A review of fuel load dynamics in Heathlands and Forested Wetlands of New South Wales

A report to the Rural Fire Service of New South Wales

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Executive summary

This report comprises one part of a contract for the Rural Fire Service of NSW project entitled "Development of Fuel Accumulation Curves for Priority Vegetation Communities in NSW". In this first report we review the current literature on fuel accumulation for two priority vegetation formations (Heathlands and Forested Wetlands) to suggest Olson curve fuel parameters for use in Phoenix (or other fuel hazard estimation). In addition to this we also conduct a field survey which quantifies fuel hazard (using the Victorian Department of Sustainability and the Environment's fuel hazard assessment guide) and derives fuel load estimates for two priority vegetation classes falling within the Heathlands and Forested Wetlands vegetation formations: Sydney Coastal Heaths and Coastal Swamp Forests. We do this to suggest Olson curve parameters for fuel hazard scores, and to add to the Olson curve fuel load parameters suggested in our literature review. The report for the second part of the contract addresses methods for assessing fuel loads including preliminary assessments of rapid field and remote sensing techniques and is titled "Survey Methods to Estimate Fuel Parameters in East Australian Forests".

Relatively few studies have quantified fuel loads and fuel accumulation in Heathlands (11 studies) and Forested Wetland (6 studies) vegetation formations when compared with sympatric vegetation formations such as Dry Sclerophyll Forests (see Watson 2012). Sydney Coastal Heath's were the best represented Heathland formation with five studies. No Forested Wetland vegetation class was represented by more than two studies.

For Heathlands, considerable differences in *Limit* and *k* fuel parameters were observed between and within vegetation classes. This indicates that site-specific variables such as topography, geology and / or species-specific growth form influence fuel dynamics at fine spatial-scales. Sydney Coastal Heaths were the best studied Heathland formation and thus provide the most reliable fuel load and fire hazard estimates. Fuel accumulation in Sydney Coastal Heaths is considered below. Rates of litter fall (*L*) and litter accumulation (*k*) were low indicating that standing litter loads and litter fire hazard can only be high in older growth Heaths. Steady state litter fuel loads (*Limit*) and litter accumulation rates (*k*) were higher in Sydney Coastal Heaths than other Heathland vegetation classes located on sandy soils. This presumably occurred because nutrient levels (and hence nutrient cycling) were higher and salt levels (which potentially retard decomposition rates) were lower in Sydney Coastal Heaths. Steady state shrub fuel loads (*Limit*) were higher in Heathlands than sympatric Dry Scherophyll forests. This suggests that elevated fuels are important fuel components in Sydney Coastal Heaths.

For Forested Wetlands, studies were grouped into those sampling temperate coastal waterways or semi-arid inland waterways. Litter fall (*L*) and steady state litter loads (*Limit*) were greater for temperate rather than semi-arid Forested Wetlands, presumably because nutrient levels, nutrient cycling and incidence of inundation by floodwaters were relatively high in temperate Forested Wetlands. No studies suggested *k* values for semi-arid Forested Wetlands. However for temperate Forested Wetlands, litter accumulation (*k*) values were high. Coupled with the factor that *Limit* values in Coastal Swamp Forested were not disproportionately high, this suggests that regular inundation facilitated high rates of litter decay and physically removes litter. Our field survey was the only study to suggest fuel parameters for the litter + herb fuel layer. For this study, steady state litter + herb fuel load (*limit*) and litter accumulation (*k*) values were high when compared with those observed in Sydney Coastal Heaths. This suggests that dense herb stratum fuels are important fuel components in Coastal Swamp Forests, however litter + herb fuels decay quickly. No studies suggested fuel parameters for shrub fuels alone, however our field survey suggested that elevated fuels are a relatively un-important fuel element in Coastal Swamp Forests.

Table 1 shows suggested Olson curve fuel load and fire hazard score parameters for inputs into fire behavior models such as Phoenix. Although many fire behavior models use Olson curve fuel parameter inputs, our literature review and field survey suggested that the Olson curve is a poor predictor of fuel accumulation in some fuel strata. Because of this, we suggest future research be directed towards the use (and development) of fire behavior models which allow user specified fuel accumulation curves for fire behavior predictions.

Table 1. Suggested Olson curve parameters for Heathlandsand Forested Wetlands vegetation formation classes of New South Wales. a) Olson curve parameters for fuel loads in t / ha. b) Olson curve parameters for fuel hazard scores as assessed by the Victorian Department of Sustainability and the Environment's (DSE) fuel hazard assessment guide*Initial* represents fuel loads immediately after a fire. *Limit* represents steady state fuel loads. *k* is a measure of fuel accumulation. All values are for fine fuel < 6 mm.

		Litter			Litter + herb			Shrub		
		Initial	*Limit*	*k*	*Initial*	*Limit*	*k*	*Initial*	*Limit*	*k*
a) Olson curve parameters for fuel loads (t / ha)										
Heathlands	Sydney Coastal Heaths	1.50	22.24	0.06	2.66	23.90	0.07	1.57	13.04	0.15
	Wallum Sand	-	17.86	0.26	-	-	-	-	-	-
	Coastal Headland Heaths		7.87	0.56						
	Northern Montane Heaths	-	6.29	0.18	-	-	-	-	-	-
Forested Wetlands	Coastal Swamp Forests	5.00	20.40	0.37	5.00	27.26	0.25	-	~ 3.75	-
	Coastal Floodplain Wetlands	-	11.32	0.68	-	-	-	-	-	-
	Inland Riverine Floodplains	-	11.48	0.38	-	-	-	-	-	-
b) Olsen curve parameters for fuel hazard scores (DSE fuel hazard assessment guide)										
Heathlands	Sydney Coastal Heaths	0.69	5.00	0.03	2.37	4.24	0.42	2.16	4.87	0.07
Forested Wetlands	Coastal Swamp Forests	1.35	3.22	0.70	3.24	4.41	0.13	-	-	-

Contents

1 Aims and Methods

Here we collate information regarding fuel load accumulation in Heathlands and Forested Wetlands of New South Wales, and suggest fuel parameters for inclusion in fire behavior models and for use in fire management practices. In commissioning this report, the Rural Fire Service (RFS NSW) was specifically interested in fuel accumulation in Sydney Coastal Heaths and Coastal Swamp Forests vegetation classes. This was because Sydney Coastal Heaths and Coastal Swamp Forests often occur on the urban fridge where fire risks human infrastructure and human life, and current fire behavior model used by RFS NSW often under-estimated or over-estimated fire spread for these vegetation classes. Because of this, we present fuel parameters with special reference to Sydney Coastal Heaths and Coastal Swamp Forests.

Fuel accumulation in Australian east coast forests is thought to conform to a negative exponential model (henceforth the Olson curve) whereby full accumulation increases as a function of time-since-fire, fuel input (growth, accumulation) and fuel output (decay, physical exclusion; Olson, 1963, Fox et al., 1979, Fogarty, 1993; Equation 1).

> Equation 1: $W_t = Limit\ (1 - e^{-kt})$; where W_t = fuel load (t / ha), *Limit* = steady state fuel load (t / ha), t = time-since-fire, k = mean annual fuel input (L) / *Limit*.

Since its development in the 1960's, authors have modified this 'Olson curve' to account for fuels left un-burnt immediately following fire (Fensham, 1992, Morrison et al., 1996; Equation 2). If unburnt fuels are not included in fuel accumulation models, fuel loads can be under-estimated, especially in the years immediately following a fire.

> Equation 2: $W_t = Initial + [(Limit - Initial) \times (1 - e^{-kt})]$; where *Initial* = unburnt fuel remaining following fire (t / ha).

Many Government agencies including RFS NSW use fire behavior models such as Phoenix to predict 'on-the-fly' fire behavior during bushfire events, and to map fire risk. To allow broad-scale modelling of fire behavior, such fire behavior models often combine time-since-fire and vegetation class maps to derive fuel load estimates using the Olson curve; vegetation class differences in fuel accumulation, fuel decay and micro-climate influence the trajectory of the Olson curve. Thus, reliable estimates for *Initial*, *Limit* and *k* are required for all mapped vegetation types to apply to the fire behavior models correctly.

The aim of this chapter is to document *Initial*, *Limit*, *L* and *k* fuel parameters for fine fuels < 6 mm to provide parameters for the Phoenix fire behavior model. To do this we have conducted 1) a thorough literature review collating all published studies regarding fuel load accumulation in Heathlands and Forested Wetlands of New South Wales, and 2) a field survey quantify fuel hazard in two priority vegetation classes. The intensity and rate of spread of fire is proportional to the particle size of fuels (Peet, 1965, McArthur, 1967, Luke and McArthur, 1978). Fine fuels < 6 mm are important determinates of fire propagation as they are readily combustible and often well aerated. Courser fuels > 6 mm will burn, however at a much lower intensity than fuels < 6 mm because they are denser and less well aerated. Because of this, fine fuels < 6 mm are typically used in fire behavior models to predict fire spread and fire hazard. Unfortunately, not all studies presented here measured fine fuel loads; many studies used a < 10 mm, < 25 mm or no cut-off point for particle size in their analyses. To standardize fuel loads between studies we have converted all fuel information to represent fine fuels < 6 mm using fuel parameter conversion factors presented in Watson (2012; Table 1.1). To categorize vegetation type, we have used the Keith (2004) vegetation classification system. This system is the '*opus primus*' for vegetation classification in New South Wales and is currently used by RFS NSW in their fire behavior models.

Table 1.1 Conversion factors used to standardize fuel parameters estimates to fine fuels < 6mm diameter. Conversion factors are from Watson (2012).

Fuel load conversion	Conversion factor
Above ground fuel	
> 25 mm diameter to < 6 mm diameter	0.82
< 25 mm diameter to < 6 mm diameter	0.87
< 10 mm diameter to < 6 mm diameter	0.97
Litter fuel	
> 25 mm diameter to < 6 mm diameter	0.91
< 25 mm diameter to < 6 mm diameter	0.94
< 10 mm diameter to < 6 mm diameter	0.99

This chapter first considers fuel accumulation in Heathlands, then in Forested Wetlands. For each vegetation formation, we initially review studies quantifying fuel loads. The accuracy and applicability of each study was qualified using a 1 to 4 scale whereby 1 represents a well replicated well designed study focused on fuel accumulation modeling, and 4 represents a poorly replicated poorly designed study where fuel accumulation information was tangential. Because climatic differences may influence fuel parameters, we have also included information regarding rainfall and elevation for each study. We then conduct a field survey which quantifies fire hazard and fuel load accumulation in two priority vegetation classes falling within Heathlands and Forested Wetlands vegetation formation: Sydney Coastal Heaths and Coastal Swamp Forests. Finally we provide a brief discussion of processes influencing fuel loads, compare field and literature fuels loads, suggest fuel parameter inputs for the Olson curve, document knowledge gaps within the literature, and suggest avenues for future research.

2 Heathlands

2.1 Introduction

Heathlands are typified by an over-story dominated by shrubs reaching ~4 m height and an under-story dominated by sedges, forbs and herbs. Heaths occur on shallow sandy soils which are nutrient poor, especially in the minerals phosphorous, nitrogen, potassium and magnesium which are important for plant growth (Keith, 2004). Although subject to nutrient poor soils, Heaths are floristically diverse communities dominated by Gondwandan heritage species falling within families and orders unique to the southern-hemisphere (Harden, 2002, Keith, 2004).

