Chapter 1.

Introduction

1.1. Background to research

Woody fuels (diameter, $d > 0.6$ cm) have an essential role in Australian forest ecosystems. Commonly referred to as coarse woody debris (CWD) in ecological studies, dead and downed woody fuels support many ecological functions and processes that contribute to biological diversity. CWD provide structural complexity and habitat on the forest floor, are a source for nutrient cycling and a substrate for many organisms that depend on dead wood for their survival.

Consumption of woody fuels in forest fires contributes to several important features relating to fire behaviour, fire suppression and firefighter safety. Woody fuels are a significant store of carbon which, when consumed by fire contribute to emissions of greenhouse gas (including carbon dioxide, carbon monoxide and methane) and smoke. Consumption of woody fuels also impacts a variety of first- and second-order fire effects such as soil heating and tree mortality associated with the heating of tree boles and superficial roots.

The ability to accurately predict woody fuel consumption is therefore essential in:

- wildfire management and suppression;
- planning prescribed fires;
- forest management and biodiversity conservation;
- determining greenhouse gas and smoke emissions resulting from fires and
- planning for the impacts of climate change.

Previous studies of woody fuel consumption in Australian forests have been relatively scant, yet have provided general figures for woody fuel consumption that are limited to specific forest types, fuel complexes and fire types. Several models have been developed to predict woody fuel consumption in North American forests, while in Australia current estimates used by the Australian Greenhouse Office are based on an assumption whereby 50% of a sites woody fuel load will be consumed under the diverse range of fire conditions (Gould and Cheney, 2007). Given the variability in the proportion of woody fuel consumption between and within forest, fuel and fire types, the development of a national model for woody fuel consumption requires greater depth, capturing deviations where woody fuel consumption has been particularly high or low. The capacity for existing models to be applied to fires in southern Australian eucalypt forests has been untested.

In particular, the effect of fireline intensity on woody fuel consumption has been widely reported in literature however the conclusions from different studies are not consistent and not necessarily applicable to Australian eucalypt forest fires. This has resulted in uncertainty about the effect of fireline intensity, particularly the difference in proportion of woody fuel consumed during high intensity wildfires compared to low intensity prescribed burns. Knowing the effect of fireline intensity on woody fuel consumption is necessary in order to understand the underlying processes affecting consumption of woody fuels and to develop a model that can be applied across a variety of southern Australian eucalypt forests and fire types.

1.2. Project and thesis objectives

This PhD thesis is an integral part of the Woody Fuel Consumption Project (WFCP) which began in 2007. The research objectives of the project and thesis are as follows:

1. To evaluate the predictive capacity of existing woody fuel consumption models and to assess their potential for application in Australia using woody fuel consumption data collected throughout southern Australian eucalypt forests. Five models were evaluated including:
    1. CONSUME Activity (Prichard *et al.*, 2005);
    2. CONSUME Western Woody (Prichard *et al.*, 2005);
    3. CONSUME Southern Woody (Prichard *et al.*, 2005);
    4. BURNUP (Albini and Reinhardt, 1995) and
    5. Australian National Carbon System Accounting System (ANCAS) recommendation for 50% consumption of woody fuels (Gould and Cheney, 2007).
2. To investigate potential variables affecting woody fuel consumption across different Australian eucalypt forests including fuel, weather, season and fire behaviour characteristics.
3. To develop an empirically based model of woody fuel consumption for southern Australian eucalypt forest fires using data collected under a wide range of burning conditions.

1.3. Thesis structure

This thesis is presented in six chapters and an appendix.

Chapter 1 is an introduction.

Chapter 2 reviews literature relating to woody fuel in southern Australian eucalypt forests and its consumption by fire. The material presented in this chapter establishes the role of woody fuel in Australian eucalypt ecosystems and why forest and fire managers require tools to ascertain the effect of fire on downed wood resources. Sections included specifically relate to:

1. ecological attributes and values of coarse woody debris;
2. role of woody fuel consumption in carbon cycles and greenhouse gas emissions and
3. factors affecting and importance of woody fuel consumption.

References cited in Chapters 2 and 6 are included at the end of Chapter 2.

Chapter 3 evaluates the performance of existing woody fuel consumption models and presents methods used for collecting field data. The potential for application of models in southern Australian eucalypt forest fires is discussed. Chapter 3 is presented as it was published in Volume 260 of *Forest Ecology and Management* in 2010, however it has been reformatted in the style of this thesis.

Chapter 4 examines the effect of fireline intensity on woody fuel consumption in southern Australian eucalypt forest fires. A model for predicting woody fuel consumption based on fireline intensity is presented. Chapter 4 is presented as it was accepted for publication in *Australian Forestry* in October 2010, however it has also been reformatted in the style of this thesis.

Chapter 5 discusses variables that potentially affect woody fuel consumption and presents an empirical model to best predict woody fuel consumption based on the analysis of these variables in a dataset relating to eucalypt forest fires in southern Australia. Chapter 5 is presented as it was accepted for publication in *Forest Ecology and Management* in March 2011, however has been reformatted in the style of this thesis.

Chapters 3, 4 and 5 have been written as manuscripts for publication and so some repetition in background information and methodology will be evident.

General conclusions and management implications from this research are brought together in Chapter 6. Recommendations for further research are also discussed.

An article written as part of this work and published in *Landscope* is included in published form in Appendix 1.

Chapter 2.

Review of woody fuel consumption in southern Australian eucalypt forest fires

2.1. Coarse woody debris: ecological attributes and values

Coarse woody debris (CWD) support many functions and processes within Australian forest ecosystems. CWD have an essential role contributing to biological diversity and ecosystem processes (Harmon *et al.*, 1986; Grove and Meggs, 2003; Woldendorp and Keenan, 2005) and have been described as being among the most important of biological legacies within disturbed forests (Franklin and MacMahon, 2000). CWD strongly affect the spatial pattern of biota distribution and the rate of post-disturbance recovery of biodiversity (Lindenmayer, 2009). Recognition of their ecological value has contributed to their increasing prominence in forest management strategies throughout Australia (Williams and Faunt, 1997; Woldendorp *et al.*, 2002a; Woldendorp and Keenan, 2005).

The particular value and functional roles of CWD have been the subject of extensive research both internationally (Harmon *et al.*, 1986) and within Australia (Lindenmayer *et al.*, 2002; Grove and Meggs, 2003; Woldendorp and Keenan, 2005). By adding to the structural complexity of the forest floor CWD foster the diverse range of microhabitats required to enable a multitude of species and individuals to co-exist together (Maser and Trappe, 1984; Harmon *et al.*, 1986; Lindenmayer *et al.*, 1999; Grove and Meggs, 2003). In some forest habitats, structural complexity appears to be more significant than vegetation composition in determining the native, terrestrial reptile and small mammal species assemblages (Garden *et al.*, 2007).

In addition to adding fuel to forest fires (Section 2.3) and being a major source or sink of carbon (Section 2.2), CWD have the capacity to support a diverse range of biota that is often distinctly different to those found in other habitat elements (Driscoll *et al.*, 2000). The different organisms dependent on CWD prefer unique microhabitats, the characteristics of which are often intertwined and complex such as:

- varying degrees of decay;
- log volume, diameter and length;
- location, orientation and suspension;
- moisture retaining properties;
- structural complexity, continuity and spatial connectivity;

- number and size of hollows;
- fire effects and
- fungal and termite associations.

These are discussed in detail in Sections 2.1.1 – 2.1.8.

CWD have many functional roles within forest ecosystems including:

- providing substrates and sites for nesting, shelter and protection, basking, foraging, reproduction and a place for key social behaviours for a diverse variety of forest dependent animals;
- providing runways and spatial connectivity to assist the movement of terrestrial animals;
- providing mesic habitat and protection for organisms during drought and/or fire;
- food sources and foraging sites for invertebrates;
- habitat and substrate for fungi, lichens and mosses;
- nursery sites for the establishment of seedlings and the development of plants including ferns;
- a long term energy source for nutrient cycling;
- a site for carbon storage and nitrogen fixation;
- fuel for forest fires and
- soil stability.

2.1.1. Structural complexity

Branches, limbs and trunks which once were part of the living trees and forest shrubs eventually make their way to the forest floor and become CWD. There are many causes that initiate this change including:

- disturbances such as wind (windthrow), snow, fire, insect damage and disease, drought and forest management practices (Stevens, 1997; Raison and Squire, 2007) and
- natural forest processes such as intra- and inter-specific competition, senescence and slope failure (Stevens, 1997).

Each situation varies enormously and is influenced by the local terrain, geology and geography (aspect, slope, soil depth), as well as forest structure (tree age, characteristics and species)

(Stevens, 1997). Once on the ground a succession of complex interactive processes begin including: colonization, decomposition, weathering, fragmentation, leaching, collapse, seasoning, respiration and species utilisation. Each successive stage is characterised by its own unique species (Harmon *et al.*, 1986; Mackensen and Bauhus, 1999; Boddy, 2001; Grove and Meggs, 2003). A continuum of CWD in varying stages of decay adds to the structural complexity of the forest floor, creating a range of microhabitats that support a diversity of species and individuals that co-exist together at any one time (Harmon *et al.*, 1986; Grove and Meggs, 2003). Many species are highly specialised and rely on CWD with specific attributes (Driscoll *et al.*, 2000). Thus decomposition results from a succession of organisms with intertwined and complex relationships and forests that have CWD with a full range of attributes will also have high species diversity.

Fire disturbance has varied impacts on the CWD attributes that support so many organisms. For example, Converse *et al.* (2006) reported that fire reduces CWD load. Such modifications to CWD attributes determine the response of CWD dependent forest organisms to both prescribed fires and wildfires. A literature review of the various impacts of fire on CWD is presented in Section 2.3. Attributes of CWD that influence the type and extent of animal use are discussed below.

2.1.2. State of decay

Decomposition of CWD is affected by a wide variety of factors including:

1. Forest type and structure:
    a. tree species (Yin, 1999; Schwarze *et al.*, 2000; Whitford and Williams, 2001; Lindenmayer *et al.*, 2002; Garrett *et al.*, 2007);
    b. substrate chemistry and wood density (Edmonds *et al.*, 1986; Edmonds, 1991);
    c. substrate quality (Mackensen and Bauhus, 1999; Garrett *et al.*, 2007);
    d. substrate position and suspension above the ground (Erickson *et al.*, 1985; Edmonds *et al.*, 1986; Lindenmayer *et al.*, 2002; Garrett *et al.*, 2007) and
    e. length and diameter (Erickson *et al.*, 1985; Edmonds *et al.*, 1986; Brown *et al.*, 1996; Lindenmayer *et al.*, 2002; Garrett *et al.*, 2007).
2. Local environmental conditions:
    a. precipitation, soil and available moisture (Erickson *et al.*, 1985; Brown *et al.*, 1996; Mackensen and Bauhus, 1999; Whitford and Williams, 2001; Mackensen *et al.*, 2003; Garrett *et al.*, 2007) and

b. mean annual air temperature (Mackensen and Bauhus, 1999; Yin, 1999; Garrett *et al.*, 2007).

3. Interaction with successional processes and biological factors acting upon it (Edmonds, 1991; Stevens, 1997; Yin, 1999; Yee *et al.*, 2001; Lindenmayer *et al.*, 2002).

4. Disturbance, for example timber harvesting or fire (Edmonds, 1991; Mackensen and Bauhus, 1999; Shorohova *et al.*, 2008).

Mean annual temperature is an important factor controlling decomposition of CWD and accounts for 34% of variation in decay rates of different species throughout Australia (Mackensen *et al.*, 2003). Factors controlling the decomposition rate of CWD are likely to vary between biomes, reflecting both environmental and biological influences.

The stage of decay can influence nutrient cycling (Harmon *et al.*, 1986; McCarthy and Bailey, 1994), the ability for CWD to stabilise soils (Woldendorp *et al.*, 2004) and store carbon (Mackensen *et al.*, 2003) and impacts significantly on diversity and habitat suitability for CWD dependent biota (Harmon *et al.*, 1986; Grove, 2002; Woldendorp and Keenan, 2005; Lindenmayer *et al.*, 2009). The CWD dependent species that make up diverse forest populations require a wide range of decay states resulting in significant implications for forest and land managers (Lindenmayer *et al.*, 2002).

The process of decay is slow and once on the ground, complex interactive processes that influence the decomposition of CWD begin. Drying promotes shedding of bark and formation of wood cracks that allow water to enter. Bacteria, invertebrates and fungi are provided with suitable conditions to colonise the CWD. A succession of fungal and microbial communities alter the structure and chemistry of wood resulting in different types of decay such as brown and white rots and wet or dry rots (May and Simpson, 1997; Yee *et al.*, 2001). Across time and space different lichens, mosses, fungi and invertebrates are present depending on the stage of decay and local environmental conditions (Driscoll *et al.*, 2000; Yee *et al.*, 2001). Some are primarily associated with the bark, while others specialise in rotting heartwood or sapwood. Logs in the most advanced stages of decay have been shown to support the richest bryophyte (moss and liverwort) flora (Ashton, 1986).

As decay proceeds, nutrients are added to the surrounding soils (Harmon *et al.*, 1986; McCarthy and Bailey, 1994; Brown *et al.*, 1996; Garrett *et al.*, 2007). Cycles of wetting and drying enlarge cracks, funnelling water into the heart of the log and assisting the decay process and creating a moist environment (Hollis *et al.*, 2008). Cracks and crevices that form provide suitable habitat and mesic protection during drought and fire for reptiles such as Napoleon's skink (*Egernia napoleonis*) (Figure 1) which shelter and hide in the cracks (Lindenmayer *et al.*, 2002). Survival of litter-dwelling stag beetles in Tasmanian wet forests during post-harvest burns has been attributed to the ability of the beetle to take refuge beneath large logs (Michaels and Bornemissza, 1999). Some species of skink such as *Sphenomorphus tympanum* and *Pseudemoia spenceri* also shelter deep inside CWD cracks over winter, attracted to the stable microclimate and protected from cold winter temperatures (Webb, 1985).

Figure 1. Napoleon's skink shelters and hides in the cracks and under the bark of coarse woody debris.

For large logs, decomposition can often take several hundred years to achieve 95% decay with those in moist environments decaying quicker than small CWD in dry environments (Erickson *et al.*, 1985; Edmonds *et al.*, 1986; Harmon *et al.*, 1986; Edmonds, 1991; Brown *et al.*, 1996; O'Connell, 1997; Mackensen and Bauhus, 1999; Garrett *et al.*, 2007). Disturbances such as wildfires also affect the decay state of forest CWD. By charring CWD, fire encourages resistance to decay, decreasing decomposition rates and modifying the chemical composition (Mackensen and Bauhus, 1999; Shorohova *et al.*, 2008).

The relationship between the decay state of CWD and small mammal abundance appears variable, with Bowman *et al.* (2000) reporting no significant effect but other studies suggesting that decay state strongly affects the suitability for vertebrates to utilise CWD (Harmon *et al.*, 1986). By influencing the development of hollow size and formation (Williams and Faunt, 1997) logs of varying decay provide a varied habitat suitable for many animals. For examples, the chuditch (*Dasyurus geoffroyii*) in south-western Western Australia utilise nesting hollows in large logs with decayed heartwood (Williams and Faunt, 1997) and populations of *Euperipatoide rowelli* invertebrates which prefer a minimum age of 45 years to allow sufficient decomposition (Barclay *et al.*, 2000). Mt Mangana beetles (*Lissotes latidens*) depend on rotting logs as the adult and larvae live entirely within decayed logs where the larvae can feed on fungi (Forest Practices Board, 1998). Other invertebrates such as termites can utilise CWD and influence the progression of decay and species utilisation at any time.

Many authors have defined decay status by differentiating the characteristics into a number of decay classes depending on the purposes of the study (Table 1).

Table 1. Decay classes and definitions from previous studies in Australian and North America.

Decay Class	Lindenmayer *et al.* (1999)[a]	Maser *et al.* (1988)	Whitford and Williams (2001)[a]	Woldendorp *et al.* (2002a)[a] (based on Pyle and Brown (1999))	Tolhurst *et al.* (2006)[a]
1	Solid log, bark intact, and recently fallen	Bark intact. Twigs present. Texture intact. Round shape. Original colour. Tree elevated on support points. Nil invading roots.	Bark intact. Sapwood hard/brown. Round shape. Log free of ground. Fissures absent. Moss absent. Heartwood hard. Minor branches intact. Nil regeneration at stump, bare ground.	Bark firmly attached. Wood has ‘fresh’ colour (not stained by weathering). Branches retain many small twigs. Bark present but not firmly attached. Log is in a solid piece (though decay may be present).	Solid. Bark mostly attached. Wood density: 550 kg/m^3.
2	Solid log, and no bark	Bark intact. Twigs absent. Texture intact/partly soft. Round shape. Original colour. Tree elevated on support points: sagging slightly. Nil invading roots.	Bark trace. Sapwood hard/grey to light brown. Round shape. Log free of ground. Cracks possible. Moss absent. Heartwood hard. Minor branches intact. Some litter, small weeds at stump.	Branches may retain many small twigs. Bark may be present but not firmly attached. Log is in a solid piece (though decay may be present).	Solid. No bark. Wood density: 600 kg/m^3.
3	Some decomposition of log, soft sapwood, and soil heart wood	Bark trace. Twigs absent. Texture hard, large pieces. Round shape. Original colour. Tree sagging near ground. Invading roots in sapwood.	Bark absent. Surface cannot be scuffed off with boot, grey. Round shape. Log in contact with ground. Cracks. Moss absent. Jarrah heartwood hard, marri might be starting to collapse. Major branches intact of not burnt away. Some litter, small weeds at stump.	Log may be in a solid piece (though decay may be present). When log is thudded perpendicularly, wood surface may flake off (2-7 cm flakes or larger) or shreddy flakes may remain attached to log or wet surface may flatten then rise back. Log is a solid piece with decay easily seen.	Solid, cracks to core (> 10mm wide). Wood density: 575 kg/m^3.
4	Intermediate decomposition, soft sapwood or sapwood not present soft heartwood, and log “breaking-up'”	Bark absent. Twigs absent. Texture small, soft, blocky pieces. Round to oval shape. Light brown/reddish colour. All of tree on ground. Invading roots in heartwood.	Bark absent. Surface cannot be scuffed off with boot, ends hard to break off, grey. Round shape. Log in contact with ground. Cracks present, fissuring 1-2 cm deep/8-10 cm apart. Moss possible. Jarrah hard, marri collapsing. Major branch stubs or none. Litter cover, small acacias.	Log may be a solid piece with decay easily seen. Log shape may be oval. Log is no longer a solid piece, but large chunks of wood remain. Kicked log may cleave into large pieces. Log may crush when thudded with a foot. Log may be predominantly powdery wood (> 85%, class 5). Log shape may be flattened.	Sapwood decayed. Heartwood solid. Wood density: 550 kg/m^3.

