates of accession and decomposition of litter (Conroy 1993, Chatto 1996). This is further reliant on the vegetation type, productivity of the overstorey and understorey, the density of the vegetation and environmental conditions of the area (Millar & Urban 2000).

The rates of fuel accumulation in Australian dry sclerophyllous vegetation are known to be low by world comparison (Pressland 1982, Chatto 1996). Studies (Raison *et al.* 1983, Simmons & Adams 1986, Fogarty 1993) have indicated that in eucalypt-dominated forests, the bulk density of fuel accumulates for the first 4-5 years post-fire after which, it remains steady as invertebrate fauna return and equilibrium between litterfall and decomposition is achieved (York 1999, Brookes *et al.* 2004). A select example of the accumulation within dry-eucalypt ecosystems is provided in Table 1.

Table 1 Summary of fuel loads obtained from other studies in eucalypt communities Australia (sources provided)

Location	Vegetation Type	Years Post-fire	Fuel Quantity(t/ha)	Source
Australian Capital Territory	*E. rossi / E. macrorhyncha*	5.6	13.5	Davis 1976
		30	15.0	
Kosciusko, NSW	*E. pauciflora*	3.0	6.6	Gill *et al.* 1976
		36	12.2	
Wombat Forest, VIC	*E. obliqua / E. radiata / E. rubida*	3-10	15.8	Tolhurst & Kelly 2003
		> 20	18.2	
Sydney, NSW	Eucalyptus woodlands	0.1	6.7	Conroy 1993
		1.3	6.9	
		3-6	15.2	
		6-10	18.3	
		10-20	22.4	
		> 20	22.4	

In dry sclerophyll forests, it was found that areas with a canopy cover of 50% or above, the build up in fuel load is relatively swift for the first 10 years, reaching an equilibrium fuel load of about 15 t/ha (Brookes *et al.* 2004). Conversely, in areas with a well-developed understorey, fuel loads can continue to increase for over 25 years (Tolhurst & Cheney 1999). Comparatively, in wet sclerophyll forests, fuel can build up for over 30 years before reaching any level of equilibrium (Guinto *et al.* 1999).

Fuel accumulation models based on this type of scientific research are an essential land manager's tool helping to realistically estimate and predict potential fire behaviour. More importantly, fuel accumulation models can assist in determining when land management practices such as hazard reduction are applied. The most commonly used model for fuel accumulation is Olson's (1963) negative exponential model to quantify litter accumulation and it has since been used as a descriptor of fuel accumulation (Sandercoe 1990). The model was developed based on data obtained from Northern America, providing a method of predicting litterfall in the natural environment by describing an asymptotic relationship between litterfall and decomposition rate using the following equation:

$$X_t = X_{ss}\,(1-e^{-kt})$$

Where: X_t = weight of fine fuel per unit area t years after fire
X_{ss} = weight of fine fuel accumulated under steady state conditions
k = decomposition constant (yr^{-1})
t = time since fire (yr)

It must be noted that, although fuel accumulation in eucalypt forests can be described using this equation, it is an oversimplification of the factors that can affect fuel accumulation and as such has been modified to reflect local conditions on a number of occasions as outlined below in Table 2 (Conroy 1993, Fernandes & Botelho 2003).

Table 2 Summary of fuel accumulation models derived from studies in Australian Eucalypt forests.

Dominant Vegetation	Site Location	Rainfall (mm)	Model	Source
E. pilularis	Seal Rocks, NSW	1400	$X_t = 1.67\,(1-e^{-0.31t})$	Fox *et al.* 1979
Eucalypt woodlands	Sydney, NSW	—	$X_t = 23.57(1-e^{(-0.2774t)})$	Conroy, 1993
E. obliqua, *E. radiata,* *E. rubida*	Wombat State Forest, Victoria	—	$X_t = 8.28\,(1.47-e^{-0.506t})$	Tolhurst & Kelly, 2003
E. obliqua, *E. radiata,* Other euclaypt species	Victoria, Australia	700	$X_t = 16.9\,(1-e^{-0.44t})$	Simmons & Adams, 1983
E. pauciflora *E. dives* *E. delegatensis*	Unspecified sub-alpine region in Australia	—	 $X_t = 11.1(1-e^{0.11t})$ $X_t = 29.4\,(1-e^{0.31t})$	Raison *et al.* 1983
Eucalyptus crebra *Eucalyptus moluccana* *Eucalyptus macrorhyncra*	Chiltern, VIC	685	$X_t = 7.15\,(1-e^{-0.876t})$	Chatto, 1996
Eucalyptus signata	Cooloola, QLD	—	$X_t = 7.3\,(1-e^{-0.64t})$	Sandercoe 1990

It is interesting to note that the decomposition constants are fairly consistent across eastern Australia even though there are large variations in climatic conditions, vegetation and rates of accumulation.