Heathlands are fire prone communities. New South Wales Heaths have an average fire interval of 22 years, a lower fire interval of 14 years (Sydney Coastal Heaths of Royal National Park; Enright et al., 2012), and an upper fire interval of > 40 years (Southern Montane Heaths of Wadbilliga National Park; Enright et al., 2012). As dominant perennial shrubs often hold their leaves for several years, and because near-surface (herbs fuels connected to the ground) vegetation is often thick and continuous between the ground and shrub fuel layers, canopy fires typically dominate Heath vegetation; ground litter loads are typically low in Heaths and thus ground litter fires are rare (Midgley and Enright, 2000, Enright et al., 2012).

Heathlands of New South Wales are categorised into seven distinct classes (Table 2.1; Keith, 2004). Coastal and Headland Heathlands are typically restricted to coastal areas, whereas Montane Heathlands are restricted to mountains areas of the Great Dividing Range. Sydney Coastal Heaths are the most well studied Heathlands class of New South Wales and occur on Hawkesbury Sandstone plateaus within the Sydney Basin. Below we review fuel accumulation in Heathlands of New South Wales, with special reference to Sydney Coastal Heaths.

Table 2.1 Vegetation classes in the Heathlands formation of Keith (2004).

Vegetation class	Pages in Keith (2004)	Extent	Relative extent
Coastal Headland Heaths	174-5	Exposed headlands and coastal plateaus along the entire NSW coast.	Small
Wallum Sand Heaths	176-7	Old, nutrient-poor sand deposits along the coast north of Sydney.	Small
Sydney Coastal Heaths	178-9	Exposed coastal sandstone plateaus between Gosford and Jervis Bay.	Small
South Coast Heaths	180-1	Exposed coastal plateaus of the far south coast.	Small
Northern Montane Heaths	182-3	Elevated rocky outcrops across the northern tablelands.	Small
Sydney Montane Heaths	184-5	Exposed sandstone tops of the Blue Mountains and Morton Plateau.	Moderate
Southern Montane Heaths	186-7	High mountain ridges in the south-east of the state.	Small

2.2 Literature review

Morrison et al. (1996)

Morrison et al. (1996), in a study which examined conflicts between fire regimes targeted at biodiversity management and property protection, developed a fuel accumulation curve for Sydney Coastal Heaths. Destructive sampling was used to quantify total fine fuel load (< 6 mm diameter) using 4 m by 4 m quadrats at 12 sites representing 12 different times-since-fire areas in Ku-ring-gai Chase National Park, Sydney. All 12 time-since-fire age classes followed low intensity hazard reduction fires. At each site, total fine fuel load was measured within 10 randomly selected 0.2 m x 4 m quadrats.

Morrison et al. (1996) present a fuel accumulation curve which shows a high degree of model fit to the Olson curve (R^2 = 0.96). ~ 3.5 t / ha of fine fuel was predicted to remained immediately following a fire event, ~ 12 t / ha was predicted to have accumulated in the 5 years following a fire, and fine fuels accumulation had not reached a steady state at 30 years-since-fire. Parameters in Morrison et al.'s (1996) model were: *Initial* = 3.5 t / ha, *Limit* = 28.4 t / ha, *k*= 0.08.

Unfortunately, Morrison et al. (1999) did not fit separate fuel accumulation curves for litter, litter + herbs, herb or shrub fuels. To explore fuel accumulation within these fuel strata we obtained litter, herb and shrub component fuel load information from authors listed on Morrison et al. (1996). The data consisted of 85 plots (making up the 8 of the 12 sites mentioned in Morrison et al. (1996)) where litter, litter + herb, herb and shrub fuel loads (< 6 mm diameter) had been measured. Because site level data (fuel loads averaged between plots within sites) often struggled to converge during model fitting, we used plot rather than site level data to assess fuel accumulation using the two forms of the Olson curve: one without a term for *Initial* (Olson, 1963, Fox et al., 1979) and one with a term for *Initial* (Fensham, 1992, Morrison et al., 1996). Olson curve fuel parameters from our analyses are shown in Table 2.2.

Our litter, litter + herb, herb and shrub fuel component analyses showed moderate to poor fits to the Olson curve (Table 2.2). This was surprising given the strong fit of Morrison's et al. (1996) total fuel load model (R^2 = 0.96). Exploratory analysis of data indicated that these differences were due to plot rather than site level replication in our analyses. i.e. R^2 values for the litter model without a term for *Initial* increased from 0.32 to 0.90 when analyses were conducted on site (n= 8) rather than plot (n = 85) level data. A second caveat regarding fuel parameters presented in Table 2.2 is that *Limit* values for the litter + herbs fuel layer are lower than those presented for the litter layer alone. This illogical result presumably occurred because the trajectory of litter and herb fuels differed from one another. To test this hypothesis we ranked the fit of linear, quadratic and Olson curves models for litter and herb fuel data separately and showed that litter fuel accumulation was best described by a linear relationship (Akakie Information Criterion value: linear curve = 544.41, quadratic curve = 546.40, Olson curve without Initial = 552.11, Olson curve with Initial = model not converged) whereas herb fuel accumulation was best described by a quadratic curve (Akakie Information Criterion value: linear curve = 393.07, quadratic curve = 369.91, Olson curve without Initial = 375.75, Olson curve with Initial = 377.74). These results strongly suggest that disjuncture in fuel accumulation trajectory between litter and herb fuel layers caused the observed disparity of *Limit* values.

Table 2.2. Parameters for the Olson curve fit to data for litter, herb and shrub components from Morrison et al.'s (1996). a) Model assumes no fuel remains immediately after fire. b) Model includes a term for fuel remaining immediately after fire. *Initial* shows fuel remaining after a fire (t / ha). *Limit* shows steady state fuel load (t / ha). *k* shows a rate measure of fuel accumulation. Standard Error (SE) is shown in brackets. Significance codes are: *** = <0.001; ** = < 0.01; * = < 0.05; ' = < 0.1.

Fuel	Initial	Limit	k	R^2
a) Model assumes no fuel remains immediately after fire				
Litter only	not included	23.89(6.01)***	0.06(0.02)*	0.32

Litter + herbs	not included	19.12(2.09)***	0.15(0.04)***	0.32
Shrubs only	not included	10.04(2.13)***	0.09(0.04)*	0.26
Herbs only	not included	3.30(0.36)***	0.53(0.26)*	0.19
b) Model assumes fuel remains immediately after fire				
Litter only	model not converged			
Litter + herbs	4.31(1.59)**	22.45(4.64)***	0.07(0.07)	0.37
Shrubs only	0.06(1.12)	10.48(2.87)***	0.08(0.05)	0.27
Herbs only	-0.06(0.70)	3.30(0.36)***	0.54(0.27)*	0.19

Rating: 2
Long-term trends in fine fuel accumulation were carefully collected, with within site replication sufficient to report precise fine fuel load estimates.

Rainfall and elevation: Morrison et al. (1996) do not provide information on rainfall or elevation. The closest long-term weather station was at West Pennant Hills (33.75˚S, 151.04˚E) where mean annual rainfall is 1111.5 mm (52 years of data) and elevation is 120 m asl.

Bewick (1994)

Bewick (1994) studied fuel loads in Sydney CoastalHeaths at Ku-ring-gai Chase National Park shortly after a wildfire. The proportion of total fuel material remaining after moderate and high intensity fire was quantified within a 0.5 m diameter by 4 m height cylindrical quadrate at 10 plots at eight sites. 98.1 % and 99.9% of fuel was consumed by moderate and high intensity wildfire, respectively. On average, 16 % of fuel remaining after fire (0.090 – 0.004 t / ha) was litter fuel < 6 mm.

In addition to post-fire fuel load, Bewick (1994) also gives a figure for total fine fuels present in Heaths representing a 28 years-since-fire fuel age. This figure which included litter, herbs and shrubs was 29.9 t / ha.

Rating: 2
This study provides useful information on *Initial* values. However some uncertainty remains regarding the identity of ‘fine fuels’ present after fire.

Rainfall and elevation: Bewick (1994) did not provide information regarding rainfall or elevation. The closest long-term weather station was at West Pennant Hills (33.75˚S, 151.04˚E) where mean annual rainfall is 1111.5 mm (52 years of data) and elevation is 120 m asl.

Conroy (1993)

Conroy (1993) presents a curve, with no term for *Initial*, for fine fuel accumulation in 'shrublands' at 15 sites located within the Sydney region, particularly Ku-ring-gai Chase National Park. On average, 17 plots were sampled at each of the 15 site. It is almost certain that sites fit within the Sydney Coastal Heath vegetation class. Parameters for Conroy’s ‘shrubland’ curve, which covers all fuel components up to 6 mm in diameter, are: *Limit* = 33.25 t / ha and *k* = 0.14 (R^2 = 0.95).

While Conroy (1993) provides an Appendix showing separate figures for litter, herb and shrub fine fuel accumulation, curves for these individual components were not fitted. To model fuel loads in these vegetation layers, we experimented with fitting fuel accumulation curves using the two forms of the Olson curve; one without a term for *Initial* (Olson, 1963, Fox et al., 1979) and one with a term for *Initial* (Fensham, 1992, Morrison et al., 1996). Fuel load figures for litter, herb and shrub components given in Conroy (1993) are expressed as means of six time-since-fire category (0 – 1, 1 – 3, 3 – 6, 6 – 10, 10 – 20, > 20 years-since-fire). In deriving our fuel accumulation curves, we have used mid-points from these time-since-fire categories (15 years for the 10 – 20 year category), and have used a time-since-fire of 30 years for the > 20 year category. Parameters from this model-fitting exercise are given in Table 2.3.

Table 2.3 Parameters for the Olson curve fit to data for ‘shrublands’ shown in the Appendix of Conroy (1993: 82). a) Model assumes no fuel remains immediately after fire. b) Model includes a term for fuel remaining immediately after fire. Standard Error (SE) is shown in brackets. *Initial* shows fuel remaining after a fire (t / ha). *Limit* shows steady state fuel load (t / ha). *k* shows a rate measure of fuel accumulation. Significance codes are: *** = <0.001; ** = < 0.01; * = < 0.05; ‘ = < 0.1.

Fuel	**Initial**	**Limit**	**k**	**R^2**
a) Model assumes no fuel remains immediately after fire				
Total fine fuel	Not included	34.9 (3.3)***	0.12 (0.03)*	0.95
Litter only	Not included	17.8 (1.5)***	0.10 (0.02)**	0.97
Litter + herbs	Not included	20.8 (2.3)***	0.10 (0.03)*	0.94
Shrubs only	Not included	14.4 (1.4)***	0.14 (0.04)*	0.92
Herbs only	Not included	3.2 (1.6)	0.08 (0.08)	0.37
b) Model includes a term for fuel remaining immediately after fire				
Total fine fuel	5.2 (1.0)*	39.0 (2.5)***	0.07 (0.01)*	0.99
Litter only	1.5 (0.8)	19.0 (1.8)**	0.08 (0.02)*	0.99
Litter + herbs	2.6 (1.1)'	23.9 (3.5)**	0.06 (0.02)'	0.98
Shrubs only	2.6 (0.4)*	15.6 (0.8)***	0.09 (0.01)***	0.99
Herbs only	n /a			

Rating: 2
The study was well replicated with an explicit focus on developing fuel accumulation curves. However a specific description of study sites is lacking.