Decay Class	Lindenmayer *et al.* (1999)[a]	Maser *et al.* (1988)	Whitford and Williams (2001)[a]	Woldendorp *et al.* (2002a)[a] (based on Pyle and Brown (1999))	Tolhurst *et al.* (2006)[a]
5	Advanced decomposition of log, soft sapwood and heartwood (if identifiable), and log fragmented	Bark absent. Twigs absent. Texture soft and powdery. Oval shape. Red brown/dark brown colour. All of tree on ground. Invading roots in heartwood.	Bark absent. Surface sapwood crumbly. 95% round shape. Log in contact with ground for full length. Fissuring 2 cm deep/10 cm apart. Moss present. Jarrah hard but decay present, marri collapsing. Major branch stubs or none. Litter cover, bracken or larger plants.	Log shape may be oval. Log may crush when thudded with a foot. Log is predominantly powdery wood (< 85%, class 4). Log shape may be flattened.	Decaying. Maintaining size integrity ± cavities. Wood density: 500 kg/m^3.
6			Bark absent. Sapwood easily broken away by hand. 90% shape. Log in contact with ground for full length. Moss present. Heartwood can be broken away by hand. Nil branches. Litter cover, bracken or larger plants.		Decaying. Partial collapse. Loss of shape. Still some solid wood. Wood density: 400 kg/m^3.
7			Bark absent. Sapwood missing on parts of log. 75% shape. Sitting on ground. Fissures 3-4 cm deep. Moss present. Heartwood easily broken away by hand and crumbled. Nil branches. Litter cover, bracken or larger plants.		Decayed. Blocky brown decayed wood. Punky remains. Wood density: 300 kg/m^3.
8			Bark absent. Sapwood gone. 50% shape. Sitting on ground. Fissures 5-7 cm deep. Moss may be absent. Heartwood easily kicked away. Nil branches. Similar to surrounding ground cover.		
9			Bark absent. Sapwood gone. < 25% shape. Merging with ground. Deep furrows in log surface. Moss may be absent. Heartwood rotten/ easily kicked away. Nil branches. Similar to surrounding ground cover.		
10			Bark absent. Sapwood gone. 10% shape. Only trace evidence of log remains. Moss may be absent. Heartwood rotten/ easily kicked away. Nil branches. Similar to surrounding ground cover.		

[a] Australian specific study.

2.1.3. Volume and dimensions characterising CWD

Within a forest ecosystem, the type and extent of biota usage is influenced by the volume and dimensions characterising forest CWD (Harmon *et al.*, 1986). The size of downed wood is critical in determining species type, richness, incidence, abundance and duration of use (Harmon *et al.*, 1986; Driscoll *et al.*, 2000; Grove and Meggs, 2003). Different species utilise downed wood of different sizes (Driscoll *et al.*, 2000). For example many rare and threatened insects are reliant on large diameter dead wood (Warren and Key, 1991) including the blind velvet worm (*Tasmanipatus anophthalmus*) which is associated with logs greater than 50 cm in diameter (Mesibov and Ruhberg, 1991). Barclay *et al.* (2000) have suggested that longer log lengths, together with larger log volumes and higher numbers of logs will assist velvet worms to find suitable habitat. Some species of fungi have also been found to be associated with only large diameter logs, for example *Podoscypha petaloides* are only associated with large logs in advanced stages of decay (McMullan-Fisher *et al.*, 2002).

In wet regions of south-western Australia, large logs also provide suitable moss-covered habitat for ferns like the forked spleenwort (*Asplenium aethiopicum*) (McCaw, 2006). The incidence of some reptiles including Coventry's skink (*Niveoscincus coventryi*) have also been reported to be related to the diameter and surface area characteristics of downed wood (Brown and Nelson, 1993). Brown and Nelson (1993) found that the total reptile count in mountain ash (*Eucalyptus regnans*) forest was significantly correlated with log diameter. The large hollows that only large logs can support (Williams and Faunt, 1997) are also critical for a number of hollow nesting mammals including chuditch which require entry widths and internal diameters greater than 15 cm (Faunt, 1992). Grove (2002) suggested that the preference shown by many organisms for larger logs is largely due to the heterogeneity of the resource being capable of supporting many co-existing specialist species. Grove also suggested that large diameter logs have a slower decomposition rate creating suitable habitat over a longer period and supporting more species of fungi.

Large volumes of CWD can occur in southern Australian eucalypt forests (Raison and Squire, 2007). In addition to affecting stored carbon and nutrient cycling (Harmon *et al.*, 1986), the overall volume of CWD within a forest has significant impacts on habitat availability and the preferences of biota (Woldendorp and Keenan, 2005; Lindenmayer, 2009; Lindenmayer *et al.*, 2009). While some authors have reported that species abundance may not be related to the volume of CWD (Hadden and Westbrooke, 1996; Driscoll *et al.*, 2000), others have noted the reliance of particular species on specific CWD volumes or loads. For example Barclay *et al.* (2000) found that of many environmental variables, the volume of CWD had the strongest association with the abundance of onychophorans. Grove (2000) has reported that invertebrate species richness in Australian lowland tropics is strongly correlated with amount of CWD. The yellow-footed antechinus (*Antechinus flavipes*) is also known to prefer sites with higher loads (> 45 t ha^{-1}) of CWD (Mac Nally *et al.*, 2001; Mac Nally and Horrocks, 2002). Another example, the brown treecreeper (*Climacteris picumnus*) has also been found to occur in larger numbers in forest floodplains with higher CWD loads where they forage on or near logs (Mac Nally *et al.*, 2002; Mac Nally, 2006).

CWD quantity and volume vary considerably within and between forest types depending on:

- forest age and structure (e.g. tree size and number of stems per unit area) (Woldendorp and Keenan, 2005);
- wood durability (or decay resistance) (Mackensen and Bauhus, 1999);
- disturbance regimes including historical silvicultural and forest management practices, fire history, windthrow and insect damage (Burrows, 1994; Meggs, 1996; Stevens, 1997; Woldendorp and Keenan, 2005; Raison and Squire, 2007) and
- the decomposer and climatic conditions that determine decomposition (Woldendorp and Keenan, 2005).

Woldendorp *et al.* (2002a) reviewed published and some unpublished literature to estimate the load (or in some cases, volume) of CWD in Australian forests. The average CWD load across studies for dry sclerophyll was 51 t ha^{-1} and 109 t ha^{-1} for wet sclerophyll forests. Table 2 summarises these estimates together with other reported values for various southern Australian eucalypt forests. It was unclear in some studies what minimum downed wood diameter was used, however because larger logs contribute most of the load or volume of CWD at a site (Hollis *et al.*, 2010), small variation in minimum downed wood diameter is expected to have little impact on reported values. Tasmanian wet sclerophyll forests have some of the highest volumes of CWD in the world (Turnbull and Madden, 1986; Meggs, 1996; Woldendorp *et al.*, 2002b; Grove and Meggs, 2003) sometimes exceeding 1000 t ha^{-1}. Woldendorp and Keenan (2005) suggested that this could be due to the height and diameter of trees which are often up to 60 m in height and 3.7 m diameter at breast height. The authors also suggest that the high latitude and cool temperate climate of the region slows down the decomposition process encouraging greater turnover times and quantities of large-sized CWD which remain on the forest floor for longer. Mackensen and Bauhus (1999) found that these turnover times can be up to 375 years for *E. camaldulensis* and *E. tereticornis* wood.

The natural fall and accumulation rate of large logs is slow (Lindenmayer *et al.*, 1991; Lindenmayer and Franklin, 1997; Whitford and Williams, 2001) and hence the provision of tree and log hollows large enough for many vertebrates is equally slow. Together with the reduction in CWD volumes and downed wood size diversity as a result of fuel reduction burning, short harvesting rotations and other silvicultural practices (Mac Nally, 2006) as well as the utilisation for firewood and char logs, has resulted in increasing prominence of CWD management strategies in forest ecosystems.

Table 2. Australian southern eucalypt forest CWD volumes.

Study/Reference	Forest Type	CWD load/volume ($t\ ha^{-1}$ except where noted)	Defined minimum downed wood diameter (cm)
	Dry sclerophyll		
Hingston *et al.* (1980)	*Eucalyptus marginata*, *E. calophylla*	130	-
Stewart and Flinn (1985)	*E. radiata, E. dives*, *E. viminalis*	221	7
Adams and Attiwill (1986)	*E. obliqua*	5	-
	E. sideroxylon	8	
	E. microcarpa	5	
Hamilton *et al.* (1991)	*E. obliqua*, *Banksia spinulosa*, *Hakea sericea*	49	2
Burrows (1994)	*E. marginata*	37	0.6
Robinson (1997)	*E. camaldulensis*	24-130	10
Mac Nally *et al.* (2000)	*E. camaldulensis*	12-24	10
Bradshaw (2007)	*E. marginata*	35-80	-
Hollis *et al.* (2010) Woody Fuel Consumption Project	*E. marginata*	42-175	0.6
Hollis *et al.* (2010) Project Aquarius	*E. marginata*	33-107	1
	Moist sclerophyll		
Ashton (1975)	*E. regnans*	11-13	-
Applegate (1982)	*E. pilularis*	33-138	-
Baker and Attiwill (1985)	*E. obliqua*	4-67	2
Adams and Attiwill (1986)	*E. regnans*	13-26	-
	E. delegatensis	24	
	E. obliqua	9	
Turnbull and Madden (1986)	*E. obliqua*	774-1089	1
Ash and Helman (1990)	*E. maculata*, *E. botryoides*, *E. pilularis*	8	5
Buckley and Corkish (1991)	*E. seiberi*, *E. globoidea*	159-234	2.6
Polglase and Attiwill (1992)	*E. regnans*	0-13	1
Meggs (1996)	*E. obliqua*	174-455 $m^3\ ha^{-1}$	-
Jones (1998)	wet sclerophyll	0-426	20
Chee (1999)	*E. delegatensis*	15-166	2.5
Lindenmayer *et al.* (1999)	*E. regnans*	309-393 $m^3\ ha^{-1}$	10
Woldendorp (2000)	*E fastigata*, *E. masculata*, *E. seiberi*, *E. saligna*, *E. pilularis*	32-263	2.5
Slijepcevic (2001)	*E. obliqua*	509-774	-
Tolhurst *et al.* (2006)	*E. dalrympleana*, *E. radiata*	74-146	2.6
Bradshaw (2007)	*E. diversicolor*	25-180	-

The volume and attributes of CWD required to maintain biodiversity and habitat availability without creating a potentially unacceptable fire hazard (related to post-frontal fire behaviour and first- and second-order fire effects (Section 2.3)) can be represented by an optimum volume and attribute characterisation. Determining the optimum can be useful for guiding the strategies of forest and land managers (Brown *et al.*, 2003). To determine the optimal volume of CWD for a specified forest area requires a detailed understanding of specific biological benefits provided by individual species, the processes affecting CWD attributes upon which these species rely, as well as a firm understanding of the land and fire management objectives of the forest (Brown *et al.*, 2003).

2.1.4. Location, orientation and suspension

Many organisms relying on CWD are highly specialised and have preferences for downed wood with a particular suspension, exposure to the sun, slope, physical orientation and aspect (Harmon *et al.*, 1986; Grove and Meggs, 2003). These preferences are largely associated with different temperature and moisture retaining properties depending on positioning in the sun or shade (Buisson, 1999). For example, some saproxylic (dependent on dead wood) invertebrates favour logs with a particular exposure to the sun (Key and Ball, 1993) such as cool, moist conditions associated with downed wood that are grounded, shaded and/or have a southerly aspect (in the southern hemisphere). This includes the velvet worm (*Euperipatoides rowelli*) in NSW (Barclay *et al.*, 2000) whose presence and abundance is strongly associated with logs on south-easterly rather than north-westerly facing slopes. Echidnas (*Tachyglossus aculeatus*) who utilise downed wood for shelter and hibernation are known to prefer north-facing slopes (Wilkinson *et al.*, 1998). Other species preferring an open, elevated, northerly aspect and/or exposed position include many sun loving, ectothermic reptile species which require sun-exposed substrates to bask and regulate body temperature (Heatwole and Taylor, 1987; Cogger, 2000; Lindenmayer *et al.*, 2002; Garden *et al.*, 2007). For example, logs that sit above the surrounding vegetation provide a sunning platform for Rosenberg's monitors (*Varanus rosenbergi*), which emerge from their burrows in winter to bask and revitalise themselves during breaks from their hibernation (Christian and Weavers, 1994). Some forest skinks are also known to bask at particular times of the day to utilise preferred levels of sun exposure (Webb, 1985).

Other species, including amphibians such as the critically endangered Baw Baw frog (*Philoria frosti*) (Figure 2) prefer the moist habitat underneath large grounded logs where they can lay their clutch of eggs, shelter and seek protection from extreme temperatures, desiccation and predation (Hollis, 2004; Lindenmayer, 2009). Fungi tend to specialise according to the particular aspect or situation of downed wood (Driscoll *et al.*, 2000), for example *Mucronella pendula* prefers the lower, shady surfaces and hollows of wet, rotting logs (Fuhrer, 2003). The ability for CWD to provide a site for seedling establishment is also highly related to the degree of sun exposure and light availability (McKenny and Kirkpatrick, 1999). A thick covering of leaves and small twigs that reduces light penetration also retards the development of many lichens and mosses which need sufficient light to develop and persist (Hollis *et al.*, 2008).

Figure 2. Baw Baw frog prefers the moist habitat underneath large grounded logs.

Some species such as the common wombat (*Vombatus ursinus*) and mountain brushtail possum (*Trichosurus cunnunghamii*) utilise downed wood as a place to deposit scats to signify territorial boundaries which suggests that the location and vertical suspension of CWD is particularly important for these species (Triggs, 1996).

2.1.5. Moisture retaining properties

The moisture retaining properties of downed wood varies with the decay status, wood properties as well as location and suspension characteristics (Section 2.3). Many authors have reported the relationship between CWD dependent species and the moisture retaining properties of downed wood (Harmon *et al.*, 1986; Key and Ball, 1993; Buisson, 1999; Barclay *et al.*, 2000; Lindenmayer *et al.*, 2002; Hollis, 2004). Examples include invertebrates such as the velvet worm which favours logs with cool, moist conditions associated with CWD in shaded, south-easterly aspects (Key and Ball, 1993; Barclay *et al.*, 2000) and the Baw Baw frog (*Philoria frosti*) which utilises the moist habitat associated with large grounded logs (Hollis, 2004;

Lindenmayer, 2009). Both these examples demonstrate the importance of CWD in providing moist habitat where animals can shelter, breed and seek protection from extreme temperatures, desiccation and predation. Moist CWD habitat also provides an important substrate for lichens, mosses (Figure 3) and seedlings. For example, the germination of seedlings such as dogwood (*Pomaderris apetala*) and musk daisy bush (*Olearia argophylla*) as well as mountain pepper (*Drimys lanceolata*) in the montane ash forests in Victoria are associated with moist CWD substrates (McKenny and Kirkpatrick, 1999; Lindenmayer, 2009). Lichen, mosses and seedlings assist moisture retention by storing water and sheltering CWD from the drying sun (Ashton, 1986; Lindenmayer *et al.*, 2002; Grove and Meggs, 2003).

Figure 3. The tall, moist eucalypt forests of Tasmania support large diameter, downed wood, providing ideal CWD habitat for dense moss growth.

2.1.6. Structural complexity, continuity and spatial connectivity

Typically, large diameter downed wood are less common and more scattered than finer particles. With increasing fuel load however, the scatter of downed wood across a forest decreases, promoting a greater density of CWD and enhanced spatial connectivity. The capacity for CWD to provide suitable habitat for organisms is influenced by the spatial patterns and distribution of downed wood which promote continuity and connectivity within a forest ecosystem (Harmon *et al.*, 1986; Grove, 2002). This is especially the case for many invertebrates which require continuity of CWD to be able to move around within the forest (Grove, 2002). Heterogeneity of CWD attributes increases with increasing volume, particularly in undisturbed forests where there is variation in decay status and size distribution of CWD (Brown, 2001). Some mammals such as the eastern barred bandicoot (*Perameles gunnii*) require a structurally complex and dense shelter site and likely due in part to the invertebrates, plants and fungi that also prefer such sites (Dufty, 1994; Lindenmayer, 2009). Structural heterogeneity has also been suggested to increase the abundance of reptiles (Brown, 2001). When a continuous network of CWD is available in disturbed forests, many animals are able to utilise CWD to move through to an unaffected area or suitable habitat (Harmon *et al.*, 1986).