A continuous litter fall model adopted by Fox *et al.* (1979) has been suggested to better suit Australian conditions. Fox *et al.* (1979) states that, in eucalypt forests, an accumulation model using two parameters; (1) steady-state accumulation and (2) the rate of accumulation, should be sufficient to describe litter accumulation. Following these studies, Fogarty (1993), Conroy (1993) have found that the assumptions of Olson's (1963) model of constant litter fall and decomposition rates over time are often not met in eucalypt forests in Australia because these forests have complex age structures that vary due to season, temperature and rainfall. The assumed constant value of k can be argued to be erroneous in itself, as it is known that decomposition rates fluctuate over time (Walker 1981, Raison *et al.* 1983). However, if the other factors are known, the decomposition constant can then be enumerated.

Two predictive models were developed by McCarthy & Tolhurst (2001) based on the Fire Danger Index (FDI) and overall fuel hazard. Both models predict that as fire danger increases the benefits of a previous fuel reduction burn starts to reduce (Tolhurst *et al.* 1992). McCarthy & Tolhurst (2001) predicted that a fuel reduction burn will only play a role in helping to reduce the severity of the fire and in assisting fire fighters with suppression for the first 4 years post-burn. This research has led to fire management strategies involving the manipulation of fuel and frequency of fire. Even so, as previously mentioned, these models are based on site specific conditions, which are as yet undetermined for southeast Queensland. The purpose of this study is to investigate fuel accumulation in two different vegetation types , *Eucalyptus racemosa* open woodland and *Eucalyptus major/Corymbia citriodora* open forest and to develop a predictive model with which to estimate surface fine fuel loads for these vegetation types.

Methods

Redland Shire consists of three distinctive regions, the mainland, southern Moreton Bay Islands and North Stradbroke Island. It is bordered by the Pacific Ocean to the east, the city of Brisbane to the north and west and Logan City to the south. The mainland area consists of extant vegetation communities that are mostly open forests or woodlands with occasional closed forests and wetlands (LAMR 2001). Much like the other areas in southeast Queensland, the Redland Shire experiences a sub-tropical climate, with temperatures ranging from 11-28 degrees Celsius for most of the year (BOM 2005, RSC 2005). The mean rainfall for the area is 1322 mm, with the October-April season being wetter than that of May-September (BOM 2005). Prevailing winds generally come from the south-east (RSC 2005). Fieldwork was conducted in the study area was between March and September 2005. This study was undertaken in the *Eucalyptus major/Corymbia citriodora* open forests and *Eucalyptus racemosa* open woodlands of mainland Redland Shire. The two major vegetation types examined in this study are;

***Eucalyptus major/ Corymbia citriodora* open forest**

Occupying 1744 ha of undulating country in the west, this vegetation type was dominated by *Eucalyptus major* and *Corymbia citriodora* with associations with individuals of *E. fibrosa*, *E. microcorys*, *E. resinifera*, *E. seeana*, and *E. siderophloia* (LAMR 2001). In the grassy understorey, the flora species consisted of predominantly *Cymbopogon refractus*, *Ottochloa gracillima* and *Themeda triandra* (LAMR 2001). Shrubby understoreys were also evident and consisted of *Acacia spp.*, *Pultanea spp*. *Leptospermum polygalyfolium*, *Jacksonia scoparia* and *Westringia eremicola* (LAMR 2001).