Rainfall and elevation: Conroy (1993) did not provide information regarding rainfall or elevation. The closest long-term weather station was at West Pennant Hills (33.75˚S, 151.04˚E) where mean annual rainfall is 1111.5 mm (52 years of data) and elevation is 120 m asl.

Plucinski (2003)

Plucinski (2003) completed a thesis on fire behavior in forests and Heathlands. Although no primary data was collected (his Heathlands chapter is largely a literature review), fuel accumulation curves with no term for *Initial* were calculated by re-analysing Conroy's (1993) data. Plucinski's (2003) analysis included all of Conroy's (1993) shrubland, woodland and forest sites, whereas Conroy (1993) modelled fuel accumulation for each vegetation group separately. Because Plucinski's (2003) analysis included sites with a thick over-story canopy dominated by *Eucalyptus* spp. (woodlands and forests), it is likely that *Limit* and *k* parameters have been over-estimated. Parameters from Plucinski's (2003) models are given in Table 2.4.

Table 2.4 Parameters used by Plucinski (2003) to re-analyse Conroy's (1993) data for shrubland, woodland and forests habitats. An Olson curve with no *Initial* term was used to fit data. *Limit* shows steady state fuel load (t / ha). *k* shows a rate measure of fuel accumulation.

Fuel	Initial	Limit	k	R^2
Total fine fuel	Not included	41.4	0.08	0.67
Litter	Not included	32.8	0.04	0.69
Herb and grass	Not included	1.6	0.64	0.31
Shrub	Not included	6.7	0.45	0.58

Using data from McFarlane (1988), Plucinski (2003) also presents equations which predict increases in fuel height with time-since-fire in wet (probably Coastal Heath Swamps) and dry Heaths (probably Wallum Sand Heaths) sampled from the Cooloola area in south-east Queensland. These results suggest values of *Limit* = 0.360 m, *k* = 0.150 for Dry Heaths, and *Limit* = 0.634 m, *k* = 0.794 for Wet Heaths.

Rating: 4
Secondary data was used in analyses. Regarding the analysis of Conroy's (1993) data, *Limit* and *k* were probably over-estimated as most of the data came from sites with a tall over-story not normally present in Heathlands; from Plucinski's location map, it appears that only 4 of over 30 sites were Conroy's (1993) 'shrubland' sites.

Rainfall and elevation: Plucinski (2003) did not provide information regarding rainfall or elevation. The closest long-term weather station was at West Pennant Hills (33.75˚S, 151.04˚E) where mean annual rainfall is 1111.5 mm (52 years of data) and elevation is 120 m asl.

Ingwersen (1977)

As part of his Master's thesis, Ingwersen (1977) measured above ground live matter biomass, litter biomass and total fuel biomass at six Heathland sites at Jervis Bay which represented four time-since-fire fuel ages. The time-since-fire fuel ages were 1.5 (1 sites), 3 (3 sites), 6 (1 site) and 14 years-since-fire (1 site). Ingwerson (1977) sites were dominated by *Banksia ericifolia, Gymonschoenus sphaerocephalus* and *Casuarina distyla* shrubs. This, and the sites location on the north headland of Jervis Bay, places them within the Sydney Coastal Heaths vegetation class. At each site, above ground and litter biomass was measured within six 2 by 2 m quadrats. Dry weight biomass was calculated post collection. Wood residuals remaining after the previous fire were included in above ground and litter biomass, and thus fuel loads included particles > 25 mm. The results of Ingwersen's (1977) results are shown in Table 2.5.

Table 2.5 Above ground live fuel, litter and total fuel biomass (t / ha) at six Sydney Coastal Heaths sites representing four time-since-fire age classes at Jervis Bay. a) Total fuel biomass of particles > 25 mm. b) Total fuel biomass of particles < 6 mm. A conversion factor of 0.82 was used to calculated total live fuel biomass and total fuel biomass of particles < 6 mm and conversion factor of 0.91 was used to calculated litter fuel biomass of particles < 6 mm. Data is from Ingwersen (1977).

Time-since-fire	Total live fuel	Litter fuel	Total fuel
a) Total Fuel			
1.5 YSF	2.54	0.01	8.12
3 YSF	8.10	5.42	28.08
6 YSF	9.50	2.23	23.42
14 YSF	46.02	8.20	54.22
b) Fuel < 6 mm			
1.5 YSF	2.08	0.01	6.66
3 YSF	6.64	4.93	23.03
6 YSF	7.79	2.03	19.20
14 YSF	37.74	7.46	44.46

In addition to fuel biomass, Ingwersen (1977) also measured the mean height of the tallest shrub species. Mean heights were 0.6 m, 0.8 m and 2.3 m for the 3, 6 and 14 time-since-fire age classes, respectfully.

Rating: 4
The use of conversion factors adds uncertainty to biomass estimates. Spatial and temporal replication was limited (one to three sites for each age class). The litter load information is insufficient to identify fuel parameters using the Olson curve as it is unlikely that 14 years-since-fire represented a steady state for litter accumulation.

Rainfall and elevation: The closest weather station to the study area was probably Jervis Bay (Point Perpendicular Lighthouse AWS; 35.09 ˚S, 150.80˚E) where average annual rainfall is 1234.2 mm (12 years of data) and elevation is 85 m asl.

Maggs and Pearson (1977a, 1977b)

Maggs and Pearson (1977a, 1977b) measured litter fall, litter load, standing vegetation load (presumably total particles > 20 mm) and nutrient levels at eight to twelve plots along two 200 m sample transects located at La Perouse, Sydney. One transect was located in 'dry sclerophyll scrub' whilst the other was located on an introduced grassland (a golf course). The 'dry sclerophyll shrub' transect is focused on here. Litter fall was measured on 22 occasions over a one year period using 0.24 m x 0.4 m boxes; results are reported in Maggs and Pearson (1977a). Litter load and standing vegetation loadwas sampled on three occasions over a one year period using 1 x 1 m quadrats; results are reported in Maggs and Pearson (1977b). Keith (2004) notes that the Heathy vegetation of Sydney'sEastern Suburbs falls into the Wallum Sand Heath vegetation class. The dominant species present at Maggs and Pearson's (1977a, 1977b) site were *Banksia aemula* (previously *B. serratifolia*), *Monotoca elliptica, Ceratopetalum gummiferum* and *Lepidosperma concavum*. Fuel age varied across the site. For most areas (defined as 'tall scrub') fuel age was estimated as 28 years-since-fire. For the remaining areas (defined as 'short scrub') fuel age was estimates as 13 years-since-fire.

Litter fall averaged 4.86 t / ha and was highest in the older time-since-fire age class. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated annual litter fall 4.42 t / ha.

Litter load averaged at 19.0 t / ha. Some of this material had to be sieved from sand, so this figure may include particles that would not have been available to burn. 'Standing dead ground cover' was also included in litter loads. Litter load was higher in the 13 (~ 37.8 t / ha) than 28 years-since-fire (~ 33.18 t/ha) area. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated litter load of 17.29 t / ha.

Assuming all material is fine fuel, and that 17.29 t / ha approximates *Limit, k* would be 0.26.

Standing live leaf load averaged 7.3 t / ha and dead standing wood averaged 5.2 t / ha. A conversion factor of 0.82 gives a total fuel load of 10.25 t / ha for particles < 6 mm. This implies that near-surface and elevated fuel loads were at least this great. There was no difference in live leaf biomass between time-since-fire fuel ages. However there was considerably more dead standing wood in the older time-since-fire Heath, which was also much taller (3 - 4 m in the older time-since-fire age class compared with 1 - 1.5 m in the younger age class).

Rating: 4
Various uncertainties are present within the study which cast doubt on *Limit* and *k* parameter estimates. The degree to which total litter load represents available fine fuel is unknown. Litter fall collection was conducted over a limited period (one year). Uncertainty exists as to the accuracy of post-fire fuel age of vegetation. No spatial replication was present.

Rainfall and elevation: Maggs and Pearson (1977b) give a figure of 1216 mm for annual rainfall. The nearest weather station to the study area was at Sydney Airport AMO (33.95˚S, 151.17 ˚E) where average annual rainfall is 1083 mm (85 years of data) and elevation is 6 m.

Lindsay (2004) and Lindsay and French (2005)

Lindsay (2004) and Lindsay and French (2005; a journal article containing much of the data from Lindsay, 2004) surveyed litter fall and surfacelitter load at a series of Heathland sites along the New South Wales coast as part of a study assessing Bitou bush invasion effects on litter loads (*Chrysanthemoides monilifera* ssp. *rotundata*). Litter fall and surface litter loads were surveyed in adjoining plots dominated by Bitou bush and native vegetation at several sites spread over a 200 km section of the New South Wales coast between Anna Bay and Warrain Beach, Culburra. Native vegetation plots were dominated by *Acacia longifolia*, *Banksia integrifolia* and *Leptospermum laevigatum* shrubs. This places them within the Coastal Headland Heath and Fore-Dune Scrub vegetation class. Lindsay (2004) and Lindsay and French (2005) did not specify a time-since-fire for their sites. However all sites supported tall thick scrub (height 2 - 6 m, cover 50 - 70%), indicating that sites were fairly old. To assess time-since-fire at Lindsay (2004) and Lindsay and French's (2005) sites we cross referenced site location descriptions with fire history and vegetation maps; all sites were confirmed to be > 40 years-since-fire.

At each site, litter fall (dry weight) was assessed seven times over a one year period using six to seven 0.5 x 0.5 m litter bags suspended 1 m from the ground. Ground litter load (dry weight) was assessed using four 2.6 x 2.6 m quadrats randomly sampled within the sample area. Here we focus on Lindsay (2004) and Lindsay and French's (2005) native vegetation sites only.

Mean litter fall from six uninvaded sites located within the Nowra region was 4.80 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated for *L* of 4.37 t/ha.

Mean litter load from four uninvaded sites in the Nowra region and one uninvaded site north of Newcastle was 9.60 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives a litter load of 8.73 t / ha.

If the assumption of steady state is valid, the rate of litter turnover in these sites is high k = 0.50.

Rating: 2
This study was well-replicated across space and time. The need to use conversion factors and our inference of time-since-fire adds uncertainty.

Rainfall and elevation: Lindsay (2004) gives a figure of 1342 mm and 1250 mm for Anna Bay and Culburra, respectively. The closest weather station to the southern study area was probably at Jervis Bay (Point Perpendicular Lighthouse AWS; 35.09 ˚S, 150.80˚E) where annual rainfall averaged 1234.2 mm (12 years of data) and elevation is 85 m asl.

Simmons and Adams (1999)

Simmons and Adams (1999) assessed total fine fuel loads at ten random points located along a 50 m sample transect in a single long-unburnt (no record of last fire present) coastal Heathland site at Stony Point on the Mornington Peninsula south of Melbourne. At each point destructive sampling was conducted within a cuboid frame 0.5 m by 0.5 m by 2 m high quadrate. Dominant species at the site included *Allocasuarina pusilla*, *Leptospermum continentale*, *Acacia oxycedrus* and *Hakea sericea*. While the match is not exact, *L. continentale, Allocasuarina* and *Hakea* spp. are prominent in South Coast Heaths.

Simmons and Adams (1999) included all material in fuel load samples (litter, grasses, sedges, and shrubs) and used a 6 mm cut-off. Total fuel load was 48.9 t / ha. Vegetation was approximately 1.8 m in height.