2.1.7. Number and size of hollows

Hollow bearing CWD are an important component of habitat essential for many organisms including mammals, reptiles and birds. They serve many functions including providing sites for nesting, shelter, protection and reproduction for a diverse variety of forest dependent animals (Harmon *et al.*, 1986; Williams and Faunt, 1997; Driscoll *et al.*, 2000; Mac Nally *et al.*, 2001; Lindenmayer *et al.*, 2002). For example, mammals including the numbat (*Myrmecobius fasciatus*) (Friend, 1990); eastern quoll (*Dasyuris viverrinua*) (Godsell, 2000); bush rat (*Rattus fuscipes*) (Lindenmayer, 2009); agile antechinus (*Antechinus agilus*) and the yellow-footed antechinus (*Antechinus flavipes*) (Dickman, 1991; Mac Nally *et al.*, 2001; Mac Nally and Horrocks, 2002) utilise CWD and particularly hollows for nesting and sheltering. CWD hollows also provide mesic habitat and protection for organisms during disturbances such as drought and fire (Williams and Faunt, 1997).

The size of the hollow is particularly important because many hollow nesting mammals often require or prefer a particular size. For example, the chuditch which is ranked as 'vulnerable' in both state and federal legislation, requires large hollows that can only be found in large logs (Faunt, 1992; Johnson and Mitchell, 2009).

Several factors influence the number and extent of hollows in CWD including log diameter (forest structure), fire damage, stage of decomposition and colonisation by termites (Lindenmayer *et al.*, 1993; Williams and Faunt, 1997; Lindenmayer and McCarthy, 2002). Log diameter is probably the most significant factor (Williams and Faunt, 1997). Many authors have also argued that the extent of fire damage to CWD is also particularly important with a greater number of hollows being associated with minor and moderate degrees of fire damage (Lindenmayer *et al.*, 1993; Williams and Faunt, 1997; Lindenmayer and McCarthy, 2002). This includes trees and limbs that collapse to the forest floor as a result of fire which often become key habitat components for a wide range of vertebrates (Lindenmayer and Franklin, 1997).

2.1.8. Fire, fungal and termite associations

Fires have long been part of southern Australian eucalypt forests and have played a major role in shaping vegetation structure and species composition (Gill *et al.*, 1981; Bradstock *et al.*, 2002; Burrows, 2008). CWD perform an important role providing mesic habitat and protection for organisms during fire (Williams and Faunt, 1997; Lindenmayer *et al.*, 2002). For example, being a heartwood rotter, the curry punk fungus (*Piptoporu australiensis*) (Figure 4) is protected from fires that char or consume only the outer surface of logs where sapwood rotters would not survive (Fuhrer, 2003; Robinson, 2010). CWD have a significant relationship with many fire-dependent species, enabling these species to out compete others (Wikars, 1995). McMullan-Fisher *et al.* (2002) in their study in the burnt *E. regnans* forest in Victoria, found that a number of macrofungi were more apparent on charred wood and burnt soil. These fire-adapted fungi are known to encourage fire dependant insects (Wikars, 2002).

As noted in Section 2.1.6 the extent of fire damage to CWD is also affected by the number of hollows available to be utilised by many hollow-dependent organisms (Lindenmayer *et al.*, 1993; Lindenmayer and Franklin, 1997; Williams and Faunt, 1997; Lindenmayer and McCarthy, 2002).

CWD and wood decay fungi contribute to the functioning of a forest ecosystem (Driscoll *et al.*, 2000). Fungi are an essential food resource for many vertebrates and invertebrates (Claridge and Lindenmayer, 1998; Wikars, 2002), and they also develop beneficial symbiotic relationships with plants (Driscoll *et al.*, 2000).

Figure 4. Curry punk fungus fruiting on a charred marri (*Corymbia calophylla)* log in March 2008 at Quillben block in Western Australia, stimulated by a prescribed burn conducted December 2007.

The stages of decomposition and various combinations of CWD attributes are known to provide a substrate, refuge and a multitude of essential microhabitats for a diverse range of fungi (Maser and Trappe, 1984; Driscoll *et al.*, 2000; Lindenmayer *et al.*, 2002; Grove and Meggs, 2003). Despite the important role of fungi in forest and ecosystem functioning (nutrient cycling, decomposition, providing a food resource for invertebrates and vertebrates (Claridge and Lindenmayer, 1998; Driscoll *et al.*, 2000)), many species remain undescribed (May and Simpson, 1997). In Australia, the habitat value of CWD for fungi has been well documented, particularly for those forming above-ground fruiting bodies and deriving nutrients and energy from decaying wood, including:

Anthracophyllum archeri	*Galerina unicolor*	*Omphalotus nidiformis*	*Scutellinia* aff. *margartiaceae*
Armillaria asprata	*Gymnopilus austrosapineus*	*Ompholina chromacea*	*Stereum hirsutum*
Armillaria hinnulea	*Gymnopilus penetrans*	*Panellus ligulatus*	*Stereum illudens*
Boletus ananiceps	*Gymnopilus purpurata*	*Panellus stipticus*	*Trametes cinnabarina*

Calocera guepinioides	*Hypholoma australe*	*Panus fasciatus*	*Trametes hirsuta*
Chlorocibaria aeruginascens	*Hypholoma fasiculare*	*Phlebia rufa*	*Trametes lilacino-gilva*
Clavicorona piperata	*Hypholoma radicosum*	*Pholiota* aff. *squarroripes*	*Trametes versicolor*
Clavicorona pyxidata	*Hypholoma sub-lateritium*	*Pholiota multicingulata*	*Tremella aurantia*
Clitocybula aff. *cyathiformis*	*Lenzites vespacea*	*Piptoporus australiensis*	*Tremella aurantia*
Coprinis disseminatus	*Lycoperdon pyriforme*	*Pluteus atromarginatus*	*Tremella fuciformis*
Coprinus spp.	*Marasmius aff. cinnamoneus*	*Pluteus cervinus*	*Tremella mesenterica*
Crepidotus applanatus	*Mucronella pendula*	*Pluteus nidiformis*	*Tremellodon gelatinosporum*
Daldinia concentrica	*Mycena interrupta*	*Polyporus arcularius*	*Tricholoma rutilans*
Descolea maculata	*Mycena subgalericulata*	*Pseudohydnum gelatinosum*	*Tubaria rufofulva*
Fistulina hepatica	*Mycoacia subceracea*	*Pycnoporus coccineus*	*Xeromphalina leonina*
Fistulinella mollis	*Neolentiporus maculatissimus*	*Schizophyllum commune*	*Xylaria polymorpha*

(Sourced from: Young, 1986; Bougher and Syme, 1998; Lindenmayer *et al.*, 2002; McMullan-Fisher *et al.*, 2002; Fuhrer, 2003; May *et al.*, 2006).

Termites are also an important component of the diets of many terrestrial animals and play a role in nutrient cycling and the decomposition of CWD (Lee and Wood, 1971; Perry *et al.*, 1985b; Williams and Faunt, 1997). Some termites utilise the heartwood of standing trees and limbs. The excavation activity and creation of clay 'pipes' can penetrate all limbs and branches, creating hollows and habitat for a variety of arboreal birds and mammals long before they fall to the ground and become CWD (Perry *et al.*, 1985a; Perry *et al.*, 1985b; Abensperg-Traun and Perry, 1998). These trees and their limbs continue to provide nesting and feeding sites for termites after they fall to the forest floor, influencing the progression of decay and species utilisation over time (Perry *et al.*, 1985a).

2.2. Coarse woody debris, woody fuel consumption and carbon

2.2.1. Carbon storage

2.2.1.1. Carbon cycles in coarse woody debris

Within forests, carbon and nitrogen continually move between the biomass, dead organic matter and soil carbon pools. As such, the integration of data over all pools is required to assess carbon stocks for a comprehensive inventory (Brack *et al.*, 2006; Department of Climate Change, 2008e).

Apps *et al.* (2006) specify the following equation to calculate the net carbon balance of an ecosystem:

$$NCB = NEP = \frac{dC_{eco}}{dt} = GPP - R \qquad (1)$$

where NCB net carbon balance;

NEP net ecosystem productivity;

C_{eco} sum of carbon stocks in vegetation, forest floor (including CWD) and soil;

t time;

GPP gross primary production which is the rate of carbon dioxide uptake by foliage through photosynthesis and

R total ecosystem respiration flux comprising autotrophic (plant) respiration and heterotrophic respiration (decomposition) of the accumulated detritus and soil pools.

Accounting for the whole ecosystem response includes assessing natural processes (e.g. turnover and mortality) with detailed inventories of both tree and non-tree components and including CWD, or dead and downed wood (Stevens, 1997; Bauer *et al.*, 2006; Brack *et al.*, 2006; Lindner *et al.*, 2008). It also includes changes over time, taking disturbance and management practices (e.g. fire and harvesting) into account.

CWD on the forest floor is a significant store of carbon which can remain in the ecosystem for many years before it is completely released to the atmosphere through decomposition or combustion processes. From 184 studies available in literature, Mackensen *et al* (2003) found that in 57% of all cases, the calculated lifetime of CWD (time to when 95% of mass is lost) is longer than 40 years (the median of the distribution was 49 years and the mean 92 years). For some species, which are particularly decay resistant, the decay process of CWD may take several hundred to more than a thousand years (Stevens, 1997). For example, the carbon storage and cycling processes within jarrah (*E. marginata*) forests may take well over 500 years given the standing growth time to maturity for standing jarrah takes roughly 60 years (pole with a diameter at breast height of 15 cm: Abbott and Loneragan, 1984), the maximum age being around 400 years and the time that each jarrah log takes to decay once on the ground.

Any fire may consume woody fuels, thereby contributing to carbon emissions (Apps *et al.*, 2006), however there may not be an equivalent reduction in surface woody fuel load (Hollis *et al.*, 2011b). Following fire, newly fallen trees and branches are often transferred from the standing biomass to the downed woody fuel load (Waterworth and Richards, 2008). The resulting woody fuel load may be as high as the pre-fire woody fuel load depending on variables such as species, stand structure, fire behaviour (e.g. fire intensity, residence time) and termite damage, consequently adding to the complexity of predicting the effect of fire on woody fuel dynamics (Hollis *et al.*, 2011b).

Australia produces two sets of national inventories identifying the sources and sinks of greenhouse gases each year: (1) the National Greenhouse Gas Inventory (NGGI), prepared under the reporting provisions applicable to the United Nations Framework Convention on Climate Change (UNFCCC), and (2) a set of reports applicable to the Kyoto Protocol. The difference between the two exists in the *Land Use* sector where the Kyoto Protocol accounts are limited to afforestation, deforestation and reforestation since 1990, whereas the UNFCCC accounts are more comprehensive, and include additional land-based fluxes associated with aspects such as wildfire emissions and drought effects. These reports are compiled using methods described in the Australian methodology for the estimation of greenhouse gases and sinks (Department of Climate Change, 2006) and 2006 IPCC Guidelines for national greenhouse gas inventories - Volume 4: Agriculture, forestry and other land use (Intergovernmental Panel on Climate Change, 2006).

While species distributions and basic management information are included in the current inventories, very little information is available at a broader scale that couples together the management impacts with tree and CWD inventories (Lindner *et al.*, 2008). In addressing the main processes and management drivers, the Full Carbon Accounting Model (*FullCAM*) (Richards, 2001) was developed based on the carbon mass balance of an ecosystem. Within *FullCAM*, fire can be introduced and modelled with varying characteristics such as fire type or intensity which affect both live and dead components. For example, debris can be left unburnt, emitted back to the atmosphere or transferred to the inert soil pool (Brack *et al.*, 2006). While the carbon and nitrogen cycling as modelled are good indicators of ecosystem productivity and condition (Brack *et al.*, 2006) due to the limited data available, CWD are particularly difficult to estimate under the same fire affects (Department of Climate Change, 2008e). Further details on

CWD combustion related contributions to the National Inventories and the *FullCAM* model are found in Section 2.2.1.2 below.

2.2.1.2. Proportion of coarse woody debris in terrestrial carbon stocks

Bolin and Sukumar (2000) suggest that roughly 60% of global terrestrial carbon stocks are found in forests and savanna vegetation. This includes overstorey trees (both above and below ground components), understorey vegetation, soil, litter and CWD. The contribution of CWD is often overlooked when accounting for carbon stocks and fluxes in forest ecosystems even though they represent approximately 18% of the total forest above-ground biomass in Australian dry sclerophyll forests and 16% in wet sclerophyll forests (Woldendorp *et al.*, 2002a). These figures are based on 17 Australasian studies where the minimum fuel size was largely unknown and those that were known varied between 2 cm and 10 cm in diameter. Roxburgh *et al.* (2006) confirmed these averages where they reported CWD (d >2.5 cm) was 19% of aboveground biomass in tall eucalypt forests in the southern forest zone region of New South Wales, Australia (Regional Forest Agreement, 2000). Hingston *et al.* (1980) reported that the CWD proportion of above ground biomass was 32% in the jarrah forest of south-western Western Australia, which is significantly higher than the average found in the culmination of studies by Woldendorp *et al.* (2002a) and by Roxburgh *et al.* (2006). In the United States, Woodall and Liknes (2008) reported that dead organic material including both fine and CWD (diameter, d > 7.62 cm) was much lower, contributing approximately 14% of the total forest carbon stock.

In forests that have been commercially harvested for wood where there are often large quantities of slash (branch and stump material) left on the forest floor, it may be possible to quantify the above ground biomass contribution of CWD more accurately based on tree species. This is based on the assumption that the majority of CWD (or residue) on the forest floor is relatively green and thus the wood density is less affected by decay and the fresh wood basic density of the species can be used. Post-harvest burning or removal of biomass for fuel would result in immediate release of some of this carbon stock (Canadell *et al.*, 2007; Ximenes *et al.*, 2008).

2.2.1.3. Carbon mass within coarse woody debris

The mass of carbon in CWD is a function of carbon concentration (%) and density. However, there is considerable uncertainty about actual contribution of CWD to forest carbon stocks due to limited information on CWD volume and decay rates and the impact of decay on wood density in Australian forests (Grierson *et al.*, 1992; Mackensen *et al.*, 2003). As a result, calculations of biomass, carbon stock values and carbon dioxide (CO_2) emissions are currently unreliable until further data is collected through long-term studies of CWD in different forest types (Mackensen *et al.*, 2003). Current estimates of carbon in CWD range from 45 to 50% (45%: Woodwell *et al.*, 1978);(47%: Tilman *et al.*, 2000);(50%: Mackensen and Bauhus, 1999).

2.2.1.4. Carbon and greenhouse gas emissions

Every fire has an impact on ecosystem carbon budgets lasting many years as a result of interactions between decomposition of remaining biomass, regrowth of vegetation, vegetation succession and soil organic matter (Mouillot and Field, 2005; Bauer *et al.*, 2006). Within a fire, spatial and temporal variation in the combustion of fuels and the subsequent carbon emissions will vary considerably due to variations in weather conditions, area burnt, fuel type and condition and fire behaviour (de Groot, 2006; Gould and Cheney, 2007; Hollis *et al.*, 2011b).

2.2.1.5. Biomass burning

Globally, biomass burning is a significant source of many important trace gases (including CO_2, CO, CH_4, NO, NMHC, NO_x, NH_3, N_2O, HCN, CH_3, CN, HNO_3, SO_2, OCS, H_2 and CH_3Cl) and aerosol particles that affect atmospheric chemistry and climate (Crutzen and Andreae, 1990; Prinn, 1991; Hurst *et al.*, 1994a; Meyer *et al.*, 2008). It is the large and increasing emissions of carbon monoxide (CO) and methane (CH_4) (the main reactors with hydroxyl compounds (OH) in the atmosphere) that will probably lead to a decrease in the overall concentration of OH free radicals and subsequently result in a decrease in the oxidation efficiency of the atmosphere (Crutzen and Andreae, 1990). The release of carbon dioxide has continually increased through the 19th and 20th centuries with current atmospheric levels of CO_2 being higher than any published estimates for the last 400,000 years (Bauer *et al.*, 2006). According to Crutzen and Andreae (1990) biomass burning accounts for 10% of global methane sources, however it probably accounts for a greater fraction of the increase in global emissions. Aerosol particulates influence the radiative balance of the earth-atmosphere system as well as affecting human health by reducing air quality and visibility. In fact, aerosols from biomass burning are generally small enough to be inhaled into the deepest parts of the human lungs (Meyer *et al.*, 2008).

The type of combustion also has an effect on the amount and type of greenhouse gases and particulates. While flaming combustion occurs with relatively efficient burning (producing higher proportions of CO_2 and water and correspondingly less partially oxidised products such as CO (Crutzen and Andreae, 1990)), smouldering combustion is characterised by lower combustion rates (Lavoue *et al.*, 2007). Smouldering combustion can occur for weeks after the passage of a fire front and woody fuels are prone to this form of combustion. Previous field and laboratory research of biomass burning has quantified the emissions for fires burning predominantly by flaming combustion in fine fuels (Bertschi *et al.*, 2003). While some work has been done to measure the emissions from the smouldering combustion of African savanna woodland (Bertschi *et al.*, 2003), little is known of the emissions from woody fuels in Australian eucalypt forests. More research is required to improve estimates related to smouldering combustion and emissions related to woody fuels. Further information on combustion types and processes and their effect on consumption is described in more detail in Section 2.3.

2.2.1.6. Biomass burning in Australia

Of the estimated 8700 Tg of global biomass consumed as a result of biomass burnt annually (Andreae, 1991), 18% is attributed to the burning of forests compared to 43% from the burning of savannah grasslands. The remainder is attributed to the burning of agricultural waste (23%) and fuel wood (17%) (Levine, 1991). Cheney *et al.* (1980) estimated that of the contribution by the burning of forests in Australia, 2% can be attributed to prescribed burning and 8% to wildfires (possibly up to 11% in extreme years) while the remaining 87-90% can be attributed to regeneration burns, which are used to expose the seedbed for regeneration of the forest after harvesting (Slijepcevic, 2001) and plantation establishment. Slijepcevic and Marsden-Smedley (2002) reported that between 145.6 and 226.6 t ha^{-1} was released to the atmosphere as a result of regeneration burning of *E. obliqua* forest and most of this was attributed to fuels larger than 7 cm in diameter.