***Eucalyptus racemosa* open woodland**

This vegetation type occur on red-yellow podzolics on low hills of sedimentary rocks and metasedimentary substrates and covered 1450 ha of the study area (LAMR 2001). *Eucalyptus racemosa* predominates these communities with occasional individuals of *E. fibrosa*, *E microcorys*, *E. seeana*, *E. siderophloia*, and *E. tereticornis* (LAMR 2001). Understoreys ranged from grassland through to shrubby dominated by *Banksia spp.*, *Hakea florulenta*, *Hibbertia stricta*, *Hovea acutifolia*, *Melaleuca sieberi* and *Pultanea villosa*. Understoreys, including herbaceous species such as *Cyperus exaltus*, *Fimbristylis spp.*, *Goodenia rotundifolia*, *Juncus usitatus* and *Viola hederacea* were common, as were those consisting of *Gahnia aspera*, *Dianella caerulea* and *Lomandra longifolia* (LAMR 2001).

Sampling sites were selected based on five criteria, these are; level of disturbance, known fire age, canopy class, topography &and soils, and accessibility.

Once selected each site was described in terms of its basic physical, spatial and vegetation characteristics. A list of observable vascular plants was recorded, along with details of foliage projective cover (FPC) and any other notable features that distinguished sites from others (i.e. changes in slope or aspect). The FPC was calculated using the method outlined in Stock (2005) and Zancola *et al.* (2000) whereby digital photographs were taken of the canopy and converted into black and white pixels by using the Imagepro (v3) computer program (Hacker 2001). The ratio of black to white pixels indicated the percentage foliar cover at each sampling point. Rainfall data for each site was obtained from the Bureau of Meteorology (BOM) records for Redland Bay. At each site the average rainfall was taken for the year following the most recent fire event.

Five columnar quadrats of 0.5 m^2 at each sampling site were taken. The column extended 0.5 m above the ground to include near surface fine fuels i.e. small shrubs, grasses and sedges (Figure 1).

Figure 1 Photograph of 0.5 m quadrat used to take fuel samples. (Photo: J. Gilroy)

The protocol for distributing the quadrats within the site involved firstly determining the size of the site. The first sampling point was selected by moving 20 meters into the site away from the edge of a track or road reducing edge effects. The sampling quadrat was then randomly thrown towards the centre of the site. From this point, the subsequent sampling points were taken along a line transect at 50 m intervals. The fuel collected was limited to the finer materials (up to 6 mm diameter for dead vegetation and 2 mm for live vegetation), or 'flash fuels', which have been shown in studies to be the key component of the total biomass capable of supporting a fire front (Walker 1981, Tolhurst & Cheney 1999). For each quadrat sampled, the fuel load was divided into four categories.

1) Leaves (including grass),
2) Twigs,
3) Bark,
4) Residual (includes flowers, fruiting bodies and semi-decomposed leaf, twig and bark material and any other unidentifiable material).

The perimeter of the inside of the quadrat was cut using secateurs, including that of grasses and plants growing within the quadrat. All surface fine fuel within the quadrat was then transferred into labeled paper bags for oven drying, weighing and sorting. The samples transferred into paper bags for oven drying at 70^0C for 72 hours. To avoid contamination and spillage Detpak© brown paper bags were used to dry samples as the paper allows passage of water vapour through the walls of a sealed bags. After drying, samples were re-weighed. Samples were weighed immediately, as they are able to take up atmospheric moisture at a rate of 0.02 g s^{-1} (Bresnehan 1998). Each sample bag is weighed first and then immediately emptied and the empty bag weighed. The net dry sample weight is obtained by taking the difference between the initial wet and final dry weight.

Data analysis

Multiple regression analysis
Preliminary data analysis indicated any potential linear relationships between fuel quantity and the other variable. Multiple regression analysis was used to examine the relationship between fuel quantity and time since fire, foliage projective cover, rainfall (1 year post-fire) and fuel depth.

Results

Surface Fine Fuel Characteristics

A total of 145 surface fine fuel samples were taken over the period of the study, 5 from each transect on each occasion. Table 4 provides a summary for each site measured, including the vegetation type, the mean fuel depth, the average surface fine fuel quantity (with standard error) the average foliage projective cover (FPC) and the average annual rainfall (1 year post-fire event) at each site. The data is ordered by the time past since the last fire event. The extent of fire history in this study ranged from 0.8-22 years.