Rating: 3
This study measured fine fuel directly, so no conversion factors were needed. Although the study was not spatially replicated, its main limitation for current purposes is the distance of the study site from its NSW equivalent.

Rainfall and elevation: Simmons and Adams (1999) give a figure of 1000 mm for this site. The nearest weather station to Stony Point was at Cerberus (38.36 ˚S, 148.18˚E) where average annual rainfall is 734.5 mm (22 years of data) and elevation is 13 m asl.

Hart (1995)

Hart (1995) assessed litter fall, litter loads and litter decomposition at a Broom-Heath, a Mallee, and a Forest site in Pilliga East State Forest near Coonabarrabran, New South Wales. Here we focus on the Broom-Heath site. The location of the Broom-Heath west of the New England Tableland places it within the Northern Montane Heathland vegetation class. However dominate plants described for the site (*Melaleuca uncinata*, *Acacia triptera* and *Calytrix tetragona*) are different from those described for Northern Montane Heathlands (*E. andrewsii*, *E. prava* and *Callitris endlicheri*). This casts doubt as to the placement of the Broom-Heath site within the Northern Montane Heathland class, or indeed any Heathland vegetation classes described by Keith (2004). This said, Hart's (1995; page 267) description of the study site accords with a Heathy form, "broom plain vegetation comprises very low Heath (2 - 5 m) of *M. uncinata*, *A. triptera* and *C. tetragona* and a ground cover comprising many lichens and mosses between shrubs". Most of the broom Heath site was long-unburnt, however some areas were burnt 20 years before the study.

Litter fall, litter loads and litter decomposition was measured over a three year period. Ten mesh litter trays (0.5 by 0.5 m) placed within a 100 by 100 m area were used to assess litter fall on 12 sampling occasions over a 153 week period. Ten 1 by 1 m quadrats placed within the same 100 x 100 m area were used to quantify rates of litter accumulation on three sampling occasions between 1987 and 1991; the ten sites represented fuel ages of 20, 24 and 39 years-since-fire. Thirty mesh bags (0.2 by 0.2 m) containing 20 g of litter were used to quantify litter decomposition. Three bags were collected for analysis on twelve occasions over a 100 week period.

Average annual litter fall was 1.01 t / ha. Seven percent of this was attributed to twigs > 10 mm, 1 % was attributed to animal faecal material, and 64 % was attributed to particulate matter < 5 mm. Using a conversion factor of 0.97 to convert litter particle size of < 10 mm to litter particle size < 6 mm gives an estimated litter fall of 0.98 t / ha.

Litter biomass was 2.99 t / ha, 7.47 t / ha and 6.29 t / ha for 20, 24 and 39 years post-fire, respectively.

Assuming the 39 years-since-fire fuel age class represented a steady state, the rate of litter turnover (*k*) in these sites was 0.19 for the mesh bag sampling method and 0.16 for litter fall sampling method.

Rating: 4
The study was well replicated temporally, but poorly replicated spatially. Uncertainty exists as to the placement of ‘Broom-Heath’ into the Northern Montane Heathland class, and litter load size cut-off’s.

Rainfall and elevation: Hart (1999) give a figure of “around 625 mm” for annual rainfall at the study sites. The closest weather station to the study sites was at Coonabarabran (31.27 ˚S, 149.27 ˚E) where average annual rainfall is 750.7 mm (135 years of rainfall data) and elevation is 505 m asl.

2.3 Field survey of fuel hazard in Sydney Coastal Heaths

A field survey was conducted to add to fuel accumulation information presented in our literature review and to suggest Olson curve parameters for field surveyed fuel hazard scores; many fire behavior models use fuel hazard scores as inputs for fire predictions. We used the Victorian Department of Sustainability and the Environment’s (DSE) fuel assessment guide to quantify fuel hazard at 18 sites. The DSE fuel hazard assessment guide uses visual estimates to categories fire hazard as low, moderate, high, very high or extreme. Tables presented in the guide allow for the conversion of fuel hazard scores to approximate fuel loads in t / ha. Sites were spread along a 230 km transect between Lake Munmorah on the central coast to Jervis Bay on the south coast of New South Wales. Sites were surveyed over ten time-since-fire fuel ages: 1, 2, 6, 8, 9, 10, 11, 12, 24 and > 41 years-since-fire. Where more than one site fell within the same time-since-fire fuel age, values at these sites were averaged. A detailed description of field sample methods is provided in section two of this two part report titled: “Survey Methods to Estimate Fuel Parameters in East Australian Forests”. Briefly, at each site fuel hazard (an ordinal scale where 1 represented low fire risk and 5 represented extreme fire risk) for surface (litter fuels), near-surface (herb and grass fuels connected to the ground) and elevated (shrub fuels disconnected from the ground) fuel layers was assessed at five 5 m radial plots spaced 20 m apart. Fuel hazard scores were averaged between plots at each site to give an overall fuel hazard score.

Field surveyed fuel hazard scores were fit to the Olson curve to estimate fuel hazard Olson curve parameters (*Initial*, *Limit*, *k*) for input into fire behaviour models. In addition to this, field derived fuel hazard scores were converted to fuel load estimates using conversion tables present in the DSE fuel hazard assessment guide. Conversion tables were altered slightly to account for the ordinal nature of field surveyed fuel hazard scores (see Table 2.6 for conversion factor). Field derived fuel load estimates were then fitted to the Olson curve to identify Olson curve fuel parameters for comparison with literature derived fuel load parameters. Because qualitative observations made during the field survey suggested that fuel accumulation may not always conform to the Olson curve, we also fit linear and quadratic model to field derived fuel load estimates. Akakie Information Criterion (AIC) was the used to select the 'best' model explaining fuel accumulation. The model with the lowest AIC values was the 'best' model.

Olson curve fire hazard and fuel parameters are shown in Tables 2.7 and 2.8, respectively. Comparisons of fuel load estimates model fit to the Olson curve (with and without an *Initial* parameter), a linear curve and a quadratic curve are shown in Table 2.9.

Table 2.6. Conversion factors used to convert field surveyed fuel hazard scores to fuel load estimates in t / ha.

Fuel Hazard Score	Surface fuel (t / ha)	Near-surface fuel (t / ha)	Elevated fuel (t / ha)
1	3	2	1
1.5	5.5	2.5	1.5
2	7.5	3	2
2.5	9.5	3.5	2.5
3	11.5	4	3
3.5	14.5	5	4
4	18.5	6	5
4.5	19.25	7	7
5	20 (max)	8 (max)	8 (max)

Table 2.7. Parameters for the Olson curves fit to field surveyed fuel hazard scores for surface, near-surface and elevated fuel layers. Data relates to a field survey assessing fuel hazard at 18 sites over a gradient of time-since-fire fuel ages between 1 and 44 years-since-fire. a) Model assumes no fuel remains immediately after a fire. b) Model includes a term for fuel remaining immediately after fire. *Initial* shows fuel remaining after a fire (t / ha). *Limit* shows steady state fuel loads (t / ha). *k* shows a rate measure of fuel accumulation. Standard Error (SE) is shown in brackets. Significance codes are: *** = <0.001; ** = < 0.01; * = < 0.05; ' = < 0.1.

Fuel	**Initial**	**Limit**	**k**	**R^2**
a) Model assumes no fuel remains immediately after fire				
Surface	not included	4.35(0.96)**	0.06(0.02)*	0.71
Near-surface	not included	4.19(0.15)***	1.09(0.29)**	0.42
Elevated	not included	3.84(0.25)***	0.60(0.24)*	0.40
b) Model includes a term for fuel remaining immediately after fire				

Surface	0.69(0.47)	5.47(3.00)	0.03(0.03)	0.77
Near-surface	2.37(1.25)	4.24(0.20)***	0.42(0.48)	0.51
Elevated	2.16(0.50)**	4.87(0.73)***	0.07(0.05)	0.69

Table 2.8. Parameters for the Olson curves fit tofield estimated fuel loads for surface, near-surface, elevated and total fuel fuel layers. Data relates to a field survey assessing fuel hazard at 18 sites over a gradient of time-since-fire fuel ages between 1 and 44 years. Conversion factors shown in Table 2.6 were used to convert fuel hazard scores to fuel load estimates. a) Model assumes no fuel remains immediately after fire. b) Model includes a term for fuel remaining immediately after fire. *Initial* shows fuel remaining after a fire in t / ha. *Limit* shows steady state fuel loads in t / ha.*k* shows a rate measure of fuel accumulation. Standard Error (SE) is shown in brackets. Significance codes are: *** = <0.001; ** = < 0.01; * = < 0.05; ‘ = < 0.1.

Fuel	Initial	Limit	k	R^2
a) Model assumes no fuel remains immediately after fire				
Surface	not included	23.82(8.05)***	0.04(0.02)	0.77
Surface + near-surface	not included	26.34(3.83)***	0.08(0.02)**	0.70
Elevated	not included	6.98(1.33) ***	0.11(0.05)*	0.50
Near-surface	not included	6.45(0.31) ***	0.67(0.20)**	0.53
Total	not included	27.12(3.87)***	0.11(0.03)*	0.43
b) Model includes a term for fuel remaining immediately after fire				
Surface	model not converged			
Surface + near-surface	model not converged			
Elevated	2.06(1.15)	9.12(4.83)***	0.04(0.05)	0.61
Near-surface	2.79(1.52)	6.64(0.48)	0.28(0.23)	0.60
Total	model not converged			

Table 2.9. Model fit of Olson, linear and quadratic curves to field surveyed fuel loads (t / ha) for surface, surface + near-surface, near-surface, elevated and total fuel fuel layers. Akakie Information Criterion (AIC) was used to rank model fit whereby the ‘best’ model (shown in bold) is that which had the lowest AIC values.

Model trajectory	AIC values				
	Surface fuels	Surface + near-surface fuels	Near-surface fuels	Elevated fuels	Total fuels
Olson (no *Initial*)	55.82	61.33	**32.92**	44.12	115.53
Olson (*Initial*)	n/a	n/a	33.25	43.23	n/a
Linear	**54.40**	**51.02**	35.39	**41.97**	102.49
Quadratic	55.91	51.47	36.72	43.37	**102.39**

2.4 Synthesis and suggested values for Phoenix

General overview of fuel parameters in Heathlands

Relatively few studies have quantified fuel loads and fuel accumulation in Heathlands when compared with sclerophyll forest and woodland vegetation classes of New South Wales (Watson, 2012). Of the seven Heathland classes, Sydney Coastal Heaths were the best represented with five studies. We could find little to no information regarding fuel loads in the remaining six Heathlandclasses. This paucity of studies is surprising given that Heathlands typically have a high fire return-rate, are often located close to housing and infrastructure (particularly around the Sydney Basin), and have been relatively well studied in relation to floristic diversity and floristic post-fire succession (see Bradstock et al., 1997, Keith et al., 2002, Tozer and Bradstock, 2002, Enright et al., 2012).