As a result of global biomass burning it is estimated that:

- 3,500 Tg of carbon is produced each year in the form of CO_2 which is 40% of the world’s annual production of carbon dioxide;
- 38% of the ozone in the troposphere is produced;
- 20-40% of the world’s CO is produced;
- 39% of the world’s particulate carbon is produced and
- more than 20% of the world’s hydrogen, non-methane hydrocarbons, methyl chloride and oxides of nitrogen is produced.

(Sources: Cheney *et al.*, 1980; Andreae, 1991; Levine, 1991; Hurst *et al.*, 1994a)

Based on a synthesis of ground based measurement and satellite imagery for the year of 2000, 8% of the global carbon emissions attributed to biomass burning can be attributed to Australia

(Ito and Penner, 2004; Kasischke and Penner, 2004), where between 80-250 Tg of carbon is consumed in biomass fires (Cheney *et al.*, 1980; Walker, 1981; Galbally *et al.*, 1992). In calculating Australia's contribution, Ito and Penner (2004) base their woody fuel load estimates on the turnover time of carbon in biomass from a study by Barrett (2002). Russell-Smith *et al.* (2007) estimate that 62% of Australian net greenhouse emissions are the result of prescribed fires and wildfires in the northern savanna regions which make up for between 60% and 75% of the carbon burned annually (Walker, 1981). This is significantly larger than that contributed by temperate forests and due to differences in the scale of area burnt. While individual wildfires in southern Australian eucalypt forests have the potential to be relatively large, fire-fighting efforts greatly reduce the potential size of many fires.

Australia is a fire prone environment and its dry sclerophyll forests have adaptations that protect it, reducing damage caused by fire and enabling reasonably quick recovery (Gill *et al.*, 1981). Cheney *et al.* (1980) suggest that because of this, they are less likely to produce a significant release of carbon due to combustion in comparison to wetter, fire sensitive forests where productivity may be reduced by frequent burning.

2.2.1.7. Kyoto Protocol accounts

On December 3 2007, the Australian government ratified the Kyoto Protocol. The Kyoto Protocol is part of the UN Framework Convention on Climate Change (UNFCCC) that aims to stabilise greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. It requires that countries quantify levels of carbon stocks and establish strategies to reduce greenhouse gas emissions and/or increase greenhouse gas removals by using agriculture, forestry and other land use or sequestration activities (United Nations, 1998). The National Greenhouse Gas Inventory 2006 was prepared under the reporting provisions applicable to the Kyoto Protocol and states that in 1990 the net greenhouse gas emissions in Australia were 515.9 Tg (CO_2 equivalence). By comparison, in 2006 net emissions were 549.9 Tg, an increase of 6.6% in 16 years (Department of Climate Change, 2008d). As a committed signatory, Australia is obliged to limit its greenhouse gas emissions in 2008-2012 to 108% of its emissions in 1990 (Department of Climate Change, 2008a) which represents a target value of 557.2 Tg.

In order for Australia to meet its obligations under the Kyoto Protocol, all relevant ecosystem components contributing to greenhouse gas sources and sinks require accurate inventories including the contributions made by forest woody fuels. The National Carbon Accounting System (NCAS) was subsequently formed to develop a comprehensive system to report on Australia's land-based greenhouse gas emissions and removals (from and to the atmosphere)

(Department of Climate Change, 2008e). Measurement of change in carbon stocks (the uptake and loss of carbon by biomass, litter and soil) is a major objective of the system (Richards and Brack, 2004). The Full Carbon Accounting Model (*FullCAM*) used by the NCAS is an empirically constrained process model (Department of Climate Change, 2008e) calculating greenhouse gas emissions and removals in both forest and agricultural lands. The model incorporates forest management practices into a database and model. *FullCAM* accounts for all carbon pools including CWD (Waterworth and Richards, 2008). Within *FullCAM*, the Forest Carbon Accounting Model (*CAMFor*) accounts for the aboveground forest debris pool consisting of both fine and woody fuels, in either a decomposable or resistant fraction where a distinct decomposition rate can be applied to each fraction (Department of Climate Change, 2008e). CWD carbon is tracked within the 'Debris' pool including natural decomposition and also fire application which result in some of the stored carbon being released to the atmosphere, producing a proportional decrease in biomass from the forest debris pool (Brack and Richards, 2002; Department of Climate Change, 2008e).

CWD source data in the *FullCAM* model were collected from available literature and field studies. While data were particularly sparse for forests without timber harvesting, estimated inputs for CWD pools were based on the live pools (based on the forest growth model) together with the imposition of fire (from the land cover change data) (Department of Climate Change, 2008e). The result is an estimate which is site and species specific. The rate of CWD decomposition reported for harvested forests by Mackensen and Bauhus (1999) (which is a 0.1 breakdown rate per year) guides the *FullCAM* model and enables carbon contents and wood densities to be established for harvested forests (Department of Climate Change, 2008e).

The NCAS suggests that a woody fuel consumption of 50% of the total woody fuel load may be a reasonable figure to apply to fires under a wide range of burning conditions (Gould and Cheney, 2007).

2.2.1.8. UNFCCC accounts

Fuel consumption by prescribed fires or wildfires falls into two categories within the UNFCCC accounts: (1) *Agriculture* and (2) *Land Use, Land Use Change and Forestry*. Under the Agriculture category, fires in Australian savannas and temperate grasslands (source category 4.E) are included as they are a key source of CH_4 and N_2O as well as CO, NO_x and non methane volatile organic compounds (NMVOCs: Department of Climate Change, 2008e). However, it is predominantly fine fuels that contribute to the savanna fuel load thus woody fuels contribute very little to emissions. The burning of residual crop material, for example stubble burning of wheat and burning sugar cane crops prior to harvest (source category 4.F) also contribute CH_4, N_2O, CO, NO_x and NMVOCs during the combustion process.

Forest lands (source category 5A) and biomass burning (source category 5(V) and 5A.1) under the *Land Use, Land Use Change and Forestry* category include emissions and removals from native forests, harvested native forests and plantations (Department of Climate Change, 2008e) and are highly relevant to greenhouse gas emissions from woody fuels. The net ‘fire effect’ balance for a given year is calculated outside of NCAS and *FullCAM* models. The ‘fire effect’ of the current year’s emissions is determined by multiplying the area burnt by the emission factor (EF) plus recovery sequestration from the previous 5 years of fires (note that it is assumed fire emissions are re-sequestered after just 5 years). In 2006 the total combined net emissions from 112 M ha of forested lands (of which 96.2 M ha was unharvested native forest) were an estimated -46 921Gg (Department of Climate Change, 2008e). Forested lands were therefore found to be a sink for greenhouse gas including emissions from both prescribed fires and wildfires. Contributing to this was -49,572 Gg CO_2 (Figure 5), 2,083 Gg CH_4 and 568 Gg N_2O. Harvested wood products and collected fuel-wood consumption are not included in this category and are included under separate categories.

Burning occurs across Australian forests as a result of wildfires and human induced activities (i.e. prescribed/ecological fires and traditional aboriginal burning). The Department of Climate Change (2008e) state that anthropogenic fires replace wildfires that would otherwise occur naturally, albeit at other times of the year. The rate of CO_2 release during a prescribed fire or wildfire is not synchronous with the rate of uptake by the regrowing forest, which can take many years to regain the quantity of carbon released (Department of Climate Change, 2008e). Importantly, the Australian method reports CO_2 emissions associated with fires which is in accordance with IPCC 2006 guidelines (Intergovernmental Panel on Climate Change, 2006). To calculate the fuel burnt and non-CO_2 emissions from prescribed and wildfires, the following equations are used by the Department of Climate Change (2008e):

To calculate the total mass of fuel burnt:

$$M = A \cdot FL \cdot Z \cdot 10^{-3} \qquad (2)$$

where: *M* mass of fuel burnt annually (Gg yr^{-1});

A area of category burnt annually (ha);

FL fuel loading (dry weight) (Mg ha^{-1}) (see Table 3) and

Z burning efficiency (prescribed burning: 0.42; wildfires: 0.72: Tolhurst, 1994; Department of Climate Change, 2008e).

Table 3. Fuel loading for Australian forests in each state.

Fuel load	ACT[a]	NSW[a]	NT[a]	Qld[a]	SA[b]	TAS[b]	VIC[a]	WA[a]
Prescribed Burn (Mg ha^{-1})	17.6	18.2	4.1	9.7	9.6	20	17.9	12
Wildfire (Mg ha^{-1})	35.2	36.4	7.2	19.4	19.2	40	35.8	33.4

[a] Sourced from state agencies.
[b] Sourced from Tolhurst (1994).

To calculate total annual emissions for CH_4, CO and NMVOCs:

$$E_i = M \times CC \times C_i \,(Gg) \tag{3}$$

where: E_i annual emission of gas *i* from biomass burning (*Gg*);

M mass of fuel burnt annually (Gg yr^{-1});

CC carbon mass fraction in vegetation (0.50 for forest: Hurst *et al.*, 1994a; Hurst *et al.*, 1994b) and

C_i factor to convert from elemental mass of gas species *i* to molecular mass (CH4: 1.33; CO: 2.33; NMVOC: 1.17: Department of Climate Change, 2008e).

To calculate total annual emissions for NO_x and N_2O:

$$E_i = M * CC * NC * EF_i * C_i \,(Gg) \tag{4}$$

where: E_i annual emission of gas *i* from biomass burning (*Gg*);

M mass of fuel burnt annually (Gg yr^{-1});

CC carbon mass fraction in vegetation (0.50 for forest: Hurst *et al.*, 1994a; Hurst *et al.*, 1994b);

NC nitrogen to carbon ratio in biomass (0.011 for forest: Hurst *et al.*, 1994a)

EF_i emission factor for gas *i* from vegetation (N_2O: 0.0077; NOx: 0.15: Hurst *et al.*, 1996) and

C_i factor to convert elemental mass of gas species *i* to molecular mass (N2O: 1.57; NOx: 3.29: Department of Climate Change, 2008e).

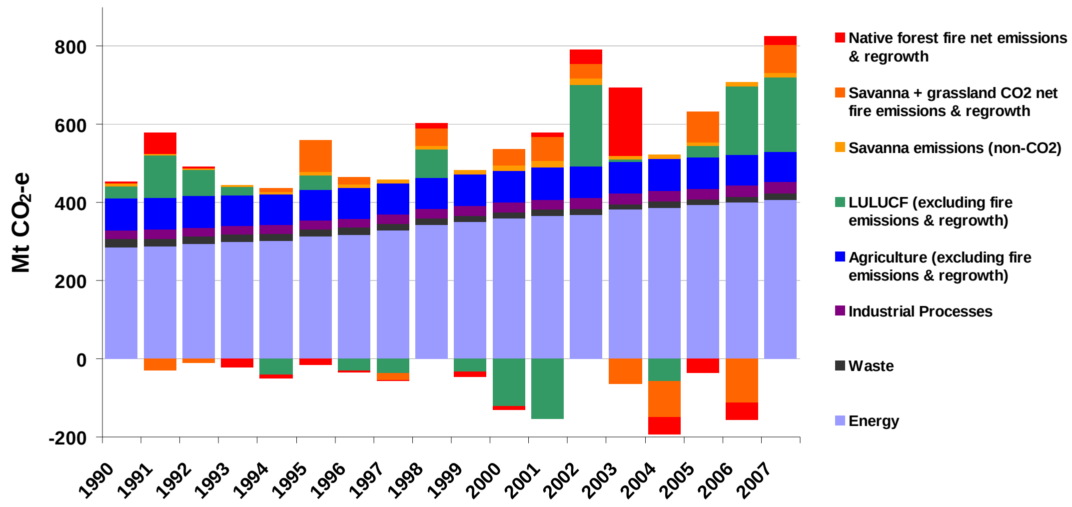

Figure 5. Change in net balance (losses plus gains for each year) of carbon dioxide in Australia since 1990 and the categories that act as sources and sinks including native forest fire net emissions (source: Roxburgh (2010)).

2.2.1.9. Fire regimes and carbon stock/emission management

Fire regime and behaviour characteristics, including fire intensity (kW m^{-1}), rate of spread (m min^{-1}), residence time (s) and frequency have the potential to significantly impact forest carbon budgets and the production of emissions. Both the intensity and frequency of fire regimes have complex interactions with species composition and forest ecosystem functions (Tilman *et al.*, 2000; Gill and Bradstock, 2003; Burrows, 2008; Ottmar *et al.*, 2009). In Australia, fire frequency tends to increase with seasonality of rainfall, resulting in a pattern where low fire frequencies and burnt forest areas in southern Australia contrast those with higher frequencies and extensive areas burnt in northern Australia (Russell-Smith *et al.*, 2007).

The area burnt each decade in Australian temperate forests has significantly decreased since the early 1900s (Mouillot and Field, 2005), particularly in the south-east of Australia (Russell-Smith *et al.*, 2007). This is largely linked to the reduction in traditional aboriginal low intensity burning across southern Australia and the implementation of the 'fire exclusion' policy and fire suppression activities (Mouillot and Field, 2005; Canadell *et al.*, 2007). Together, these have promoted a thickening in the understorey vegetation and have increased the amount of carbon stored within the southern forests (Canadell *et al.*, 2007).

While thickening of understory vegetation has resulted in an increased carbon store, the effects of fire suppression and reduced fire frequency may have also increased forest floor carbon stocks. In a 35 year controlled burning experiment in Minnesota oak savanna, Tilman *et al.*

(2000) found that fire suppression activities led to an annual average increase in carbon stocks of 1.8 Mg ha^{-1} in oak savanna forest with most of the carbon stored in woody biomass. In their experiment fire suppression was defined by a fire treatment of 0, 1 or 2 fires over 35 years. Tilman *et al.* (2000) suggest that fire suppression could decrease the CO_2 rate of release as a result of burning by allowing forest stands to reach older ages, allowing carbon to accumulate in tree boles, soils, standing dead trees, litter and CWD (Sohngen and Haynes, 1997). Tilman *et al.* (2000) did not apply variations in fire intensity to the experiment, however they acknowledged the potential long term implications of long unburnt forests on fire hazard potential which would be an important factor in the fire tolerant sclerophyll forests of southern Australia.

In addition to effects on mitigating fire behaviour (McCaw *et al.*, 2003) and biodiversity conservation (Burrows, 2008), prescribed fire may also have an important role conserving stores of CWD. Fire regimes that include low intensity fires and a variety of seasons and intervals between fires are capable of creating a mosaic of burned and unburned forest areas (Burrows, 2000). Such fire regimes have the potential to reduce the area burnt by high intensity and dry summer wildfires on a national scale (Gould and Cheney, 2007) resulting in lower amounts of woody fuel consumption (Hollis *et al.*, 2011b; Hollis *et al.*, 2011a) and therefore reduced instantaneous release of carbon emissions (Cheney *et al.*, 1980). There may also be an increase in the quantity of slowly decaying, charred CWD remaining on the forest floor as opposed to being burnt out (Shorohova *et al.*, 2008). In a study of emissions comparing prescribed fires and wildfires in Portuguese maritime pine (*Pinus pinaster* A.) stands, Fernandes (2005) showed that prescribed burning has the potential to lower greenhouse emissions from wildfires, given the wildfire return interval was approximately 40 years. Fernandes estimated the release of CO_2 from prescribed burning applications under normal moisture conditions was 62% lower than the emissions from a severe wildfire.

The potential to reduce CO_2 emissions from forests with high wildfire occurrence through prescribed fire may be an important tool for Australian fire and land managers in the context of the Kyoto Protocol and future systems to reduce carbon emissions. Narayan *et al.* (2007) suggest that in fire-prone countries such as Australia, reductions in CO_2 emissions of 50% or more could be obtained and that prescribed burning could prove to be a viable management tool for mitigating CO_2 emissions from forest fires.

At the time of writing, the current Australian Government proposes to include forestry on an ‘opt-in’ basis for the Carbon Pollution Reduction Scheme (CPRS), whereby forest managers would be issued carbon pollution permits which are additional to the cap for the increased net quantity of CO_2 that is stored in the forest (Department of Climate Change, 2008b). Consistent with Kyoto Protocol accounting rules, forest managers opting into the CPRS would also be accountable for any net reductions in stored CO_2. For forest managers, the strength of the incentive will depend on each forest's unique values and management framework. It will also largely depend on the ability to accurately account for forest carbon stocks and the processes that affect them.

In terms of fire management, the CPRS may also present opportunities for land/fire managers to be rewarded 'offset credits' for reductions in emissions measured against an assumed baseline. Such offset schemes are administratively complex and subjective in determining the correct baseline (for example, what would have happened in the absence of a particular decision?). The Department of Climate Change (2008b) state that offsets may only be considered if the sector is uncovered by Australia's Kyoto Protocol accounts and that some particular sources of emissions, including prescribed burning of northern savannas, are unlikely to ever be included in offset schemes. Further consultation and research is required in relation to emission offsets related to fire in southern eucalypt forests.

2.2.2. Climate change implications

Fires have been part of the Australian bush for a long time and have played a major role in shaping vegetation and species diversity (Gill *et al.*, 1981; Bradstock *et al.*, 2002; Burrows, 2008). Australian fire behaviour and regimes are closely related to climate and meteorological conditions including temperature, humidity, wind speed and diurnal and seasonal patterns of fuel dryness and ignition probability (Luke and McArthur, 1977; Cheney, 1981; McCaw *et al.*, 2003). Climate change projections for southern Australia which include rising annual mean temperatures as well as local variations in rainfall patterns with longer dry periods broken by heavier rainfall events (CSIRO and BoM, 2007; Lucas *et al.*, 2007) could modify fire regimes.

2.2.2.1. Changes in fire regimes

Climate change has the potential to affect fire frequency, size, intensity and the length of the fire season including the period suitable for prescribed burning (CSIRO and BoM, 2007; Lucas *et al.*, 2007). Lucas *et al.* (2007) have suggested that by 2020, fire seasons could start earlier, end later, and be more intense. In south-east Australia, particularly in the interior of NSW and northern Victoria, the number of 'very high' and 'extreme' fire dangers days (defined by the Forest Fire Danger Index (FFDI): McArthur, 1967) could increase by 4-25% by 2020 and 15-70% by 2050 (not including Tasmania which showed little increase). The south-west of Australia is also expected to become increasingly warmer and drier than the last century (Indian Ocean Climate Initiative, 2002; Bates *et al.*, 2008). For fire and land managers the increase in frequency of catastrophic fires as well as community expectations for effective control of unplanned fires and protection of assets poses significant resource issues (Department of Climate Change, 2008c).