For *Eucalyptus major/Corymbia citriodora* open forest total surface fine fuel loads ranged between 6.32-16.09 t/ha with an overall mean (± S.E.) of 12.44±1.34 t/ha. The individual samples ranged from 4.83-21.93 t/ha with the largest being almost ten times greater than the mean. The variation found within the surface fine fuel load clearly indicates the patchy distribution associated with fuel loads across the study area. It also indicates the unevenness of fuel that can accumulate in areas after a fire event. In this study, low fuels were associated with open canopy areas or near fallen logs whereas higher fuel loads were associated in areas with dense canopy cover and noticeable fuel build up near the base of senescing trees or shrubs. The fuel depth ranged from 8.6-24.95 mm, (mean 18.66±1.78 mm). The deepest fuel bed depth measurement that was taken over the study period was 35 mm.

For *Eucalyptus racemosa* open woodland, the total surface fine fuel loads ranged between 3.77-19.51 t/ha with an overall mean of 11.84±1.58 t/ha. The individual surface fine fuel quantities for this vegetation type ranged between 0.97-33.26 t/ha thereby indicating the great disparate heterogeneity of fuel found within the study area. The fuel depth ranged from 7.4-34 mm averaging 17.03±2.76 mm. The deepest fuel bed depth measurement taken for this vegetation type was 57 mm.

Multiple linear regression techniques

Tables 3 and 4 summarises the output from the multiple linear regression model (from SPSS ® v12). The model suggests that time since fire, fuel depth and FPC are reliable predictors of surface fine fuel quantity and they can independently explain a total of 68% of the variation within the data set (Table 6 & 7). The variation also suggests that fuel is related to other factors other than those measured here. The regression models were subjected to a model fit test based on data residuals. Graphing the residual (*observed minus predicted*) with fire age for each site indicated if the model was consistently over-predicting or under-predicting fuel weight in the accumulation curve.

Table 3 Linear regression models for *E. racemosa* open woodland. Models differ in use of rainfall and logarithm of *time since fire* variable.

***E. racemosa* open woodland**	**Sig.**	**Adjusted R^2**
Model 1: Fuel Load (t/ha) = *x (Time since fire) + y (FPC) + z (Fuel depth) +x_1 (Rainfall Average 1 year post-fire)*	***0.000***	0.692
Model 2: Fuel Load (t/ha) = *x (Time since fire) + y (FPC) + z (Fuel depth)*	***0.000***	0.679
Model 3: Fuel Load (t/ha) = *x (lnTime since fire) + y (FPC) + z (Fuel depth) +x_1 (Rainfall Average 1 year post-fire)*	***0.000***	0.708
Model 4: Fuel Load (t/ha) = *x (lnTime since fire) + y (FPC) + z (Fuel depth)*	***0.000***	0.706

Table 4 Linear Regression data output from SPSS for *E. racemosa* open woodland. NB: Bold coefficients indicate statistically significant contribution to regression model.

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model 1	B	Std. Error	Beta		
(Constant)	3.364	2.122		1.585	.118
Fuel_Depth	**.341**	**.071**	**.423**	**4.795**	**.000**
Time_Since_Fire	**.328**	**.066**	**.415**	**4.994**	**.000**
FPC	**.084**	**.028**	**.243**	**3.036**	**.004**
Rainfall	-.035	.018	-.150	-1.937	.057

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model 2	B	Std. Error	Beta		

(Constant)	-.059	1.200		-.049	.961
Fuel_Depth	**.286**	**.067**	**.355**	**4.293**	**.000**
Time_Since_Fire	**.321**	**.067**	**.406**	**4.789**	**.000**
FPC	**.100**	**.027**	**.291**	**3.728**	**.000**

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model 3	B	Std. Error	Beta		
(Constant)	.764	2.083		.367	.715
Fuel_Depth	**.282**	**.073**	**.350**	**3.844**	**.000**
FPC	**.098**	**.026**	**.284**	**3.733**	**.000**
Ln_Time_Since_Fire	**2.532**	**.466**	**.448**	**5.437**	**.000**
Rainfall	-.021	.018	-.090	-1.185	.241

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model 4	B	Std. Error	Beta		
(Constant)	-1.293	1.155		-1.119	.267
Fuel_Depth	**.243**	**.066**	**.302**	**3.690**	**.000**
FPC	**.106**	**.025**	**.309**	**4.217**	**.000**
Ln_Time_Since_Fire	**2.583**	**.465**	**.457**	**5.554**	**.000**

From the analysis it was found that time since fire accounted for most of the variability in surface fine fuel quantity data. This was closely followed by fuel depth and FPC (Table 4 & 5). Time since fire and fuel depth explained almost one third of the variation in surface fine fuel samples for *E. racemosa* open woodland. The data was also analysed by taking the logarithm of *time since fire*, which improved the model explaining slightly more of the variation. However, on reviewing the residual scatter plots from the untransformed and transformed time since fire, the untransformed data were more uniformly distributed.