The trajectory of fuel accumulation through time as measured by Conroy (1993; Conry's origonal analysis and our re-analysis of Conroy's data) and Morrison et al. (1996; Morrison's original analysis and not our re-analysis of Morrison's data) suggest that fuel accumulation in Heathlands conforms to the Olson curve. However data presented by Maggs and Pearson (1977b, 1977a) and Hart (1995) suggest that Heathland fuel accumulation may more closely resemble a parabolic than the Olson curve. This is because litter fuel loads were lower at older time-since-fire sites than at intermediate time-since-fire sites; Maggs and Pearson (1977b) show greater litter loads at 13 (~ 37.8 t / ha) than 28 years-since-fire (~ 33.18 t/ha), Hart (1995) show greater litter biomass at 24 (7.5 t / ha) than 39 (6.3 t / ha) years-since-fire. Our re-analysis of Morrison's et al. (1996) data and our field survey also suggested that the Olson curve may not always be the best predictor of fuel accumulation in different fuel components. For example, in re-analysing Morrison et al. (1996) we assessed model fit using Olson, linear and quadratic curves and showed that: 1) the Olson curve best described trends in shrub fuel accumulation (AIC comparison for model fit: linear = 497.34, quadratic = 495.74, Olson curve no Initial = 495.97, Olson curve Initia l= 494.27), 2) a linear curve best described trends in surface fuel accumulation (see our review of Morrison et al. (1996)) and 3) a quadratic curve best described trends in herb fuel accumulation (see our review of Morrison et al. (1996)). For our field survey, surface, surface + near-surface and elevated fuel accumulation were best described by linear rather than Olson curve model (Table 2.9). The Olson curve was developed to model fuel accumulation in tall over-story canopy forests (Olson, 1963, Fox et al., 1979, Morrison et al., 1996). Given this, it is not surprising that the Olson curve may struggle, at times, to correctly predict fuel loads in Heathlands where over-story vegetation is rare and a thick and often continuous near-surface and elevated fuel layer occurs.

Considerable differences in *L*, *Limit* and *k* were apparent between the eight studies recording litter fuel < 6 mm (Table 2.10). The range of *Limit* values for the Sydney Coastal Heaths studies (7.46 – 23.89 t / ha; excluding the Plucinski (2003) study where over-story trees were present at many sites) was similar to those observed in the other Heathland classes (6.29 – 17.86 t / ha). This suggests that small changes in the physical, climatic and / or chemical environment (i.e. changes in topography, nutrient levels, evaluation, or water availability), both within and between Heathland vegetation classes, may eventuate in vastly different litter loads. Plucinski (2003) supports this assertion, noting that site-specific differences in species composition and species dominance stemming from changes in topography and micro-climate probably accounted for the different estimates of *Limit* and *k* presented by Conroy (1993) and Morrison et al. (1996); both studies sampled similar Sydney Coastal Heaths sites in Ku-ring-gai Chase National Park, Sydney.

Table 2.10 Values for *L*, *Initial*, *Limit* and *k* from studies quantify a) litter fuel, b) litter + herb fuels, c) shrub fuels, and d) total fuels < 6 mm in Heathlands of New South Wales. R'g represents weighting of confidence and relevance.

Source	Heathland class	L	Initial	Limit	k	R's
a) Litter fuels						
Morrison el al. (1996)	Sydney Coastal Heaths	1.43	-	23.89	0.06	2
Conroy (1993)	Sydney Coastal Heaths	1.52	1.5	19.00	0.08	2
Plucinski (2003)	Sydney Coastal Heaths	1.31	-	32.8	0.04	4
Ingwerson (1977)	Sydney Coastal Heaths		-	7.46	-	4
Our field survey	Sydney Coastal Heaths	0.95	-	23.82	0.04	-
Maggs (1977 a, b)	Wallum Sand Heaths	4.50	-	17.29	0.26	4
Lindsay (2004, 2005)	Coastal Headland Heaths	4.41	-	8.73	0.50	2
Hart (1995)	Northern Montane Heaths?	1.13	-	6.29	0.18	4
b) Litter + herb fuels	Sydney Coastal Heaths					
Morrison et al. (1996)	Sydney Coastal Heaths	1.57	4.31	22.45	0.07	2
Conroy (1993)	Sydney Coastal Heaths	1.43	2.6	23.9	0.06	2
Our field survey	Sydney Coastal Heaths	2.11	-	26.34	0.08	-
c) Shrub fuels						
Morrison et al. (1996)	Sydney Coastal Heaths	0.84	0.06	10.48	0.08	2
Conroy (1993)	Sydney Coastal Heaths	1.40	2.6	15.6	0.09	2
Plucinski (2003)	Sydney Coastal Heaths	3.02	-	6.7	0.45	4
Our field survey	Sydney Coastal Heaths	0.36	2.06	9.12	0.04	-
d) Total fuels						
Morrsion et al. (1996)	Sydney Coastal Heaths	2.27	3.5	28.4	0.08	2
Bewick (1994)	Sydney Coastal Heaths		0.09	29.9	-	2
Conroy (1993)	Sydney Coastal Heaths	2.73	5.2	39.00	0.07	2
Plucinski (2003)	Sydney Coastal Heaths	3.31	-	41.4	0.08	4
Ingwerson (1977)	Sydney Coastal Heaths		-	44.46	-	4
Maggs (1977 a, b)	Wallum Sand Heaths		-	10.25	-	4
Simmon and Adams (1999)	South Coast Heaths		-	48.9	-	3
Our field survey	Sydney Coastal Heaths	2.98	-	27.12	0.11	

Interestingly, *L* and *k* parameters were lower for studiesconducted in Sydney Coastal Heaths, where sandstone soils are present, than studies conducted in Wallum Sand Heaths and Coastal Headland Heaths, where sandy sand-dune dominated soils are present. Watson (2012) observed similar trend in co-occurring Shrubby Dry Schelerophyll Forests, whereby *L* and *k* were lower in Shrubby Dry Schelerophyll Forests located on sandstone dominated soils (L= 2.3, k = 0.16) than deep sandy soils (L = 5.2, k = 0.31). We can think of two explanations for these divergent trends. First, soil nutrient content and retention is often lower in sand-dune than sandstone dominated soils; although sand-dune and sandstone soils are both nutrient depauperate (McKenzie et al., 2004). Lower nutrient content may have resulted in decreased litter production and litter input (L) which resulted in decreased 'on-ground' litter levels available for decomposition. Second, differences in climatic factors such as rainfall, wind speed or salt content between sandy soil sand-dune area (which are limited to within hundreds of meters from the coast) and sandstone soils areas (which may extend many kilometers inland) may have resulted in lower *L* and *k* parameters. For example, increased average wind speed may limit litter input (*L*) within surrounding areas by physically removing litter, or increases in salt content may retard litter decomposition (influencing *k*).

Fuel parameters for management applications in Sydney Coastal Heaths

Below we suggest fuel parameters for use in Phoenix and other management applications. Sydney Coastal Heaths have two district growth forms. The dominant 'tall' growth form (up to 4m in height) occurs away from the coast, whereas the subordinate 'short' growth form (< 2m in height) occurs within a few hundred meters of the coast. Structure difference associated with 'tall' and 'short' Sydney Coastal Heaths are likely to influence fire behavior, and hence fuel parameters for inclusion in fire behavior models such as Phoenix (*pers. comm.* Belinda Kennedy). To our knowledge, all studies mentioned in our literature review occurred in the 'tall' Sydney Coastal Heaths growth form. Because of this we limit our suggested fuel parameters for us in 'tall' Sydney Coastal Heaths.

For litter values alone which equate to surface fuels, the *Limit* parameter suggested by Plucinski (2003) is much higher and the *k* parameter is much lower than those suggested by Morrison et al. (1996; fit without a term for *Initial*) and Conroy (1993; fit with a terms for *Initial*) or by our field study (Table 2.10). This is unsurprising given that Plucinski (2003) included many sites with a *Eucalyptus* over-story in his analysis. *Eucalyptus* species have relatively high rates of litter-fall when compared with Heathland shrubs which often retain their leaves for several years (Enright et al., 2012, Watson, 2012). Because values from *Limit* and *k* were similar for Morrison et al. (1996), Conroy (1993) and our field study, we averaged *Limit* and *k* values between these studies to suggest a *Limit* fuel parameter of 22.24 and a *k* fuel parameter of 0.06. Although Ingwerson (1977) provided an estimate for *Limit*, Ingwerson's (1977) *Limit* value was excluded due to the low degree of certainty associated with this study. Because our re-analysis of Conroy (1993) was the only study to assess an *Initial* fuel parameter for litter fuels we recommend the use of this value. Fuel parameters recommended for litter fuel < 6 mm are: *Initial = 1.5, Limit = 22.24, k = 0.*06.

For litter + herb fuel < 6 mm which equate to surface plus near-surface fuels, Morrison et al. (1996; our re-analysis of data fit with a term for *Initial*), Conroy (1993; our re-analysis of data fit with a terms for *Initial*) and our field survey were the only studies to estimate *Limit* and *k*. Because values from *Limit* and *k* were similar for Morrison el al. (1996), Conroy (1993) and our field study, we averaged *Limit* and *k* values between these studies to suggest a *Limit* fuel parameter of 23.9 and a *k* fuel parameter of 0.07. However because qualitative observation made during our field survey suggested that the DSE fuel hazard assessment guide conversion factors under-estimated near-surface fuel loads, we suggest that our *Limit* parameter of 23.9 may under-estimate fuel loads in some circumstances. Our re-analysis of Morrison's et al. (1996) and Conroy's (1993) data and our field survey suggested litter + herb fuel *Initial* parameter of 4.31, 2.60 and 2.06 t / ha, respectively. Morrison et al. (1996) and Bewich (1994) showed that fire intensity is strongly linked to *Initial* values; Morrison et al. (1996) showed total fuel *Initial* parameters of 3.5 t / ha, 1 t /ha and 0.2 t / ha for low, moderate and high intensity fires, respectfully; Bewick (1994) showed total fuel *Initial* parameters of 0.57 t / ha and 0.02 t / ha for moderate and high intensity fires, respectively. We suggest an *Inital* fuel parameters from Conroy (1993) of 2.6 t / ha. We chose to exclude Morrison's (1996) *Initial* parameter because 1) it was very high when compared with other *Initial* parameters presented in Table 2.10, and 2) averaged values for Morrison et al. (1996) and Conroy (1993) showed that near-surface *Initial* values (1.95 t / ha) were higher than *Limit* values (1.66 t / ha; this is clearly an illogical result). Fuel parameters recommended for litter + herb fuel < 6 mm are: *Initial* = 2.66, *Limit* = 23.9, *k* = 0.07

For shrub fuel < 6 mm which equate to elevated fuels, the *k* parameter suggested by Plucinski (2003) was much higher than those suggested by Morrison et al. (1996), Conroy (1993) or our field survey. Because Plucinski's (2003) estimate for *k* exhibited poor model fit (0.58), heathland shrubs often hold their leaves for many years and thus decompositions rates are expected to be fairly low (Enright et al., 2012), and *k* parameters suggested by Morrison et al. (1996), Conroy (1993) and our field survey were similar to one another, we suggest a *k* parameter averaged between the later mentioned studies of 0.15. *Limit* parameters for Plucinski (2003) and our field survey were lower than for Morrison et al. (1996) or Conroy (1993). The low *Limit* values presented by Plucinski (2003) may have occurred due to the presence of over-story Eucalyptus trees which possibly increase competition for resources or physically retarded shrub growth. The low *Limit* values presented in our field survey may have resulted from conversion error between our fuel hazard scores and fuel loads (qualitative observations made during fuel sampling suggested that DSE fuel hazard assessment guide conversion factors under-estimated elevated fuel loads). We averaged values between Morrison et al. (1996) and Conroy (1993) to suggest a *Limit* parameter of 13.04 t / ha. Fuel parameters recommended for shrub fuel < 6 mm are: *Initial* = 1.57, *Limit* = 13.04, *k* = 0.15.