With current trends for a decreasing amount of prescribed burning for fuel reduction and bio-diversity management throughout Australia (Gould and Cheney, 2007), changes to fire regimes are likely to result in an increase in the area burnt by wildfires (Amiro *et al.*, 2001; Gould and Cheney, 2007) resulting in an increase in instantaneous releases of greenhouse gases linked to biomass (including woody fuels) burning while the regenerating forest is a smaller sink.

Hollis *et al.* (2011b) proposed that predicted changes to fire regimes and fire intensity associated with climate change in southern Australia could also result in greater proportions of woody fuel consumption and subsequently carbon release during bushfires and a reduction in woody fuel loads in dry eucalypt forests. For example, increased occurrence of summer bushfires would tend to increase the proportion of woody fuel consumed and hence reduce the quantity of woody fuel over time. Because woody fuels are an important carbon sink and provide habitat for a diverse biota in many southern Australian eucalypt forests, any reduction in woody fuel load, particularly large logs, has potentially detrimental effects on conservation. Hollis *et al.* (2011b) suggested that this may be moderated to some extent, at least in the short term by contributions of woody fuel resulting from post-fire branch fall, tree mortality and fall of snags.

2.2.2.2. Changes in decay rate

By analysing a global set of data on CWD decay rates, Mackensen *et al.* (2003) showed that the primary driver of decomposition was mean annual temperature; accounting for 34% of the variation in decay rates. A stepwise multiple linear regression based on diameter, initial wood density and mean annual temperature explained 44% of variation in decay rates. This finding was also supported by Woodall and Liknes (2008) who reported that in the United States, CWD carbon stocks were highest in forests with at high latitudes. Given that temperature is the strongest predictor of CWD decay rates, increases in mean temperature as a result of climate change may increase decay rates and carbon release to the atmosphere through decomposition of CWD. However, this could be offset by decreased decay resulting from drier conditions (Barrett, 2002).

2.3. Woody fuels and fire

'Few kinds of experimental treatments offer as great a probability of interaction between variables as does fire.' Norum (1976)

The proportion of woody fuel (*d* > 0.6 cm) burnt in eucalypt forest fires in southern Australia varies a great deal and is influenced by a myriad of variables (Sullivan *et al.*, 2002; Tolhurst *et al.*, 2006; Hollis *et al.*, 2011b), many of which are correlated. For the most part, factors influencing woody fuel consumption have been identified; however their relative effect on consumption in the southern eucalypt forests of Australia remains poorly quantified. This section examines the processes of woody fuel combustion and the factors affecting the consumption of woody fuels during forest fires. The implications of woody fuel consumption for fire suppressions and firefighter safety, fire behaviour, ecological impact and emissions of carbon and smoke fire are also presented.

2.3.1. Combustion type and phases

Woody fuels are chemically complex substances, composed mostly of cellulose, hemicellulose and lignin (Browning, 1963; Brown and Davis, 1973; Luke and McArthur, 1977). During a forest fire, woody fuels react with oxygen through the oxidation process of combustion to form carbon dioxide, water vapour and large amounts of heat (Byram, 1959). Combustion efficiency can be described as the overall oxidation capacity or conversion of carbon to carbon dioxide under a given set of weather and fuel conditions (Ward and Hardy, 1991; Ward, 2001). Complete combustion results in the production of water and carbon dioxide. However, in forest fires the combustion of woody material is rarely complete and/or fully efficient and as a result of incomplete or inefficient combustion, carbon monoxide is the major carbonaceous product (Ward, 2001).

Due to their larger size and thermal inertia, woody fuel ignition lags behind the leading edge of the flame front. This time lag will depend on the fire intensity and the characteristics of the woody fuel, for example the moisture content, presence of fissures or bark and chemical composition. Ignition can occur seconds after the passage of the ignition interface or minutes after the passage of the active flame front due to post-frontal combustion of compacted litter, woody and duff fuels (Cheney, 1990a; Finney, 1999). Woody fuels undergo three phases of combustion in a moving forest fire. In both prescribed fires and wildfires, these phases compete for available fuel and often exist simultaneously (Figure 6), contributing to a diversity of combustion products (Byram, 1959; Brown and Davis, 1973; Ward, 2001; Carvalho *et al.*, 2002).

2.3.1.1. Phase 1: Drying and preheating

The drying and preheating phase starts as the flame front approaches woody fuel particles. At this stage the surface temperature of a woody fuel particle is raised mostly through radiation (Byram, 1959; Brown and Davis, 1973; Pagni and Peterson, 1973). The magnitude of pre-heating will depend essentially on flame size. Simultaneously, as the flaming front approaches, advection from the plume and direct flame contact will further raise temperature and drive off moisture from the woody fuel surface and generation of flammable hydrocarbon gases begins (Albini and Reinhardt, 1995; Silvani and Morandini, 2009). If the source of heat is withdrawn, drying and preheating will not be self-sustaining (Luke and McArthur, 1977). This phase may be referred to as ‘ignitability’ or ‘ignition delay time’: the time before ignition when heat without flame is applied to fuel (Anderson, 1970). Others have referred to it as the ‘ignition time’ which also includes the period of initial combustion (Gill *et al.*, 1978).

2.3.1.2. Phase 2: Ignition and flaming combustion

Ignition of hydrocarbon gases supplies additional heat and links the preheating phase with the next phase of flaming combustion (Byram, 1959; Brown and Davis, 1973; Gill *et al.*, 1978). Flames propagate through the fuel bed and become attached to the outer surface of woody fuels immersing them into a flaming environment (Clements and Alkidas, 1973; Albini and Reinhardt, 1995). Important to woody fuel ignition is the concept of flame front residence time. Flame front residence time, or reaction time, is used to describe the duration of flaming combustion at a fixed location on the fuelbed (Fons *et al.*, 1962; Nelson, 2003). This will determine the time a woody fuel particle spends immersed in the flame. When the combination of duration and heating is sufficient to raise the mass of fuel to ignition temperature (about 320°C is usually assumed (Sussot, 1984)) and fuel/air ratio is appropriate, then woody fuels will ignite (Clements and Alkidas, 1973). Once ignited, burning woody fuels produce water vapour and carbon dioxide, releasing heat and providing energy to bring additional fuel to ignition (Anderson, 1970; Clements and Alkidas, 1973; Shafizadeh *et al.*, 1977; Pyne *et al.*, 1996). This reaction is self-sustaining (Luke and McArthur, 1977) and in the absence of oxygen, pyrolysis works to break down fuels (Ward, 2001). Pyrolysis may follow one of two different pathways depending on fuel characteristics and temperature conditions. Under high temperatures (between 280 and 340°C) pyrolysis results in the production of levoglucosan which is particularly volatile (Shafizadeh, 1968; Ward, 2001). Under low-temperature conditions (between 200 and 280°C) pyrolysis results in the dehydration of cellulose and the formation of char (Byram, 1959; Shafizadeh, 1968; Ward, 2001; Benkoussas *et al.*, 2007).

2.3.1.3. Phase 3: Smouldering and glowing combustion

In this phase, when vapours produced earlier have been consumed (Luke and McArthur, 1977), the charcoal deposited on fuel is burnt at a relatively slower rate by surface oxidation in glowing combustion (Byram, 1959; Brown and Davis, 1973; Sussot *et al.*, 1975). If heat is conserved on the reacting surface of the fuel, glowing combustion will continue (Drysdale, 1998). After the fuel surface has released volatile matter, smouldering combustion proceeds (Carvalho *et al.*, 2002). The smouldering combustion phases can produce large quantities of particulates and carbon monoxide (Ward, 2001). Residual charcoal will continue to burn away leaving only mineral ash (Luke and McArthur, 1977) until the point of extinction when the combustion process is no longer able to be sustained (Pyne *et al.*, 1996). Combined, these phases influence the ‘flammability’ of woody fuels (Anderson, 1970).

Figure 6. Combustion phases often exist simultaneously in woody fuels, making transitions from one stage to another difficult to identify in the field.

2.3.2. Factors affecting woody fuel consumption

Section 2.3.2 examines the factors affecting consumption of woody fuels during forest fires (Figure 7).

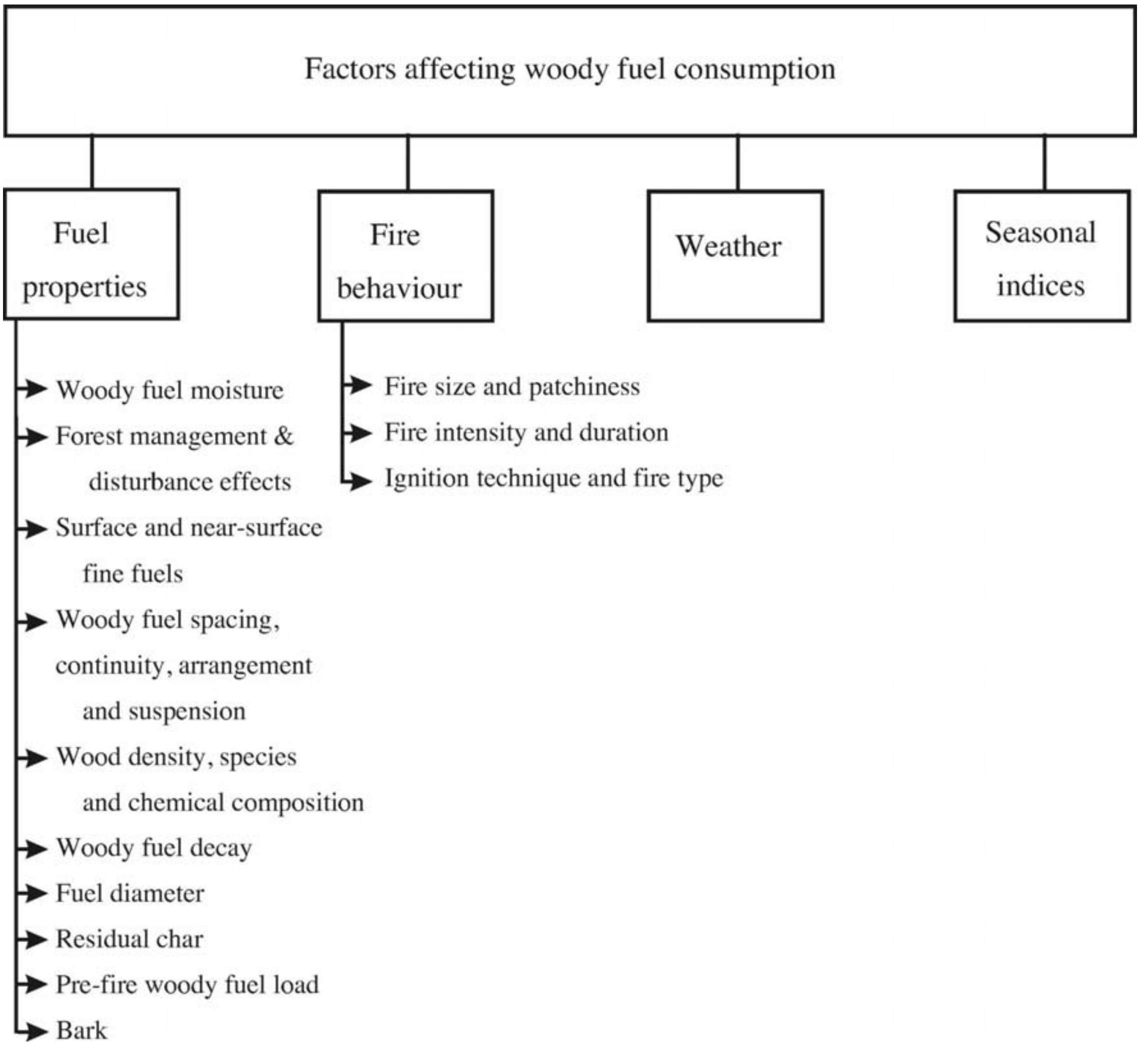

Figure 7. Structure of Section 2.3.2, Factors affecting woody fuel consumption.

2.3.2.1. Fuel properties

2.3.2.1.1. Woody fuel moisture

Despite being widely reported as being one of the most important variables influencing woody fuel ignitability, rate of combustion and the amount of consumption (Byram, 1959; Gill *et al.*, 1978; Walker, 1981; Harrington, 1982; Chandler *et al.*, 1983; Albini and Reinhardt, 1997), and being one of the primary variables driving many woody fuel ignition and consumption models (Sandberg, 1985; Albini and Reinhardt, 1997; Call and Albini, 1997; Prichard *et al.*, 2005; Schroeder *et al.*, 2006), woody fuel moisture content is extremely variable and reports of the relationship between woody fuel consumption and woody fuel moisture content have been mixed. Natural variation of woody fuel moisture content, both within a fuel particle and between fuels is particularly large making modelling and defining the relationship extremely difficult (Brown *et al.*, 1985; Tolhurst *et al.*, 2006). Considering seasonal changes in woody fuel moisture conditions, Byram (1959) reported this variation between woody fuels, where for example the moisture content of fine twigs may be as little as 2% while large, punky (decayed) logs may have a moisture content over 200% after prolonged rainfall. Tolhurst *et al.* (2006) also reported a large variation in the moisture content from the exterior to the core of downed eucalypt woody fuels, ranging from 10% to 480%.

In the United States and Canada, many studies have supported the finding that woody fuel consumption is largely dependent on and inversely related to woody fuel moisture. These studies included: Hough (1968) in understorey burning in the southeast United States; Norum (1976) in understorey burning of larch (*Larix occidentalis*) and Douglas-fir (*Pseudotsuga menziesii*) stands; Sandberg and Ottmar (1983) in the Douglas-fir subregion; Brown *et al.* (1985) in mixed conifer logging slash in northern Idaho; Ottmar (1987) in uncured logging slash in red alder (*Alnus rubra*); Stocks (1987) in immature jack pine (*P. banksiana*); Reinhardt *et al.* (1989) in northern Idaho logging slash; Anderson (1990) in laboratory crib experiments; Ottmar *et al.* (1990) in Douglas-fir and western hemlock (*Tsuga heterophylla*) clearcut units; Call and Albini (1997); Knapp *et al.* (2005) in Sierra Nevada mixed conifer forest; Beese *et al.* (2006) in spring and fall burns near Port Alberni, on Vancouver Island, British Columbia and Wright and Prichard (2006) in prescribed fires of big sagebrush ecosystems.

Brown *et al.* (1985) in their study in the northern Rocky Mountains found that woody fuel consumption was relatively high at moisture contents between 10-15% but was more than halved when moisture content exceeded 25-30%. Anderson (1990) also reported that at higher moisture contents, the rate of weight loss was more variable. Some studies have also found a relationship between woody fuel consumption and duff moisture content (Stocks and Walker, 1972) where duff is the layer found between the litter layer and mineral soil and consists of fermentation and humus layers on the forest floor (Brown *et al.*, 1985). However duff is absent from most open eucalypt forests in southern Australia so published relationships between woody fuel consumption and duff may therefore not be applicable.

The important relationship between woody fuel consumption and moisture content has been well demonstrated in the literature and suggests that as woody fuel consumption is inversely related to woody fuel moisture, there could be a moisture threshold above which fire will not be sustained in woody fuels (Ferguson *et al.*, 2002). In a series of experimental fires, McArthur and Cheney (1966) reported moisture conditions related to the Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968) where no woody fuel > 0.6 cm in diameter was consumed; however these results related to radiata pine and no other research has been able to determine a threshold for Australian eucalypt forests. Further research is needed to confirm whether a moisture threshold exists in Australian eucalypt forest woody fuels and if it does, at what moisture content extinction occurs.

Byram (1959) states that the probability of woody fuel ignition decreases with increasing fuel moisture content and so woody fuels with a high moisture content will not ignite as readily as dry fuels and are unlikely to sustain combustion when the surrounding fuels have burnt out (Cheney, 1990a). This is reportedly due to the lower heat of combustion and higher heat of pre-ignition, meaning that additional energy is required to heat particles to combustion temperatures and propagate flaming combustion in fuels with high moisture content (Shafizadeh, 1978; Frandsen, 1987; Nelson Jr., 2001; Wright and Prichard, 2006). Woody fuels with high moisture content will contribute a larger amount of water vapour compared with woody fuels with low moisture content where the majority of water vapour in the combustion gases comes from the combustion reaction (Brown and Davis, 1973). Byram (1959) reported that the decrease in heat yield for complete combustion conditions results in a smothering process whereby the water vapour coming out of the fuel dilutes oxygen in the air surrounding the fuel. Fuels with high moisture content also produce more char reducing the intensity during flaming combustion (Shafizadeh, 1978).

The lack of a clearly established link between the moisture content of woody fuels and the forward spread of a moving fire (McArthur, 1967; Rothermel, 1972; Gould *et al.*, 2007), coupled with variability in woody fuel moisture and the time consuming and onerous nature of sampling (Fosberg *et al.*, 1981; Harrington, 1982) has discouraged collection of woody fuel moisture data in Australian fire behaviour studies. This has limited our understanding and ability to investigate the effect of moisture on woody fuel consumption in Australian eucalypt forests. Tolhurst *et al.* (2006) found woody fuel moisture was so variable and correlated with so many other predictor variables, that they weren't able to define the relationship with woody fuel consumption. McCaw *et al.* (1997) were also unable to find a clear relationship between the proportion of woody fuel consumed within individual fractions of the fuel bed and their respective moisture contents in thinning slash in regrowth stands of karri (*E. diversicolor*).