Table 5 Parameters which explain the most variation of surface fine fuel.

Parameter	% Variation
Time since fire	32 ($p < 0.000$)
Fuel depth	29 ($p < 0.000$)
Foliage projective cover	10 ($p < 0.000$)

Discussion

Multiple Regression Analysis

Even though the non-linear curve estimation provided a reasonable predictor for fuel load in *E. racemosa* open woodland, the assumption that the model is based on can retard the usefulness of the model. Further, where the negative exponential curve is better suited to actual conditions, multiple regression was also tested. Whilst it is acknowledged that fuel growth does not continue linearly with time, this may be explained in further studies which may examine longer time since fire than was examined in the present study. Until this is completed, the multiple regression model prepared in this study represents the best understanding of fuel growth for *E. racemosa* open woodland and comparable eucalyptus dominated woodlands in southeast Queensland.

The relationship between surface fine fuel quantity and time since fire, fuel depth, foliage projective cover (FPC) and rainfall (1 year post-fire) were investigated to determine if any or all of these parameters could provide a useful and accurate indirect estimation of surface fine fuel quantity. The multiple regression results indicate that fuel depth and foliage projective cover are good predictors of surface fine fuel quantity. Other studies have found that rainfall is strongly correlated with litterfall accumulation rates, as high rainfall is generally associated with higher productivity therefore contributing to the overall fuel quantity (Simmons & Adams 1983, Hutson 1985, Chatto, 1996). However the rainfall analysis used in this study showed that rainfall (one year post-fire) did not contribute significantly to surface fine fuel quantity. Perhaps other measures of rainfall may provide more useful indicators of plant growth and possible fuel development.

In line with previous research (Wilson 1993, McCarthy *et al.* 1999), this study has found a linear relationship between fuel depth and surface fine fuel quantity. It has been noted by several studies (Anderson 1982, McCarthy 1996, Sandberg *et al*. 2001) that fuel depth and structure can directly influence a fire's forward rate of spread and flame height. Chatto (1996) found that 44% of the variation in surface fine fuel quantities could be explained by fuel depth. In this study, 29% of the variation in their study of surface fine fuel quantity was explained by fuel depth. Fuel depth may also be affected by such things as compaction, sandy substrates and the overlying canopy and associated understorey (Tolhurst & Cheney 1999). In this study, it is assumed that these influences have remained relatively constant as specific vegetation types were chosen for sampling of which neither were on sandy substrates and the amount of FPC was measured and included in the analysis. Fuel depth has been used elsewhere in Australian eucalypt communities, (NSW and VIC) to estimate surface fine fuel quantity and this study has confirmed the potential for applicable use of this measurement in southeast Queensland (Fogarty 1993, Chatto 1996, McCarthy *et al.* 1999). In total, the multiple regression analysis explained 67% of the variability in the data. This is a good outcome given the considerable within and between site variation.

There is limited research into the use of foliage projective cover (FPC) as an estimate of surface fine fuel loading in Australia (Brandis & Jacobson 2003). A recent study conducted by Brandis & Jacobson (2003) employs the use of satellite images to determine site productivity, providing an estimate of the surface fine fuel levels. Even though this work provides 'useful' information on fuel loads within a given area, it did not to directly estimate surface fuel and how this is distributed beneath varying levels of canopy cover, which is known to directly affect fire behaviour. Although, the linear regression draws a clear linear association of fuel load and FPC. FPC seems to provide a useful indicator of site productivity (more FPC = more growth = potentially more fuel accumulation).This study has determined that FPC has the potential to be used in conjunction with fuel depth and known fire history to provide a reliable estimate of surface fine fuel loads in *E. racemosa* open woodlands. The ability to take a measure of fuel depth along with FPC and accurately estimate the surface fine fuel load will enable a more accurate estimation without the time-consuming task of collecting, drying and weighing a number of fuel samples. If successfully tested in other area it may be able to estimate the time since fire component at those sites where fire history is unknown or subjective. Further study to determine the applicability of this method is warranted and recommended.

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