With *Limit* parameters of 23.9 t / ha for litter + herb fuels and 13.04 t / ha for shrub fuels, total fine fuels < 6 mm is 36.94 t / ha. This figure falls well within the range of the total fuel *Limit* parameters reported by Morrison et al. (1996; 28.4 t / ha), Bewick (1994; 29.9 t / ha), Conroy (1993; 34.9 t / ha), Plucinski (2003; 41.4 t /ha), and Ingwersen (1977; 44.5 t / ha) (1999; 48.9 t /ha).

Fuel parameters for management applications in Other Heathland classes

Few studies have examined post-fuel accumulation in Heathland classes other than Sydney Coastal Heaths. Those which have have focused on litter fuels alone, and none suggest *Initial* fuel parameters. Lindsay (2004) and Lindsay and French (2005) studies were well replicated spatially. Because of this we feel that their Coastal Headland Heaths / Fore-dune Heaths fuel parameters of *Limit* of 7.87 and *k* of 0.56 are relatively reliable; although a *Limit* values of 7.87 t / ha seems low when compared with Sydney Coastal Heaths. Maggs and Pearson's (1977a, 1977b) studies sampled a small patch of Wallum Sands Heaths and Hart (1996) sampled Broom Heaths which were presumed to be part of the Northern Montane Heaths vegetation class. The uncertainty associated with these studies questions the reliability of *Limit* and *k* fuel parameters.

Comparison of fuel loads in Sydney Coastal Heaths and Shrubby Dry and Wet Sclerophyll forests

Sydney Coastal Heaths and Shrubby sub-forms of Dry and Wet Sclerophyll Forests often co-occur on sandstone plateaus of the greater Sydney Basin (Keith, 2004). Here we compare fuel load parameters between Sydney Coastal Heaths and Shrubby Dry and Wet Sclerophyll Forests to understand how and why fire behavior may differ between these sympatric vegetation classes.

Table 2.11 a) Suggested fuel parameters for Phoenix:a) Sydney Coastal Heath, b) Shrubby Dry Sclerophyll Forests east of the divide and c) Shrubby Wet Sclerophyll Forests east of the divide. Values for b) and c) haven been taken form Watson (2012). *Initial* and *Limit* are in t / ha.

Fuel	**Initial**	**Limit**	**k**
a) Sydney Coastal Heaths			
Litter only	1.5	22.24	0.06
Litter + herb	2.66	23.90	0.07
Shrub	1.57	13.04	0.15
b) Shrubby Dry Sclerophyll Forests east of the divide			
Litter only	1.5	14.5	0.16
Litter + herb	1.7	16.4	0.17
Shrub	0.7	4.9	0.20
c) Shrubby Wet Sclerophyll Forests			
Litter only	1.0	17.0	0.45
Litter + herb	1.0	19.0	0.35
Shrub	0	3.0	0.15

Litter *Limit* parameters suggest that steady state litter biomass is lower for Sydney Coastal Heaths than Shrubby Dry and Wet Sclerophyll Forests (Table 2.6). This is un-surprising given that litter input is high in Shrubby Sclerophyll Forests where a thick over-story canopy is often present, but low in Heathland where tall over-story trees are rare and shrubs often retain their leaves for many years (Enright et al., 2012). Litter + herb parameters were similarly higher for the Sydney Coastal Heaths and Shrubby Wet Sclerophyll Forests, both of which have a relatively thick under-story of herb growth, when compared with Shrubby Dry Sclerophyll Forests which often lack a dense under-story vegetation layer (Table 2.6; Keith, 2004, Watson, 2012). The shrub *Limit* parameter for the Sydney Coastal Heaths, which has a canopy dominated by dense and well connected shrubs, was much higher than for both Shrubby Dry and Wet Schlerophyll forests, where the elevated shrub layer is relatively spare (Table 2.6).

Initial parameters were higher for Sydney Coastal Heaths than Dry and Wet Sclerophyll Forests suggesting that more fine fuel remains following fire. This is interesting as mature Heathlands which often have fuel elements connected from the ground to the canopy can burn at high intensity with high rates of spread (Keith et al., 2002, Enright et al., 2012). Thus you would expect that most fine fuel would be removed during fire. We suggest that species-species traits associated with leaf flammability likely influenced this result, as *Eucalyptus* leaves which are highly flammable are rare in Heaths but common in Sclerophyll forests.

k parameters were slightly lower in Sydney Coastal Heaths than Shrubby Dry Sclerophyll Forests, however ground fuels (litter and litter + herb) were much lower in Sydney Coastal Heaths than Shrubby Wet Sclerophyll Forests (Table 2.11). Sydney Coastal Heaths and Shrubby Dry Sclerophyll Forests both reside on dry nutrient poor soils, whereas Shrubby Wet Sclerophyll forests typically reside in more temperate micro-climates where soils are moderately fertile. The lower *k* parameters in Sydney Coastal Heaths and Shrubby Dry Sclerophyll Forests is probably due to slower decompositions rates in their typically dry micro-climates. Conversely, the higher *k* parameter presented for Shrubby Wet Sclerophyll Forests probably result from faster decomposition rates which occur in the wetter micro-climates within which they occur.

2.5 Knowledge gaps and future research

Relatively few studies have quantified fuel loads in Heathlands of New South Wales, especially classes other than Sydney Coastal Heath. The available studies highlight a great deal of variability among sites, probably due to fine-scale variation in soil quality and species composition. This casts some doubt as to the reliability of fuel parameters suggested here. Studies which quantify fuel loads over large spatial and temporal scales are needed to further understand processes influencing fuel accumulation within and between Heathland vegetation classes of New South Wales. Specific areas for research could include:

- Exploration of the ability of the Olson curve to model Heathland fuel accumulation when compared with other models (i.e. linear and parabolic curves).
- Understanding of how site-specific variability in micro-habitat and micro-climate influence fuel accumulation within Heathland vegetation classes.
- Examination of how and why *L* and *k* fuel parameters may differ between Heathland communities located on sandy sand-dune dominated soils close to the coast and sandstone dominated soils inland.
- Further quantification of how fire intensity influences the amount of fuel remaining after fire (*Initial*).

3 Forested wetlands

3.1 Introduction

Forested wetlands are widely distributed throughout New South Wales on nutrient rich coastal marsh, floodplain and riverine soils of low elevation which are subject to inundation (Kingsford, 2003, Keith, 2004). Vegetation is typified by a tall over-story (20 – 40 m) of Sclerophyllous trees including *Eucalyptus* spp., *Melaleuca* spp., *Leptospermum* spp. and *Casuarina* spp., and an often thick under-story of hydrophyte monocots (grasses, rushes and sedges) which are adapted to periodic inundation. Many of New South Wales Forested Wetlands have been cleared for timber, agriculture, or to provide land for housing and infra-structure (Adam, 1995, Keith, 2004). A significant proportion of extant Forested Wetlands adjoin urban areas along the coastal and riverine fringe.

Inundation by floodwaters is an important aspect of nutrient cycling in Forested Wetlands. In low rainfall areas of semi-arid New South Wales, flooding may be an ephemeral event which only occurs after high rainfall periods spaced years apart (Bren et al., 1988). Conversely, in higher rainfall areas with low elevations, flooding may occur monthly, weekly or daily (Roy et al., 2001). Following inundation, soils can absorb large quantities of water (Pressey and Harris, 1988, Roy et al., 2001). Resulting moist soil profiles facilitate high rates of litter decomposition and nutrient turnover. In addition to this, inundation can further decrease standing litter load by physically removing surface litter (Clarke and Allaway, 1996).

Fuel loads are often high in Forested Wetlands, and dominant Sclerophyllous trees are well ‘fire adapted’. High frequency burning regimes may occur in Forested Wetlands, however fire propagation and thus frequency is largely determined by soil moisture profiles and inundation histories (Adam et al., 1985, Keith, 2004, Kenny et al., 2004). Fire intervals of between 7 and 35 years have been suggested to optimize biodiversity in Forested Wetlands (Kenny et al., 2004).

Forested Wetlands of New South Wales are categorised into four distinct classes (Keith, 2004; Table 3.1). Coastal Swamp Forests, Coastal Floodplain Wetland and Eastern Riverine Forests are restricted to coastal areas and associated tributaries. Inland Riverine forests are restricted to inland rivers and floodplains with nutrient rich soils. Fuel accumulation in Forested Wetlands of New South Wales is reviewed in the following section, with special reference to Coastal Swamp Forests.

Table 3.1 Vegetation classes in the Forested Wetlands formation of Keith (2004).

Vegetation class	Pages in Keith (2004)	Extent	Relative extent
Coastal Swamp Forests	224-5	On coastal dune swales and flats in waterlogged soils rarely above 50 m elevation north of Port Stephens.	Small
Coastal Floodplain Wetlands	226-7	On coastal floodplains and associate flats along the entire New South Wales coast.	Small
Eastern Riverine Forests	228-9	Coastal hinterland riparian corridors up to 800 m elevation north of Bega.	Small
Inland Riverine Forests	230-1	Inland waterways and floodplains throughout semi-arid New South Wales.	Moderate

3.2 Literature review

Greenway (1994)

Greenway (1994) studied litter fall and standing litter load in two adjacent paperbark-dominated wetland sites near Carbrook in south-east Queensland, a riparian site located next to a creek and a floodplain site located 100 m from this creek. Vegetation consisted of seasonally-inundated closed forest dominated by *Melaleuca quinquenervia*, with *E. tereticornis*, *E. robusta* and *Casuarina glauca* also present. The fern *Blechnam indicum* was a dominant understorey species. This description fits closely with Keith's description of Coastal Swamp Forests. Forest floor litter load was measured on two occasions, July 1992 and July 1993. Time-since-fire is not discussed, however the presence of abundant *Parsonsia staminea* in the under-story, and considerable bark shed, suggests the forest had not experienced a fire for decades.

Litter fall was measured over two years using eight traps at each of the two sites. No size cut-off is mentioned. Litter fall did not significantly differ between sites or year of sample.

The average annual litter fall across the two sites, and two years, was 7.43 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated annual litter fall of 6.77 t / ha.

Litter load was lower in 1992 (27.53 t / ha) than in 1993 (30.25 t / ha), and at the riparian site (23.21 t / ha) than the wetland site (34.58 t / ha). However these differences were not statistically different from one another. Averaging the 1993 figures across the two sites gives 28.90 t / ha. Assuming steady state, and using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimate for *Limit* of 26.30 t / ha.

An estimate for *k* was derived by dividing *L* (6.77 t/ha) by *Limit* (26.30 t/ha), being 0.26.

Rating: 2
While replication across both time and space was reasonable in this study, uncertainties around time-since-fire and particle size cut-off somewhat limits the reliability of *L*, *Limit* and *k* estimates.

Rainfall and elevation: Greenway (1994) does not report rainfall or elevation. Logan City Water Treatment Plant (27.68°S, 153.19°E) is the nearest weather station where average annual rainfall is 1087 mm (18 yrs of data) and elevation is 14 m asl. Greenway (1994) sites were located a floodplain next to the coast, so an elevation of 10m asl seems reasonable.