Limited research has been conducted in Australian eucalypt forests to clearly identify factors influencing woody fuel moisture and the continuous cycles of gaining and losing moisture. Understanding how these variables contribute to woody fuel moisture and how they interact with each other is essential for model development, predicting woody fuel moisture and therefore woody fuel consumption. In south-western Western Australia, Jones (1978) found that factors affecting the KBDI (Keetch and Byram, 1968) were also related to fluctuations in the average moisture content of karri slash fuels, reporting that 72% of variation in moisture content could be explained by the KBDI. However, Jones noted that the short, cut sample logs used to sample moisture content, were not necessarily a good representation of woody fuel moisture content in the field and so should be treated as an indicative comparison rather than actual fuel moisture. Burrows (1987b) later reported that the moisture content of karri logs was best represented by the Soil Dryness Index (SDI; Mount, 1972). Burrows also found that grounded karri and marri (*Corymbia calophylla*) logs had consistently higher moisture content (10-15% higher) than elevated logs.

In international literature, the effect of several variables on woody fuel moisture has been well documented. These variables include:

(1) weather variables which control moisture including amount, intensity, duration and frequency of precipitation, temperature and relative humidity (Byram, 1959; Fosberg *et al.*, 1981; Chandler *et al.*, 1983; Avramidis, 1989; Samran *et al.*, 1995; Drysdale, 1998; Tolhurst *et al.*, 2006);

(2) weather variables which influence evaporation and drying including temperature, wind speed, relative humidity and sunshine (Luke and McArthur, 1977). For example both wind and sunshine influence drying rates by modifying the environment (i.e. temperature and relative humidity) of the air adjacent to the fuel (Byram, 1959);

(3) seasonal conditions: variations with season are influenced by the amount, intensity, duration and frequency of rainfall and directly reflect woody fuel moisture contents (Jones, 1978; Tolhurst *et al.*, 2006). Of these variables, it is generally excepted that precipitation is the primary source of hydration (Samran *et al.*, 1995);

(4) soil moisture: woody fuels in contact with the ground are hydrated through upward capillary soil water flow (Samran *et al.*, 1995);

(5) site and position variables which influence moisture absorption, evaporation and drying such as site exposure (Pyne *et al.*, 1996; Drysdale, 1998) and slope. For instance Samran *et al.* (1995) reported that woody fuel moisture content varies with slope position (i.e. fuels positioned at the bottom of a slope are wetter than those found upslope) however this may not be an important factor affecting woody fuel moisture at well drained sites;

(6) canopy cover: woody fuels located under sparse canopy cover have increased exposure to solar radiation and evaporation. This results in lower woody moisture contents than those located under more dense canopies (Simard, 1968; Samran *et al.*, 1995);

(7) fuel species: drying rate is influenced by specific characteristics of the wood (Fosberg, 1970; Drysdale, 1998);

(8) fuel suspension: significant differences in woody fuel moisture content have been found between woody material that is suspended above the forest floor and woody material that is in contact with the ground. Materials that are located on the ground are subject to a more humid environment following rain whereas fuels suspended above the ground are more exposed to wind and will dry more readily (Simard and Main, 1982; Tolhurst *et al.*, 2006). Reinhardt *et al.* (1991) found that the moisture content of mixed conifer logging slash depended on whether the slash was elevated or grounded;

(9) fuel size: moisture exchange decreases with increasing particle size (Simard and Main, 1982; Simard *et al.*, 1983);

(10) fuel decay: moisture content of woody fuels will vary with decay state. Decayed wood typically has many open spaces between woody fibres which allows water to enter and be stored (Pyne *et al.*, 1996). Pyne *et al.* (1996) note that decayed wood can store a fuel moisture content up to 300% or more. Reinhardt *et al.* (1991) reported variation in fuel moisture content within woody fuels depending on the condition of the fuel (i.e. whether it was sound or rotten). Surprisingly, in a study by Tolhurst *et al.* (2006), moisture content was not well related to decay class, apart from the green wood;

(11) distance from fuel core: woody fuels are not homogeneous and the moisture content within can vary dramatically. In Australia, Tolhurst *et al.* (2006) reported a large variation in fuel moisture of grounded fuels between the core and outer wood. In mixed conifer logging slash in north Idaho, Reinhardt *et al.* (1991) reported variation in fuel moisture content within woody fuels from samples taken at the top, bottom, centre and sides of logs. This is largely due to the intricate pathways and pores along which moisture is transported as well as the physical processes where moisture is removed from the outer surface by evaporation (Chandler *et al.*, 1983). Inside fuels, capillary diffusion will govern the slower movement of water depending on fuel structure (Chandler *et al.*, 1983);

(12) fuel bed depth: fuel moisture exchange decreases with increasing fuel bed depth (Simard and Main, 1982) and

(13) bark: tight bark on small woody fuels reduces permeability and the rate of moisture exchange (Simard and Main, 1982; Simard *et al.*, 1983).

These variables combine with fuel size to produce a moisture timelag (or moisture response time) effect, representative of the time required to achieve 63% of change from initial fuel moisture towards an equilibrium value (Fosberg, 1970; Anderson *et al.*, 1978; Simard and Main, 1982). The timelag concept has proven to be useful in predicting woody fuel moisture content (Chandler *et al.*, 1983) whereby the lag time increases with the size of the fuel. Thus small diameter fuels are capable of changing rapidly in response to weather changes, while larger diameter fuels respond more slowly, sometimes taking several months or even years (Byram, 1959; Tolhurst and Cheney, 1999). The rate of change in woody fuel moisture will be limited by the slowest process (Luke and McArthur, 1977). Fosberg (1971) describes an example where the rate of water absorption into wood on the forest floor is often slower than the rate of rainfall, and so most of the excess rain is shed from the wood. The National Fire Danger Rating System (NFDRS: Cohen and Deeming, 1985) utilises fuel sizes that correspond approximately to timelag classes; 10-hour: 0.625 - 2.5 cm; 100-hour: 2.5 cm - 7.6 cm; 1000-hour > 7.6 cm. The Canadian Forest Fire Weather Index System (FWI System: Van Wagner, 1987a) predicts woody fuel moisture content on a daily basis for three timelag classes of forest fuels.

In North America, two principal models are used to predict woody fuel moisture. One is the National Fire Danger Rating System 1000-hour fuel moisture model (NFDR-Th) which incorporates a theoretical equation based on meteorological measurements of daily maximum and minimum humidity and temperature as well as duration of precipitation (Nelson, 1964; Fosberg, 1972). The other is the Buildup Index (BUI) calculation in the Canadian Forest Fire Weather Index System. While the BUI is not essentially a woody fuel moisture model it is indicative of woody fuel moisture content because it is calculated using weather variables for Duff Moisture Code (DMC: rainfall, relative humidity and temperature) and Drought Code (DC: rainfall and temperature) which are both well correlated with forest floor moisture (Van Wagner, 1987a; Lawson and Dalrymple, 1996; Wotton *et al.*, 2005; de Groot *et al.*, 2009). Other models used throughout North America include Van Wagner's (1987b) medium slash model using standard daily weather observations, Ottmar's (1980) large fuel moisture model and Ottmar and Sandberg's (1983; 1985) adjusted 1000-hour fuel moisture model (ADJ-Th) based on daily measurements of precipitation duration, maximum and minimum relative humidity's, and maximum and minimum temperatures.

Other techniques that have proved useful in estimating woody fuel moisture content include the use of fuel moisture sticks or dowel (Nelson, 2000), direct readout fuel moisture meters (Lawson and Hawkes, 1989) and electronic fuel moisture and temperature sensors (Nelson, 2000). However their usefulness in predicting variation in a range of natural woody fuels in Australian eucalypt fuels is largely untested.

2.3.2.1.2. Forest management and disturbance effects

Varying forest management practices and disturbance regimes will result in a diversity of landscape, forest stand attributes and fuelbed characteristics that have potential to affect woody fuel consumption and/or influence fire behaviour (Lindenmayer and McCarthy, 2002; Vaillant *et al.*, 2009). Variations in fire behaviour will subsequently affect woody fuel consumption (Section 2.3.2.2). An obvious example related to harvesting practice is the difference between a silvicultural regeneration fire conducted following a clearfelling timber harvest and a prescribed fire or wildfire in an undisturbed forest. In Australia, clearfelling is a traditional timber harvesting technique for tall open forests, where virtually all standing trees are removed from an area (Government of Victoria, 1986). Harvesting is then followed by fire to burn remaining fine and woody logging debris (Slijepcevic and Marsden-Smedley, 2002), heat the soil, expose the seedbed, provide germination conditions thus promoting regeneration of the forest (Slijepcevic, 2001). Post-harvest burning is almost entirely dependent on dead fuels and their moisture status (Norum, 1976) with fuelbeds often characterised by:

- relatively high, modified woody fuel loads;
- deep average fuelbed depth;
- high fuel loadings in localised areas;
- transition of live understorey shrubs into additional dead fuel and
- ground disturbance caused during tree felling and log extraction (McCaw, 2010).

After burning, the regenerated forest has a simplified stand structure with a single cohort of regrowth trees (Lindenmayer and McCarthy, 2002). In contrast, fire in unharvested forest burns without harvesting debris and with multiple fuelbed layers present, results in a multi-aged forest stand including a mixture of living and dead trees (Lindenmayer and McCarthy, 2002).

Variation in time since disturbance and ongoing disturbance regimes will affect fire behaviour and woody fuel consumption. For instance, stand age at the time of harvest and harvesting practices such as thinning both affect the rate of input of woody material to the forest floor (Mac Nally, 2006). Thinning operations temporarily add substantially to the woody fuel load through the addition of harvesting residue (Buckley and Corkish, 1991; O'Connell, 1991; Meggs, 1996; McCaw *et al.*, 1997; Grove and Meggs, 2003). The resulting fuel bed is characterised by fuels (litter, elevated live and dead fuel and woody debris including large, defective logs) which are often drier than those without harvesting residue (McCaw *et al.*, 1997). In the United States, mechanical treatments including thinning and mastication, significantly alter forest structure resulting in increased surface fuel loads that effect fire behaviour variables such as flame length, fireline intensity and rate of spread (Vaillant *et al.*, 2009). In a study within dry Australian eucalypt forests Gould *et al.* (2007) noted that fuelbed characteristics will be affected by the fuel age since last fire; an increase in time since last fire will have direct effects on fuel hazard and subsequent fire behaviour. The impact of fire on forest stand attributes and fuelbed characteristics will vary with forest type and tolerance to fire. In dry sclerophyll forests such as jarrah forest, a moderate to high intensity wildfire will typically result in a partial kill of the stand while a fire of the same intensity in a wet eucalypt forest (e.g. mountain ash forest) will result in complete stand replacement.

Changes to forest attributes and fuelbed structure have been reported to affect woody fuel consumption and fire behaviour. In southern Australian eucalypt forests this typically includes changes to stand growth and woody fuel load as a result of timber harvesting and silvicultural treatments. In south-western Western Australia McCaw *et al.* (2009) reported vigorous stand growth in shelterwood and gap release harvested treatments studied as part of the *Forestcheck* project. Also as part of the *Forestcheck* project, Whitford and Robinson (2009) reported that woody fuel load was highly variable across all treatments, obscuring effects of harvesting treatment. Outside Australia, a study by Brown *et al.* (1985) of prescribed burns in mixed conifer, reported a substantial difference in consumption between slash and non-slash fuels. In slash fuels consumption was 81% and in non-slash fuels only 46%. McCaw *et al.*(1997) also reported that fires burning thinned forest stands are likely to be more intense than in unthinned forests as a result of the increased fuel loads, decrease in fuel moisture and tendency for stronger winds. The silvicultural method may also have an effect on woody fuel consumption. Buckley and Corkish (1991) confirmed this in reporting that heaped, rather than broadcast residues in thinned eucalypt regrowth forest in East Gippsland resulted in increased woody fuel consumption. In forests managed for timber production, the time between harvest and burning will also have an important effect on the degree of woody fuel consumption. Ottmar (1987) reported that in prescribed burns of red alder, a large variation in woody fuel consumption was observed as a result of the number of summer months and therefore the amount of curing and drying since the burned unit was harvested.

Differences in forest stand attributes and fuelbed characteristics due to disturbance have implications for woody fuel consumption model selection and application. Models for woody fuel consumption have been developed for both undisturbed forests and those managed for timber production, however due to differences between fuelbed characteristics and fire behaviour, these models may not be directly applicable for both undisturbed and managed forests. This is supported by Hollis *et al.* (2010) who reported that while there was no clear distinction in the amount of woody fuel consumption between sites characterised by natural, unmodified fuelbeds and those recently harvested, the BURNUP model for predicting woody fuel consumption performed better with large woody fuel loads associated with recently harvested sites due to the generation of sufficient energy to sustain combustion of large fuels.

2.3.2.1.3. Surface and near-surface fine fuels

In Australian eucalypt forests, the structure of the fuel is complex and can be characterised by layers of fuel that influence fire behaviour. Gould *et al.* (2007) define these layers as follows: overstorey tree and canopy; intermediate tree and canopy; elevated fuel; near-surface fuel and surface fuel. Through their influence on fire behaviour, each of these layers has potential to affect the processes of combustion and woody fuel consumption (Wright and Prichard, 2006), however the surface litter (or fine) fuels in particular have been reported to influence the amount of woody fuel consumption. Luke and McArthur (1977) note that large woody fuels cannot be readily ignited in the absence of fine, surface fuels. McCaw *et al.* (1997) in their study of fuel consumption in prescribed burns of thinning slash in regrowth stands of karri found that consumption of woody fuels < 10 cm in diameter was inversely related to the moisture content of the surface litter layer. Fine fuel moisture content also affects woody fuel consumption through its affect on the area burned (patchiness) within a fire perimeter (Hargrove *et al.*, 2000; Knapp *et al.*, 2005). Finney (1999) has also suggested that while only fine, surface fuel moisture will be sensitive to diurnal and atmospheric changes in humidity, temperature and solar radiation, these changes will be sufficient to affect the proportion of flaming and smouldering combustion and therefore the ignition and consumption of woody fuel.

The depth of the surface layer has also been reported to have an effect on the extent of woody fuel consumption. For instance, Prichard *et al.* (2006) utilised both litter fuel moisture and depth to predict the consumption of woody fuels between 22.9 – 50.8 cm in diameter. Norum (1976), in his study of experimental fires in Douglas-fir and western larch also reported that the herbaceous fuels, (often found in the near-surface fuel layer in eucalypt forests (Gould *et al.*, 2007)) and particularly their moisture content and weight, were important factors influencing woody fuel consumption. Despite these reported relationships, Tolhurst *et al.* (2006) were unable to identify an effect of either surface and near surface fuels on woody fuel consumption in mature eucalypt forest in the foothills of south-eastern NSW.

2.3.2.1.4. Fuel spacing, continuity, arrangement and suspension

The relationship between particle spacing and ignition probability, flammability and sustained combustion has been well established throughout literature (Byram, 1959; McArthur and Cheney, 1966; Clements and Alkidas, 1973; Martin *et al.*, 1979; Anderson, 1990; Cheney, 1990a; Albini and Reinhardt, 1995, 1997; Drysdale, 1998). A fuel particle in isolation in a fuelbed (i.e. where fuel spacing is large) will burn with little vigour and incompletely if its own combustion is the only source of heat. This is often the case for woody fuels in natural fuelbeds (Albini and Reinhardt, 1995). However the same particle in close proximity to other dry fuel particles of similar size, increases the transmission of heat in the direction of other fuel particles which ignite more readily and burn with greater vigour (Pyne *et al.*, 1996). For example, woody fuels in a silvicultural regeneration burn may continue to burn after the passage of the fire front because they are sufficiently grouped to sustain combustion. If the spacing between fuel becomes too small (restricting air flow in the fuelbed), combustion will not be sustained. The spacing of woody fuels within the fuelbed is sometimes referred to as ‘fuel arrangement’ (Byram, 1959; Sandberg and Ottmar, 1983) reflecting the relationship between fuel particles and their continuity throughout the fuelbed. The relationship between spacing and combustion characteristics of large sized woody fuels in laboratory fuel cribs was assessed by Anderson (1990), who reported that fuel spacing influences the flaming phase of combustion. Anderson found that flame lengths in particular were reduced as a result of increasing fuel spacing and therefore opening the fuelbed. At a site level, the resulting spatial connectivity from closely spaced fuels has the potential to influence fire behaviour, including the spread of fire, resulting in an increase of the area burnt and reduction in unburnt fuel patches (Brown *et al.*, 1985; Knapp *et al.*, 2005).

Byram (1959) noted that fuel arrangement will have the greatest effect on lower-intensity fires, such as prescribed burns and during the initial stages of the build-up of a fire when other factors (e.g. ignition probability, spotting potential) that influence fire behaviour have little impact. In some forest types, arrangement may not influence woody fuel consumption. Sandberg and Ottmar (1983) in their study of slash burning and fuel consumption in Douglas-fir forests reported that unit average consumption was not affected by piece arrangement but noted that their results may have been influenced by the technique used to assess woody fuel arrangement.

In Australia, Woodman and Rawson (1982) reported differences in woody fuel consumption in radiata pine (*P. radiata*) thinning slash due to variation in fuel suspension and arrangement. The authors attributed this to increased flammability and aeration of the suspended fuels. Tolhurst *et al.* (2006) also reported that fuel suspension (i.e. whether the fuel was predominantly suspended above the ground (suspended) or lying on the ground (grounded)) also influenced consumption and moisture content of small diameter woody fuels in an Australian eucalypt forest of predominantly mountain gum (*E. dalrympleana*) and narrow-leaf peppermint (*E. radiata*).

Accurate assessment of woody fuel spatial distribution and woody fuel arrangement require detailed sampling and can be difficult to achieve on a broad scale the field (Sullivan *et al.*, 2002). Most techniques are related to measurements of fuel load, where high counts of woody fuels and high woody fuel loads are indicative of a closer spacing of fuels.

2.3.2.1.5. Wood density, species and chemical composition

Calculation of pre-fire and post-fire woody fuel load using Van Wagner's line intersect method (Van Wagner, 1968) requires a value for wood density:

$$W = (\Pi^2 / 8 \cdot n \cdot QMD^2 \cdot \rho_p) / L \qquad (5)$$

where W is the fuel load (Mg ha^{-1}), n is the number of intersecting fuels, QMD is the quadratic mean diameter (cm), ρ_p is the wood density (g cm^{-3}) and L is the length of transect line (m). Small differences in wood density can translate into large differences in estimated woody fuel loads, so accurate determination of wood density is important.

Wood density varies between tree species and subspecies (Miranda *et al.*, 2001) and across site locations (Miranda *et al.*, 2001; Pliura *et al.*, 2007) making it difficult to apply a constant value. Low-density wood generally has a larger porosity than high-density wood (de Souza Costa and Sandberg, 2004). Together with differences in the proportions of cellulose, hemicellulose and lignin between woody fuels (Brown and Davis, 1973; Drysdale, 1998) these disparities between species result in varying ignitability (Anderson, 1970), burning rates (Shafizadeh, 1968; Anderson, 1990) and rates of moisture absorption and dehydration (Drysdale, 1998). This means that at any one site, woody fuels with the same characteristics and under the same conditions but of different species, may have different woody fuel moisture content.

The thermophysical and chemical composition of woody fuels, including resinous content and the presence of combustible volatiles also varies between species (Brown and Davis, 1973; Albini and Reinhardt, 1997). These variations between species will result in different ignition and combustion characteristics (e.g. heat of combustion) which will directly affect the rate of burning and woody fuel consumption (Byram, 1959; Brown and Davis, 1973; Shafizadeh *et al.*, 1977; Gill *et al.*, 1978; Shafizadeh, 1978; Walker, 1981; Knapp *et al.*, 2005). Sullivan *et al.* (2002) noted this in some Australian species such as marri which readily burn away leaving a white ash bed, while others such as jarrah, are more likely to char and not maintain combustion. Not all studies that have assessed the effect of species on woody fuel consumption have reported such a relationship. For instance in the Unites States, a study of Douglas-fir slash burns by Sandberg and Ottmar (1983) reported that average unit consumption was not influenced by species composition.

2.3.2.1.6. Woody fuel decay

Australian eucalypt forests support a broad range of woody debris decomposition and decay stages. Many variables and complex interactive processes affect the decay state of woody fuels including forest type and structure, local environmental conditions and the interaction with successional processes and biological factors. These are discussed in more detail in Section 2.1.2.

The decay status of woody fuel has the capacity to influence combustion processes by changing the chemical composition of wood with increasing decay resulting in higher lignin content (Sussot *et al.*, 1975). Decayed fuels have a lower ignition temperature (sound fuels will mostly ignite at about 327°C whereas rotten fuels may ignite between 277-301°C), a higher heat of combustion and reduced temperature of peak rate of pyrolysis (Sussot *et al.*, 1975; Albini *et al.*, 1995; Albini and Reinhardt, 1997; Tolhurst and Cheney, 1999). This explains why woody fuels with a high state of decay are more likely to ignite and burn more readily (Tolhurst and Cheney, 1999; Knapp *et al.*, 2005). They may also support smouldering combustion, and hold fire over a long period of time as opposed to quickly burning away during flaming combustion (Sussot *et al.*, 1975).

Several studies of woody fuel consumption have reported the importance of decay status in determining the consumption of woody fuels including Tolhurst *et al.* (2006) who studied woody fuel consumption in an undisturbed Australian eucalypt forest as well as studies from North America including Brown *et al.* (1985), Hawkes and Taylor (1993), Knapp *et al.* (2005), Kauffman and Martin (1989), Norum (1976), Skinner (2002), and Uzoh and Skinner (2009). These studies all report greater consumption of woody fuels in advanced stages of decay.

Fissures and cracks, characteristic of decaying woody fuels also facilitate ignition and combustion processes by providing a location where embers can lodge and promote sustained ignition (Tolhurst *et al.*, 2006; McCaw, 2010). Cracks and fissures also increase the surface-area-to-volume ratio which in turn increases the rate of burning provided there is an adequate oxygen supply (Byram, 1959). Even small cracks and fissures have a potential effect on ignition and heat transfer in woody fuel particles during the passage of a fire front (Figure 8).

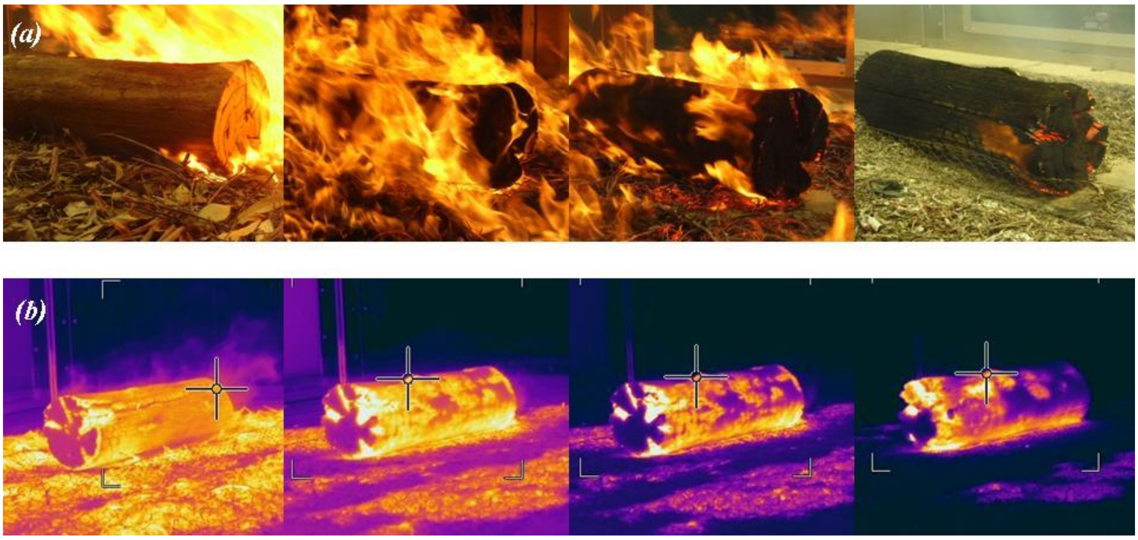

Figure 8. Ignition and heat transfer in a relatively dry Eucalyptus log approximately 20 cm in diameter and in the early stages of decay during the passage of a fire front ((a) visual and (b) infra red temperature profile) (Hollis, 2010).

2.3.2.1.7. Fuel diameter

It is well established that the physical dimensions of fuels directly affect flammability, ignition potential, sustainability and combustion processes (Anderson, 1970; Luke and McArthur, 1977; Fernandes and Rego, 1998; Burrows, 2001). Fine surface fuels and small woody fuels are largely consumed during the passage of the flame front and directly contribute to the forward movement of the fire (Cheney, 1990a; Pyne *et al.*, 1996; Gould *et al.*, 2007). This makes predicting small woody fuel consumption a relatively simple and accurate task (Brown *et al.*, 1985).

Unlike small woody fuels, larger woody fuels will mostly burn after the passage of the fire front. They comprise most of the surface fuel load of a particular forest and form the major proportion of surface fuels consumed by fire. They also contribute more to post-frontal fire behaviour including characteristics of heat release, convection column development and smoke emissions (Sandberg and Ottmar, 1983; Slijepcevic, 2001; Slijepcevic and Marsden-Smedley, 2002). Tools for predicting large woody fuel consumption are less well developed (Brown *et al.*, 1985).

Many Australian studies have reported that larger proportions of small diameter woody fuels are consumed by a wide range of fire conditions than large woody fuels. Tolhurst *et al.* (2006) reported that this effect was particularly pronounced in grounded woody fuels during high intensity fires and in suspended fuels in low intensity fires in a mature eucalypt forest. Cheney (1990a) also found that continuous flaming and glowing combustion was only maintained in fuels less than 12.5 cm in burning experiments conducted on a weight loss, load cell platform. O'Loughlin *et al.* (1982) reported findings from the *Bushrangers Experiment* in a long undisturbed eucalypt forest in the Brindabella range in the ACT, consisting of sub-alpine eucalypt species including *E. dalrympleana*, *E. pauciflora*, *E. radiata*, *E. dives* & *E. delegatensis*. These findings included a direct relationship between fuel size and the proportion of fuel consumed. There was 100% consumption of twigs (diameter: 0.6 – 5.0 cm); 74% consumption of fuels 5-10 cm in diameter; 57% consumption of fuels 10-20 cm in diameter and only 26% consumption of fuels greater than 20 cm in diameter (mean consumption was 50%).

The relationship between fuel size and consumption in eucalypt fuels may be largely due to variation in woody fuel moisture content. In Section 2.3.2.1.1, the relationship between fuel size and fuel moisture content was described where a decrease in moisture exchange was the result of increasing particle size (Simard and Main, 1982; Simard *et al.*, 1983). The relationship may also be attributed to variation in residence time, rate of weight loss and burn out time with fuel size. McArthur and Cheney (1966) reported that burnout time and flame persistence in thinning debris of young stands of *E. seiberi* in New South Wales was largely related to fuel particle size. Cheney (1990a) later defined the relationship between residence time and initial diameter as:

$$t_r = 1.7 \cdot d^{1.686} \tag{6}$$

where t_r is the residence time in minutes and d is the diameter of log in centimetres.

Rates of weight loss and burn out time for woody jarrah forest fuels up to 8 cm in diameter were later determined by Burrows (1994) who established that the rate of weight loss and flame residence time is related to particle diameter (Equation 7). Fuels were burnt on a load cell platform and consumption was complete. However the author found that the extent of consumption in the field was more variable and depended on fuel dryness, wind speed and fire intensity. Burrows (2001) later confirmed that the proportion of fuel consumed by glowing combustion increased with fuel particle size and that the rate of weight loss increased with decreasing round wood diameter (Equation 8):

$$t_r = 0.871 \cdot d^{1.875} \tag{7}$$

$$WL = 36.98 \cdot d^{-0.910} \tag{8}$$

where t_r is the flame residence time in seconds, d is the round wood diameter in millimetres (1-16 mm) and WL is the rate of weight loss per 1000 g of fuel (g s^{-1}). The Cheney (1990a) and Burrows (2001) equations for flame residence time and diameter are similar.

Similar relationships between woody fuel consumption and fuel size have been reported in North America throughout the years. Byram (1959) was one of the first to recognise that rate of burning was proportional to fuel surface area, reporting that the rate of burning increased with increasing fuel surface area provided there was an adequate oxygen supply i.e. smaller woody fuels have a greater surface-area-to-volume ratio so convection and radiation are increased during preheating. In the 1960s, Anderson (1969) reported that the burning characteristics such as flame depth and residence time are strongly controlled by fuel size. In the 1970s, Clements and Alkidas (1973) subsequently studied the combustion of wood in methanol flames and reported that the burning time and rate of weight loss was primarily dependant on the diameter (or thickness) of the fuel. Norum (1976) also studied fuel consumption in Douglas-fir and western larch stands and reported that the presence of rotten fuel larger than 3 inches in diameter was the most dominant variable. Soon after these studies, Martin *et al.* (1979) reported that small fuels less than 7.6 cm diameter are largely consumed by fire over a wide range of fire and environmental conditions. In the 1980s, Brown *et al.* (1985) reported that the pre-fire diameter of fuels was one of the most important independent variables for predicting diameter reduction and that diameter reduction of large fuels was positively related to pre-fire diameter in mixed conifer logging slash in Northern Idaho. Chandler *et al.* (1983) state that a large surface area-to-volume ratio results in an increase in the rates of energy exchange and leads to lower ignition delays and higher rates of fire spread. In the 1990s Anderson (1990) studied the relationship of fuel size and spacing to combustion characteristics in laboratory fuel cribs and found that the flaming phase of combustion was partly dependent on the fuel size. Benkoussas *et al.* (2007) reported that pyrolysis in thin particles is kinetically-controlled while in large particles, it is controlled by heat diffusion.

The majority of woody fuel consumption models include fuel diameter or fuel load distribution by size class as an influencing variable affecting consumption outcomes. For example, Call and Albini (1997) developed an empirical model which related fractional reduction in fuel loading to fuel element diameter and moisture content using data from experimental fires in immature jack pine in central Ontario (Stocks, 1987). The CONSUME models for both activity (slash) and natural fuels (Prichard *et al.*, 2005) incorporate variation in consumption due to fuel size distribution. These models use individual algorithms to predict consumption of woody fuels by pre-defined size classes. The process-based BURNUP model for woody fuel consumption also incorporates variability due to size (Albini and Reinhardt, 1995). BURNUP predicts the diameter of fuel classes as a function over time until the fire self extinguishes or all fuel is consumed. Fuel consumption is then described as percent mass reduction for each size class at the end of the burn.

2.3.2.1.8. Residual char

After a woody particle ignites and gas phase and surface temperatures rise rapidly, thermal degradation and the formation of small cracks, fissures and char begins on the surface of woody fuel (Figure 9) (Byram, 1959; Zicherman and Williamson, 1981; Pyne, 1984). The cracks and fissures that form are similar to those caused by fungal decay (section 2.3.2.1.6) (Cowling, 1961; Zicherman and Williamson, 1981). Zicherman and Williams (1981) state that char forms in two distinct zones overlying non-degraded wood: (1) a heavily distorted outer layer and (2) a mildly distorted, charred inner layer. If these layers of charcoal are not completely consumed by surface oxidation in glowing combustion, a layer of black char will remain on the fuel (Byram, 1959; Brown and Davis, 1973; Drysdale, 1998). The conversion of woody fuels to char can be substantial and can account for a significant amount of mass loss (Donato *et al.*, 2009). Residual char on forest fuels consists mostly of pure carbon (80-97%) and ash (Benkoussas *et al.*, 2007) and is difficult for microbes to break down. Charring on the surface of woody fuel also acts to insulate underlying non-degraded wood from endothermic pyrolysis (Brown and Davis, 1973; Park *et al.*, 2007). The insulating effect of char impacts usage by microorganisms resulting in slower rates of decomposition and decay and sustaining carbon in the forest cycle for a longer period of time (Krull, 2009).

Char yield depends on the chemical characteristics of wood as well as prevailing physical and environmental conditions (Shafizadeh, 1968; Sussot *et al.*, 1975; Rothermel, 1976; Drysdale, 1998) but is also influenced by pyrolysis temperature, heating rate and rate of burning, with a greater proportion of char produced at low heating rates and under lower temperatures (Shafizadeh, 1968; Broido and Nelson, 1975; Sussot *et al.*, 1975; Sussot, 1980; Zicherman and Williamson, 1981; Pyne *et al.*, 1996; Drysdale, 1998; Guerrero *et al.*, 2005). Rapid pyrolysis at elevated temperatures results in little char (Shafizadeh, 1968; Sussot *et al.*, 1975).

Formation of char is also influenced by fuel characteristics including geometry and structural features (Zicherman and Williamson, 1981), diameter, arrangement and moisture content. Byram (1959) notes that wet fuels have a lower heat of combustion and a higher heat of pre-ignition resulting in the production of greater quantities of char and reducing the intensity of flaming combustion (Byram, 1959; Donato *et al.*, 2009). Donato *et al.* (2009) suggest that charring will be greater in closely arranged fuels with poor aeration and in fuels that are largely decayed. The proportion of char deposited on woody fuels will largely depend on the diameter of the fuel (Donato *et al.*, 2009). For example, fine fuels < 0.6 cm remaining after the passage of the active flame front can largely be presumed to be all char while for large woody fuels > 50 cm, char may comprise less than 5% of the mass (Donato *et al.*, 2009). While the proportion of char on large woody fuels maybe small, woody fuels are typically the main source of black carbon within a forest post-fire (Donato *et al.*, 2009).

Figure 9. Formation of small cracks, fissures and char on the surface of woody fuel as a result of thermal degradation.

2.3.2.1.9. Pre-fire woody fuel load

While pre-fire woody fuel load is required to calculate the amount of woody fuel consumed in a fire, and is expected to be correlated with this total value, it is not clear whether it has a causal effect (Smithson, 2000) on the proportion (or fraction) of fuel consumed. In studies throughout North America, it has been widely reported that total woody fuel consumption is strongly correlated with pre-fire fuel loadings, but this is not necessarily true of percentage consumption. These studies included those by: Norum (1976) in experimental fires in mature Douglas-fir and western larch stands; Quintilio *et al.* (1977) in Canadian upland jack pine; Brown *et al.* (1985) in slash and non-slash prescribed fires comprising mixtures of western larch, Douglas-fir, ponderosa pine (*P. ponderosa*), lodgepole pine (*P. contorta*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and grand fir (*A. grandis*); Quintilio *et al.* (1991) in spring fires in a semi-mature trembling aspen (*Populus tremuloides*) stand in central Alberta; Prichard *et al.* (2006) in prescribed burns of ponderosa pine forests; Wright and Prichard (2006) in prescribed fires in big sagebrush ecosystems and most recently de Groot *et al.* (2009) in Canadian boreal forests.

Pre-fire woody fuel load influences the rate of burning and heat release of a fire (Byram, 1959; Shafizadeh *et al.*, 1977; Shafizadeh, 1978) and as woody fuel load increases, so does the number of points where sustained ignition can occur (Schroeder *et al.*, 2006). Brown *et al.* (1985) reported that the proportion of small woody fuel (< 7.5 cm diameter) consumed is affected by pre-fire fuel loading; consumption was consistently high for pre-fire fuel loads over 22.4 Mg ha^{-1} and considerably less for lighter loads. Hollis *et al.* (2010) reported that the process-based woody fuel consumption model BURNUP (Albini and Reinhardt, 1995) performed better with large fuel loads due to the generation of sufficient heat flux as a result of the higher fuel loads which then enables ignition and sustained fire in the larger fuels. McArthur and Cheney (1966) also suggested that the burnout time or residence time of a fire will depend in part on the quantity of fuel that is available for combustion. While the available fuel may only be a fraction of the total fuel load, the quantity of available fuel will generally increase with increasing woody fuel load. Increasing available fuel will then support a longer fire duration, more effective heat transfer and increased rate of drying (McArthur and Cheney, 1966) resulting in the involvement of other woody fuel particles in ignition and combustion processes.