Sandercoe (1989, 1992)

Sandercoe (1989, 1992) report on a fuel sampling programconducted in Cooloola National Park north of Noosa, south-east Queensland. One of the vegetation types assessed as part of this study was a "*Melaleuca quinquenervia* dominated woodland with closed graminoid heathland," with at least some degree of impeded drainage. *Lophostemon suaveolens*, *Banksia robur*, *Baumea juncea*, *Boronia falcifolia*, *Hakea spp*, *Leptospermum liversidgei*, *Xanthorrhoea fulva* were dominant vegetation at sites. This vegetation description fits closely with Keith's description of Coastal Swamp Forests.

Total fuel load was measured at ten sites representing a range of time-since-fire between 0 – 8 years. At each site, all material up to 1.5 m above the ground and less than 10 mm in diameter was harvested from within three 50 x 50 cm width by 150 cm height quadrats. Results are reported for all fuel, and for the dead fraction only.

A linear relationship was observed between total fuel and time-since-fire, indicating that fuels had not reached steady state by 8 years post fire. The two sites with the greatest fuel age (8 years-since-fire) carried a total fuel load of approximately 14 t / ha. The load of dead fuel was between 6 and 8 t / ha, implying a living fuel load of an equivalent amount. Sandercoe (1989) notes that much of the dead material is suspended in the under-story, rather than forming a typical litter layer on the ground. The two sites with the lowest fuel age, being ~ 6 and 14 months since fire, carried total fuel loads of 3.5 t / ha and 3.9 t / ha, respectively.

Rating: 3

The data presented by Sandercoe (1989, 1992) is insufficient to identify fuel parameters as fuel loads had not reached a steady state. It does, however, attest to the fact that Coastal Swamp Forests can carry high fuel loads, much of which is held in potentially flammable elevated and near-surface fuel layers.

Rainfall and elevation: Sandercoe (1992) reports an annual rainfall of approximately 1500 mm. The most relevant weather station was likely Rainbow Beach (25.90°S, 153.09°E) where annual rainfall averaged 1480 mm (22 years of data) and elevation is 14 m asl. Both sites experienced some degree of impeded drainage and thus must be located at fairly low elevations.

Clarke and Allaway (1996)

Clarke and Allaway (1996) measured litter fall attwo sites near Sydney, both dominated by *Casuarina glauca* and subject to periodic inundation. Site A, at Towra Point Nature Reserve on the Kurnell Peninsula to the south of Botany Bay, was located on sandy soils. Site B, the Hawkesbury River and its tributary Mill Creek, was located on sandy soil with higher clay content than those present at Site A. Standing litter load was measured at Site B only. The description of the vegetation in Clarke and Allaway (1996) clearly allocates both sites to Keith's Coastal Floodplain Wetland class; Dominant under-story species included *Juncus kraussii*, *Baumea juncea*, *Carex appressa* and dominant shrubs included *Glochidion ferdinandi* (Site A), *Parsonsia straminea* (Site B). Clarke and Allaway (1996) do not specify a time-since-fire for their sites, however the presence of abundant *Parsonsia straminea* suggests the site had not burned recently.

Litter fall was assessed monthly over a three year period using 12 (Site A) or 13 (Site B) 1 x 1 m litter traps suspended 2 m above the ground. All litter falling into traps was included and average litter fall across sites and years was 8.48 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated litter fall of 7.72 t / ha.

Standing litter load was measured within a 1 x 1 m area at Site B using five single measurements over a 10 month period. Average litter load was 12.44 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated litter load of 11.32 t / ha. Standing litter load was also measured four months after a flood - the only inundation at this site over the three years of the study - again using five samples. Standing litter load was 4.62 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated litter load of 4.20 t / ha. This result suggests that flooding had washed away the bulk of standing litter.

Using figures of 7.72 t / ha for *L* and 11.32 t / ha for *Limit* gives an estimate of 0.68 for *k*.

Rating: 3

For litter fall, replication across time and space is good. Litter load on the other hand, was measured in only one site, using a small number of samples. Uncertainties around time-since-fire and the use on particle size conversion factors somewhat limits the reliability of *L*, *Limit* and *k* estimates.

Rainfall and elevation: Clarke and Allaway (1996) do not give figures for rainfall or elevation. The most relevant weather station is likely Sydney Airport on Botany Bay (33.95°S, 151.17°E) where annual rainfall averaged 1083 mm (84 years of data) and elevation is 6 m asl. Both sites experienced inundation and thus must be located at a low elevation.

Briggs and Maher (1983)

Briggs and Maher (1983) measured litter fall in aRiver Red Gum (*Eucalyptus camaldulensis*) forest (Murrumbidgil Swamp) north of Hay in south-western NSW which had an under-story dominated by *Muehlenbeckia cunninghamii* and *Xanthium occidentale*. This vegetation description places Briggs and Maher (1983) site within Keith's Inland Riverine Forest vegetation class. No time-since-fire is mentioned in Briggs and Maher (1983), however the presence of abundant *Parsonsia straminea* suggests the site had not burned recently.

Litter fall was assessed monthly over a period of 31 months using twenty 1 x 1 m width by 0.3 m height floating litter traps. No size cut-off was specified, although one large branch was excluded.

Average litter fall for between 1977 and 1979 gives an average annual litter fall of 4.74 t / ha. Using a conversion factor of 0.91 to convert litter particle size of > 25 mm to litter particle size < 6 mm gives an estimated litter fall of 4.31 t / ha. Total litter fall, and especially that of fruit and leaf litter, was much greater in the summer than winter months.

Rating: 3
Briggs and Maher (1983) study includes replication across time, but not across space. Lack of a clear cut-off point for litter size and information regarding time-since-fire adds uncertainty to litter fall estimates.

Rainfall and elevation: Briggs and Maher (1983) report an average annual rainfall figure of 363 mm (Hay weather station). The current figure for average annual rainfall at the Hay (Mulberrygong; 34.49°S, 145.25°E) weather station is 366 mm (109 years of data). Elevation at Hay is 104 m.

Glazebrook and Robertson (1999)

Glazebrook and Robertson (1999) assessed standing litter load in River Red Gum (*Eucalyptus camaldulensis*) forests south of Deniliquin (Gulpa Island State Forest) in south west NSW. Forests had a dominant grassy under-story and were subject to periodic flooding. This description places Glazebrook and Robertson (1999) sites within Keith's Inland Riverine Forest vegetation class.

Standing litter load was measured at four sites (two in flood runner habitat and two in "higher ground" habitats) during two seasons (Autumn and Winter) using ten 1 x 1 m quadrats sampled along a 100 m sampling transect. All organic matter including twigs up to 10 mm in diameter were collected.

Across all sites and both seasons, average standing litter load was 11.84 t / ha. Using a conversion factor of 0.99 to convert litter particle size of < 10 mm to litter particle size < 6 mm gives an estimated litter load of 11.72 t / ha. Perhaps the primary finding of the study was the massive difference in average litter load observed between sampling seasons: autumn (17.28 t / ha), winter (6.41 t / ha). By contrast, habitat differences (flood runner habitats versus higher ground habitats) were minor and inconsistent. The authors attribute the high autumn figure to heavy summer litter fall − they refer to unpublished data to support this − and to rapid rates of decomposition evidenced by the large percentage of semi-decomposed material found even in the autumn sites.

Rating: 3
Glazebrook and Robertson (1999) replicate across habitats and seasons. However these factors were not randomly selected for. In addition to this, the use of conversion factors adds uncertainty to litter load estimates.

Rainfall and elevation: Glazebrook and Robertson (1999) point out that their study site is in the semi-arid zone, with a rainfall average of 460 mm. The nearest weather station on the Murray River is Echuca Aerodrome (36.16°S, 144.7°E) where average annual rainfall is 428 mm and elevation is 96 m asl (132 yrs of data).

3.3 Field survey of fuel hazard in Coastal Swamp Forests

The same field survey described in section 2.3 was extended to include 17 sites in Coastal Swamp Forests representing six time-since-fire fuel age classes (0, 1, 4, 12, 13, and >41 years since fire). Unlike the field survey in Sydney Coastal Heaths we treated site, and not each time-since-fire age class, as the replicate unit for analyses. This was because preliminary analyses indicated that six replicate time-since-fire age class points was insufficient for statistical modelling. Field survey methods and analyses are described in section 2.3.

Olson curve fuel hazard and fuel parameters are shown in Tables 3.2 and 3.3, respectively. Comparisons of fuel load estimates model fit to the Olson curve (with and without an *Initial* parameter), a linear curve and a quadratic curve are shown in Table 3.4.

Table 3.2. Parameters for Olson curves fit to field surveyed fuel hazard scores for surface, near-surface and elevated fuel layers. Data relates to a field survey assessing fuel hazard at 17 sites over a gradient of time-since-fire fuel ages between 0 and 44 years-since-fire. a) Model assumes no fuel remains immediately after a fire. b) Model includes a term for fuel remaining immediately after fire. *Initial* shows fuel remaining after a fire (t / ha). *Limit* shows steady state fuel loads (t / ha). *k* shows a rate measure of fuel accumulation. Standard Error (SE) is shown in brackets. Significance codes are: *** = <0.001; ** = < 0.01; * = < 0.05; ' = < 0.1.

Fuel	Initial	Limit	k	R^2
a) Model assumes no fuel remains immediately after fire				

Surface	not included	3.22(0.26)***	1.04(0.86)	0.16
Near-surface	not included	4.23(0.40)***	0.91(0.83)	-3.27
Elevated	not included	2.14(0.31)***	1.24(1.91)	-1.24
b)Model includes a term for fuel remaining immediately after fire				
Surface	1.35(0.60)*	3.22(0.24)***	0.70(0.84)	0.38
Near-surface	3.24(0.34)***	4.41(0.23)***	0.13(0.10)	0.38
Elevated	model not converged			

Table 3.3. Parameters for Olson curves fit to fieldestimated fuel loads for surface, near-surface and elevated fuel layers. Data relates to a field survey assessing fuel hazard at 17 sites over a gradient of time-since-fire fuel ages between 1 and 44 years. Conversion factors shown in Table 2.6 were used to convert fuel hazard scores to fuel load estimates. a) Model assumes no fuel remains immediately after the passage of a fire. b) Model includes a term for fuel remaining immediately after fire. *Initial* shows fuel remaining after a fire (t / ha). *Limit* shows steady state fuel loads (t / ha). *k* shows a rate measure of fuel accumulation. Standard Error (SE) is shown in brackets. Significance codes are: *** = <0.001; ** = < 0.01; * = < 0.05; ‘ = < 0.1.

Fuel	Initial	Limit	k	R^2
a) Model assumes no fuel remains immediately after fire				
Surface	not included	14.40(1.40)***	0.71(0.62)	0.24
Surface + near-surface	not included	21.01(1.74)***	0.59(0.40)	0.08
Elevated	not included	2.29(0.37)***	0.67(0.94)	0
Near-surface	not included	6.75(0.69)***	0.32(0.20)	0
Total	not included	23.30(1.90)**	0.59(0.40)	0
b) Model includes a term for fuel remaining immediately after fire				
Surface	5.00(3.25)	14.45(1.40)***	0.47(0.53)	0.35
Surface + near-surface	9.73(3.27)*	21.19(1.59)***	0.31(0.28)	0.44
Elevated	model not converged			
Near-surface	4.25(0.72)***	6.86(0.51)***	0.13(0.10)	0.40
Total	11.92(3.26)**	23.47(1.60)***	0.30(0.27)	0.44

Table 3.4. Model fit of Olson, linear and quadratic curves to field surveyed fuel load estimates (t / ha) for surface, surface + near-surface, near-surface, elevated and total fuel fuel layers. Akakie Information Criterion (AIC) was used to rank model fit whereby the 'best' model (shown in black) is that which had the lowest AIC values.

Model trajectory	AIC values				
	Surface fuels	Surface + near-surface fuels	Near-surface fuels	Elevated fuels	Total fuels
Olson (no Initial)	106.67	78.48	113.51	61.63	116.63
Olson (Initial)	**106.02**	59.67	107.19	n/a	107.11
Linear	110.61	62.51	113.37	50.08	113.93
Quadratic	106.25	**57.93**	**106.34**	**48.72**	**104.60**

3.4 Synthesis and suggested values for Phoenix

General overview of fuel parameters in Forested Wetlands

Information regarding fuel load accumulation in Forested Wetlands was scant. Of the studies presented here, three (including our field survey) quantified litter fall and litter loads in Coastal Forested Wetlands and two quantified litter fall and litter loads in semi-arid Inland Riverine Wetlands. The paucity of studies quantifying fuel loads in Forested Wetlands adds some uncertainty to the fuel load parameter estimates presented here.

Studies quantifying litter loads were in two discrete groups, those surveying temperate coastal Forested Wetlands and those surveying semi-arid inland Forested Wetlands. Annual rainfall was much greater for coastal (1217 mm) than inland (396 mm) area, whereas average annual summer maximum temperatures were greater for inland (31 ˚C) than coastal (26 ˚C) areas. Fuel parameters for *L* and *Limit* were on average greater for coastal Forested Wetlands than inland Forested Wetlands (Table 3.2). These differences probably stemmed from higher nutrient levels and nutrient cycling in moist coastal forests where rates of litter accumulation and decomposition were probably high, as opposed to dry inland forests where rates of litter accumulation and decomposition were probably low. Unfortunately, *k* estimates were not available for inland Forested Wetlands. However, because Briggs and Maher (1983) and Glazbrook and Robertson (1999) conducted their surveys in similar areas along the Murray river, we calculated *k* from *L* and *Limit* parameters provided by these studies. *k* was 0.37. This values was less than the *k* values averaged between the Coastal Forested Wetlands studies (*k* = 0.47; Table 3.2), presumably because regular inundation in coastal areas facilitated decomposition and litter removal. *k* parameters for coastal Forested Wetlands suggest decompositions rates can be very high when compared with other vegetation classes such as for Heathlands (Table 2.10; Watson, 2012).

Table 3.5 Values of *L*, *Initial*, *Limit* and *k* for studies quantify a) litter, b) litter + herb and c) total fuels < 6 mm in Forested Wetlands of New South Wales. R'g represents weighting of confidence and relevance.

Source	Forested wetland class	L	Initial	Limit	k	R'g
a) Litter fuels						
Greenway (1994)	Coastal Swamp Forest	6.83	-	26.30	0.26	2
Our field survey	Coastal Swamp Forest	6.82	5.00	14.50	0.47	
Clarke and Allaway (1996)	Coastal Floodplain Wetland	7.70	-	11.32	0.68	3
Briggs and Maher (1983)	Inland Riverine Forest	4.31	-			3
Glazbrook and Robertson (1999)	Inland Riverine Forest		-	11.72		3
b) Litter + herb fuels						
Our field survey	Coastal Swamp Forest	6.57	9.73	21.19	0.31	
c) Total fuels						
	Sydney Coastal Heaths	7.04	11.92	23.47	0.30	

For temperate Forested Wetlands litter fuels, *Limit* values averaged between the two Coastal Swamp Forest studies (*Limit* = 20.40) were higher than those for the Coastal Floodplain Wetlands study (*Limit* = 11.32). Conversely, *k* values averaged between the two Coastal Swamp Forest studies (*k* = 0.37) were lower than those for the Coastal Floodplain Wetlands study (*k* = 0.68). This result is somewhat surprising given that both vegetation classes occupy similar spatial and climatic areas. However Coastal Swamp Forests typically occur in low elevation coastal areas with sandy soils, whereas Coastal Floodplain Wetlands typically occur on river flats. Because Coastal Floodplain Wetland occur along-side rivers it is likely that inundation occurs more regularly than in Coastal Swamp Forests. Semi-regular inundation of Forested Wetlands is thought to: 1) constrain the floristic structure of vegetation communities by physically altering habitat (Pressey and Harris, 1988, Keith, 2004), 2) increase litter decomposition by increasing soil moisture content (Pressey and Harris, 1988, Greenway, 1994, Clarke and Allaway, 1996) and 3) physically remove litter. Because of this, we propose that the divergent trends in *Limit* and *k* observed here between Coastal Swamp Forests and Coastal Floodplain Wetlands may have resulted from increased rates of litter decomposition and physical litter removal by regular river inundation in Coastal Floodplains site. This assertion is speculatory however.

Although empirical data relevant for fuel load parameterisation were scarce, information regarding site-specific processes influencing litter fuel accumulation and flammability in Forested Wetlands was more commonly encountered. First, data presented by Clarke and Allaway (1996) suggest that inundation removes large quantities of litter. Thus litter accumulation is a function of inundation frequency. Second, Boon and Johnstone (1997) suggest that oil derived from the leaves and twigs of *Melaleuca* spp. but not *Casuarina* spp. may slow the decomposition of organic matter in *Melaleuca*-dominated wetlands through inhibiting microbes present in *Melaleuca* spp. leaves. Thus decomposition is a function of chemical leaf properties. Third, because flammability is a function of litter moisture content (Bradstock, 2010), even if large quantities of litter fuel are present, these litter fuels will not burn if litter is moist following inundation. Thus litter flammability is a function of interplay between inundation timing and prevailing weather conditions which facilitate litter drying. Fourth, Glazebrook and Robertson's (1999) study demonstrated considerable seasonality in standing litter loads; litter loads were highest in spring and summer when rates of litter fall (and fire risk) were high. Thus season is likely to be an important determinant of litter loads.

Our field survey was the only study to quantify herb or shrub fuel loads. This study suggested that post-fire herb and shrub fuels accumulate via a quadratic (and not Olson) curve whereby fuel loads are greatest at intermediate fuel ages. Fuel hazard score to fuel load conversion tables present in the DSE fuel hazard assessment guide suggested that herb and shrub layer fuels peaked 12 years post-fire at 7.5 t / ha and 3.75 t / ha, respectfully. Although conversion tables in the DSE fuel hazard assessment guide provided an estimate of fuel load, qualitative observations made during the field survey suggest that herb fuels can be very dense in Coastal Swamp Forests. Given this, and the fact that the DSE fuel hazard assessment guide was developed for fuel load assessment in Dry Schlerophyll where processes controlling herb growth are likely to be vastly different from those in Coastal Swamp Forests, it is likely that our field survey estimates for *Limit* under-estimate herb fuel loads. Qualitative observation made during our field survey accord with the DSE fuel hazard assessment guide in suggesting that shrub layer fuels are consistently low at all time-since-fire ages in Coastal Swamp Forests.

A final note regarding fuel dynamics in Forested Wetlands is that our field survey showed that the Olson curve was a poor predictor of fuel accumulation for all fuel layers excluding litter fuels. In lieu of an Olson curve, a quadratic curve (whereby fire fuels are greatest at intermediate time-since-fire ages) best describe trends in post-fire fuel accumulation. Because of this, the Olson curve may dramatically underestimate litter + herb, herb and shrub fuel load at older time-since-fire fuel ages. Although we suggest Olson curve fuel parameters below, we stress that fire management actions which use our suggested Olson curve fuel parameters may over-estimated fuel loads at older time-since-fire fuel ages.

Fuel parameters for management applications in Coastal Swamp Forests

For litter fuels, *Limit* values were higher and *k* values lower for Greenways (1994) than for our field survey. However because *k* values were higher for our study than Greenways (1994) it is likely that standing fuel loads, at least at younger and intermediate time-since-fire fuel ages, are similar between the two studies. Because of this we have averaged *Limit* and *k* parameters for these studies to suggest a *Limit* value of 20.4 t / ha and a *k* value of 0.37. Our field survey was the only study to suggest *Initial* values for litterfuels, being 5.00 t / ha. This value seems very high given that Sandercoe (1989, 1992) showed 3.5 t / ha of total fuel remained in a Coastal Swamp Forests six months after fire. However in the absence of any other data we suggest this value with a caveat that it may over-estimate *Initial*. Suggested litter fuel parameters are: *Initial* = 5.00, *Limit* = 20.4, *k* = 0.37.

For litter + herb fuels, our field survey suggested Olson curve fuel parameters of *Initial* = 9.73, *Limit* = 21.19, *k* = 0.31. Because 1) our field survey showed a *Limit* value of 6.86 t / ha for herbs fuels alone and 2) our suggested *Limit* parameter for litter fuels alone was 20.4 t / ha (see paragraph above), it is likely that the *Limit* value for litter + herb fuels of 21.19 t / ha under-estimates near-surface fuel loads. This probably occurred because an Olson curve best described post-fire litter fuel accumulation, however a quadratic curve best described post-fire herb fuel accumulation (i.e. the fit of the Olson curve to the litter + herb fuel layer was poor). For the above mentioned reasons, we have added the *Limit* value from our field survey for herb fuel alone (*Limit* = 6.86) to the *Limit* value for litter fuels alone (see above paragraph; *Limit* = 20.4) to suggested a *Limit* value for litter + herbs of 27.26 t / ha. In accord with our rational to suggest *Limit* values for the litter +herb fuel layer, we have averaged *k* values between the litter fuel layer alone (see paragraph above, *k* = 0.37) and the herb fuel layer alone (from our field survey; *k* = 0.13) to suggest a value for *k* of 0.25. The *Initial* values produced by our field survey for litter + herb fuels was extremely high (9.25 t / ha) and is likely to have over-estimated the amount of fuel remaining after a fire. Thus for management applications we suggest a conservative value for *Initial* of 5.00 t / ha. Suggested litter + herb fuel parameters are: *Initial* = 5.00, *Limit* = 27.26 , *k* = 0.25.

No studies (including ours) suggested Olson fuel parameters for the shrub fuels. This noted, our field survey suggested that elevated fuels are a relatively unimportant fuel element in Coast Swamp Forests, with *Limit* values at ~ 3.75 t / ha.

3.5 Knowledge gaps and future research

Few studies have quantified fuels loads in Forested Wetlands of New South Wales. Even fewer have quantified fuel loads in Coastal Swamp Forests. This lack of replication must be considered when interpreting the fuel load estimates presented here. Although little empirical data exists regarding fuel load accumulation in Forested Wetland, corroborative evidence suggests that: 1) fuel loads can accurate quickly following fire, 2) litter accumulation is dependent on inundation which removes litter fuels, 3) litter accumulation is seasonal 4) litter fuel decomposition rates are often high due to the presence of moist soils, and 5) litter decomposition is influenced by chemicals present in dominant tree / shrubs leaves.

To better understand fuel load accumulation in Forested Wetlands, more studies quantifying litter, herb and shrub fuel loads over large spatial and temporal areas are needed. Such research will also need to develop empirical models which quantify fuel load characteristics in relation to water inundation, spoil moisture profiles, climatic variability and season. Information regarding fuel loads present immediately following fire (*Initial* fuel parameters) is also needed.

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