Pre-fire woody fuel loading is influenced by many site and vegetation characteristics including:

- site productivity and stand characteristics;
- time since last fire;
- previous fire characteristics such as fire intensity and season of fire;
- forest management influences such as whether the site as been logged and if so, the intensity of harvest and the level of utilisation and
- grazing practices (Wright and Prichard, 2006; McCaw, 2010).

2.3.2.1.10. Presence or absence of bark

The presence of bark on woody fuels will vary with wood species and timber condition. As in standing trees in Australian eucalypt forests, bark on downed woody fuels can vary from fibrous, stringy textures or long ribbon-like strands to woody fuels with no bark present at all (Wilson, 1992; McCarthy *et al.*, 1999). The degree to which bark is held to the fuel will vary with species and also by the condition and decay status of the fuel. On standing trees, bark affects fire behaviour by producing short and long distance spotting as well as linking the ground with canopy fuels (Wilson, 1992; McCarthy *et al.*, 1999). On downed woody fuels, it is the effect of bark on woody fuel moisture (described in Section 2.3.2.1.1) and its influence on radiative characteristics of the fuel surface (Vines, 1968; Albini and Reinhardt, 1997) that is probably more important. These roles in turn affect the heat of combustion and rate of combustion (Albini and Reinhardt, 1997). Dry bark will insulate well, while wet bark will conduct heat better depending on its thickness (Vines, 1968). Although Albini and Reinhardt (1997) were unable to find a definitive relationship between the presence of bark and ignition or burning rate, bark contains a much higher quantity of chemical extractives and lignin or phenolic compounds, indicative of a higher heat of combustion (Shafizadeh, 1978). These factors, together with the potential for fibrous bark to provide fissures where embers can lodge and ignite woody fuels (McCaw, 2010), demonstrate that bark influences ignition.

2.3.2.2. Fire behaviour

2.3.2.2.1. Fire size and patchiness

The area burned in a forest fire has obvious implications for the amount of woody fuel consumed (i.e. the greater the area burned, the more woody fuel is subject to fire) but it may also affect combustion process. Brown and Davis (1973) reported that combustion was more complete and heat yield was greater in small fires than in large fires, resulting in more woody fuel consumption in the flaming phase in small fires. The proportion of area burned within a fire perimeter is often referred to as fire ‘patchiness’ (Catchpole, 2002), which has been found to be largely dependent on variables affecting fire spread (i.e. near-surface fuel height and hazard score, surface fuel hazard score, 10-m open wind speed, dead fuel moisture and slope in dry open Australian eucalypt forests (Gould *et al.*, 2007)). The total woody fuel load subject to fire is dependent on the patchiness of a fire and therefore the actual area burned. It is important to take this into account when determining woody fuel consumption. For example, while an intense wildfire may burn 100% of the area within a fire perimeter, a low intensity prescribed fire will often only burn 50-60% of the area within a fire perimeter, leaving large unburnt areas. An example of this is the low intensity prescribed burn conducted by Hamilton *et al.* (1991) in *E. obliqua* forest in Victoria which resulted in 13.6% of the woody fuel being consumed, a relatively low proportion due in part to only 50% of area being burnt within the fire perimeter. Wright and Prichard (2006) reported that the proportion of area burned was a strong predictor of biomass consumption in big sagebrush ecosystems. While calculating the degree of patchiness is necessary to determine total woody fuel consumption, it is probably not a variable that has a causal effect on the proportion of woody fuel consumed.

2.3.2.2.2. Fireline intensity and fire duration

Byram (1959) defined fireline intensity as the rate of energy released per unit length of flame front. Fireline intensity I (kW m^{-1}) is widely used to characterise the active flaming zone, and is calculated as:

$$I = H \cdot w_a \cdot r, \tag{9}$$

where H is the low heat of combustion (kJ kg^{-1}), w_a is the fuel consumed in the active flaming front (kg m^{-2}), and r is the fire rate of spread (m s^{-1}). This simple measure of fire intensity is directly related to flame size (Alexander, 1982) and provides a quantitative description that can be used to evaluate the effect of fire on ecosystem components.

Defining and quantifying fireline intensity is particularly difficult for complex burn patterns which may result, for example, from multiple ignition points or ring ignitions that are commonly used in prescribed burn operations. These burn patterns can lead to stationary fires with mass fire behaviour (McRae and Flannigan, 1990) and are characterised by significant heat release and extreme turbulence for which the concept of a moving flame front is not applicable. McArthur and Cheney (1966) and Cheney (1990b) suggest total heat release as a more appropriate descriptor of fire energy release in such situations.

The effect of fireline intensity on woody fuel consumption has been widely reported in the literature but the conclusions from different studies are not consistent. This has resulted in uncertainty about the effect of fireline intensity, and particularly the difference in woody fuel consumption between high intensity wildfires and low intensity prescribed burns. Some Australian research has shown that the proportion of woody fuels consumed by fire will increase with increasing fire intensity. Hamilton *et al.* (1991) reported that only 13.6% of woody fuels were consumed by a low intensity (< 250 kW m^{-1}) prescribed burn in *E. obliqua* forest in Victoria. However, this was probably because the burn was patchy and a large proportion of total biomass came down from overstorey post-burn and contributed to the post-fire fuel load. McArthur and Cheney (1966) found a positive relationship between fireline intensity (ranging from 230 to 3900 kW m^{-1}) and woody fuel consumption in prescribed burns in thinned *P. radiata* stands. Similarly Tolhurst *et al.* (2006) reported a strong positive relationship between fire intensity (ranging between 585 and 3304 kW m^{-1}) and woody fuel consumption for wet sclerophyll forest of *E. dalrympleana* and *E. radiata* near Tumbarumba, NSW. Burrows (2001) reported that woody fuel consumption was dependent on the intensity of fire through the litter fuel as well as on fuel dryness and wind speed.

Positive relationships between woody fuel consumption and fire intensity have also been reported in several North American studies. Fahnestock and Agee (1983), using data from prescribed fires in other studies (Fujimori *et al.*, 1976; Grier, 1976; Grier and Logan, 1977; Grier *et al.*, 1981) as well as their own data, estimated that snag and downed log consumption in western Washington wildfires would be 20% in moderate intensity fires and 30% in high intensity fires. Youngblood *et al.* (2008) argued that low intensity, surface burning prescriptions are likely to result in lesser amounts of woody fuel consumption in dry conifer forests in northeastern Oregon than more intense fires that consume overstorey canopy. Others studies have demonstrated how changes to seasonal and weather variables that influence both fuel moisture and fire behaviour (including fire intensity) will also affect woody fuel consumption. Analysing fire behaviour through immature jack pine stands in Ontario Canada, Stocks (1987) reported that the amount of fuel available for combustion and the consumption of ground and surface fuels correlated well with the Build Up Index (BUI) of the Canadian Fire Weather Index (FWI) System (Van Wagner, 1987a). Sparks *et al.* (2002) in their study of season of burn influences on fire behaviour and fuel consumption in restored shortleaf pine (*P. echinata*) -grassland communities reported that the proportion of fuel consumed was significantly less in growing season fires than in dormant season fires due in part to the fireline intensity being greater in the latter. In a study on Vancouver Island in British Columbia, Beese *et al.* (2006) also reported differences in woody fuel consumption between low-severity spring burns and high-severity fall burns. While their study demonstrated substantial differences in woody fuel consumption due to seasonal differences, particularly in fuel moisture, the authors also concluded that woody fuel consumption increased significantly with increasing fire severity. Most recently, a study of woody fuel consumption in Canadian boreal forest fires by de Groot *et al.* (2009) showed that high intensity surface fires (around 4400 kW m^{-1}) resulted in greater consumption of forest fuel than low intensity fires (between 15 and 390 kW m^{-1}). The process-based BURNUP model (Albini and Reinhardt, 1995) used to predict woody fuel consumption in the FARSITE fire area simulator (Finney, 2004) incorporates a positive effect of fire intensity and residence time on the consumption of woody fuels.

In contrast, several authors have reported that the proportion of woody fuels consumed by fire decreases with increasing fire intensity. Hall (1991) compared fuel consumption between mass-ignited high intensity fires and moderate intensity fires in logging slash, and concluded that high intensity fires consume less woody fuel than lower intensity fires. Hall’s study has been widely cited (Ottmar *et al.*, 1993; Tinker and Knight, 2000; Ottmar *et al.*, 2001; Wright and Prichard, 2006) and its conclusions have been incorporated into the CONSUME model of woody fuel consumption for activity fuels (logging slash) (Prichard *et al.*, 2005). Hall (1991) argued that high intensity fires had a faster rate of flaming consumption and that this reduced the duration of heat supplied to wood, therefore influencing the rate of woody fuel consumption. While this finding has been influential in research and model development, the method used to define and measure fire intensity was subjective. Hall (1991) did not measure fire intensity per se but categorised fires according to ignition method, namely mass-ignition (high intensity burns) versus strip ignition (low intensity burns). Taylor and Sherman (1996) in their report on biomass consumption and smoke emissions from contemporary and prehistoric wildland fires in British Columbia, estimated that the proportion of woody fuel consumed decreased with increasing fire intensity, with 85% of woody fuels consumed in a surface crown fire and only 60% in a crown fire. This estimation was based on data collected during experimental fires (Quintilio *et al.*, 1977; Brown and DeByle, 1989; Alexander *et al.*, 1991; Quintilio *et al.*, 1991) and from unpublished data from the Canadian Forest Service (Taylor and Sherman, 1996).

Other studies have reported no significant difference in woody fuel consumption under varying fire intensities. For example, Tinker and Knight (2000) found no significant differences in post-fire woody fuel loads following crown fires and those following intense surface fires. In slash hazard reduction burns of longleaf pine, Hough (1968) reported no difference in woody fuel consumption between backfires and headfires. Due to a distinct difference between backing versus headfire rates of spread, this result indicates that woody fuel consumption is not affected by fire intensity in this fuel type. Sandberg and Ottmar (1983), in their study of slash burning and fuel consumption in the Douglas-fir subregion, did not measure fire intensity or rate of spread because they assumed that these would have no effect on woody fuel consumption.

2.3.2.2.3. Ignition technique and fire type

The effects of ignition technique and fire types on woody fuel consumption have received little attention. Hall (1991) compared fuel consumption between mass-ignited fires and strip-ignited fires in coniferous logging slash and found that mass-ignited fires had a faster rate of flaming consumption thus reducing woody fuel consumption. On the other hand, the United States National Wildfire Coordinating Group (2001) recommends using mass-ignition fires to ensure maximum fuel consumption even when fuel moisture contents are high. In southern Australian eucalypt forests Hollis *et al.* (2011b) did not find a relationship between ignition technique (namely multiple point ignition versus line ignition) and woody fuel consumption.

2.3.2.3. Weather variables

Fire weather variables including temperature, relative humidity, precipitation and wind speed have been reported to directly and indirectly affect the combustion processes in woody fuels and their consumption (Shafizadeh, 1968; Tinker and Knight, 2000; Carvalho *et al.*, 2002; Wright and Prichard, 2006). Most of these variables also influence fuel moisture and fire behaviour, and their relationship to woody fuel consumption may be due in part to these underlying relationships.

Designing and conducting field experiments to determine the effects of weather variables on woody fuel consumption is difficult due to natural variability at a site level and variability over time. The inability to partition the effects of each factor from other correlated variables and underlying relationships has resulted in very few documented studies that have defined a direct relationship between fire weather variables including wind speed on woody fuel consumption.

Wind speed is one of the major factors influencing forest fire danger (McArthur, 1967; Deeming *et al.*, 1972; Van Wagner, 1987a) and fire behaviour through its influence on heat transfer processes, supply of oxygen and affect on the burning rate of forest fuels (Byram, 1959; Rothermel, 1972; Carvalho *et al.*, 2002; Gould *et al.*, 2007; Andrews *et al.*, 2008). An increase in wind speed results in an increase in oxygen supply, directly impacting the rate of fire spread through fuels, tilting flames forward increasing radiative and convective heat transfer to the unburnt fuels. In woody fuels, wind speed is critical in determining ignition success (Shafizadeh, 1968; Lawson *et al.*, 1997), burning rate (Byram, 1959), residence time (Burrows, 2001), sustenance of the smouldering process (Carvalho *et al.*, 2002) and the proportion consumed by fire (Burrows, 2001; Wright and Prichard, 2006). Ottmar *et al.* (1990) in their study to assess the consumption of woody fuels under spring-like burning conditions in Douglas-fir and western hemlock clearcut units provided improved models for predicting woody fuel consumption. These models were based on multiple linear regression relationships and the authors found that including wind speed did not improve model fit.

2.3.2.4. Seasonal indices of drought or fuel availability

Several studies from North America have reported relationships between woody fuel consumption and seasonal indices, mostly because they are indicative of fuel moisture content (Section 2.3.2.1.1). One such study by Knapp *et al.* (2005) on fuel consumption in prescribed fires ignited under different fuel moisture conditions reported a difference in the consumption of dead and downed organic matter between early season (67%) and late season burns (88%). This was attributed to early season burns having higher wood moisture levels and patchier burn characteristics. Beese *et al.* (2006) reported that differences in large woody fuel (> 7 cm) consumption between low-severity spring burns and high severity autumn burns reflected spring and fall woody fuel moisture contents of 50-60% and 20-30% respectively (Taylor *et al.*, 1991) in British Columbia. Kauffman and Martin (1989) in their study of fuel consumption in prescribed understory fires in Sierra Nevada mixed conifer forests also found this variation in woody fuel consumption with season. The authors reported that early spring fires consumed between 16-77% of the total available fuel, while early autumn fires consumed between 75-92% when fuels within all size categories had higher fuel moisture content. A study by McRae (1980) of prescribed burning in Ontario slash fuel complexes found that woody fuel consumption was related to fire weather as expressed by the Buildup Index (BUI) component of the Canadian Forest Fire Weather Index (CFFWI) system (Van Wagner, 1987a). Models based on the early work of McRae (1980) are used throughout Canada to predict woody fuel consumption. These are empirical models primarily driven by the Buildup Index (BUI) values of the CFFWI and require values for Duff Moisture Code (DMC) and Drought Code (DC). These models include the empirical forest floor consumption regression models recently developed by de Groot *at al*. (2009) for Canadian boreal forest fires which also uses Drought Code (DC), Duff Moisture Code (DMC) and the Buildup Index (BUI).

In Australia, estimates of woody fuel consumption are often determined using McArthur's Drought Factor (DF) calculation (Tolhurst *et al.*, 2006) which employs either the KBDI (Keetch and Byram, 1968) or Mount's SDI (Mount, 1972) depending on agreed practice within the State or Territory. These indices are directly related to seasonal trends in drying and woody fuel moisture and therefore also fuel availability (Luke and McArthur, 1977; Tolhurst and Cheney, 1999). Luke and McArthur (1977), in demonstrating the drying trends of woody fuels 20-30 cm in diameter in relation to the KBDI, showed that woody fuel moisture content varied between 32 and 13% over an annual KBDI cycle. This would suggest that woody fuel consumption in Australia may also be related to seasonal indices.

Other studies have struggled to define the relationships with fire and seasonal indices which may in part be due to difficulties in experimental design. Lawson's (1973) study of fire behaviour in lodgepole pine stands in central British Columbia reported that woody fuel consumption was not well correlated with fire danger indices, possible due to variability of pre-fire fuel loading between sites. Another Canadian study by Quintilio *et al.* (1991) also reported poor correlations between woody fuel consumption and seasonal indices including DMC and BUI. The authors pointed out that this may have been due to very high moisture content in the lower forest floor layers. Sparks *et al.* (2002) in their study of season of burn influences on fuel consumption in restored shortleaf pine-grassland communities found no linear relationship between the KBDI and the proportion of fuel consumed. A study by Jones (1978) investigating the relationship between fuel removal and fuel conditions in karri slash disposal burns found that woody fuel consumption could not be predicted based on KBDI (or fuel moisture content) alone.

2.3.3. The importance of woody fuel consumption

In Australian eucalypt forests, fire management is driven by the need to minimise the impact of wildfires on human life and property, reduce the occurrence and severity of large wildfires impacting on natural values and protect, regenerate and conserve biota (Burrows and Abbott, 2003; Forest Fire Management Group, 2007). To achieve fire management objectives, prescribed fire programs are conducted on varying scales that result in the combustion and removal of woody biomass. The ability to accurately predict woody fuel consumption is therefore essential in their skilful planning (Fahnestock and Agee, 1983; Brown *et al.*, 1985). Fire prescriptions are often complicated due to the need to accommodate trade-offs between conflicting management objectives (e.g. habitat and carbon management versus fuel load reduction) and require a detailed knowledge of woody fuel characteristics (Martin *et al.*, 1979; Ottmar *et al.*, 2001; Beese *et al.*, 2006). Accurate prediction of woody fuel consumption is also essential for managing the long-term effects of wildfire and prescribed fire programs on woody fuels.

The degree of woody fuel consumption as a result of forest fires has direct implications relating to fire suppression and firefighter safety, fire behaviour, the ecological impact of fire and emissions of carbon and smoke. These are described below in sections 2.3.3.1– 2.3.3.4.

2.3.3.1. Fire suppression and firefighter safety

Consumption of woody fuel in forest fires is an important consideration for the safe management and suppression of both prescribed fires and wildfires. Consumption of woody fuels on the forest floor greatly influences the total energy output and rate of heat release from a fire (Byram, 1959; Rothermel, 1993). In eucalypt forests, this consumption will determine the heat radiating from a fire ground and how soon after the passage of fire that firefighters can safely commence suppression and mop-up activities. Depending on the amount and size of the woody fuels burning behind the active flame front, this may take more than 30 minutes before the radiation reduces to a survivable threshold (Sullivan *et al.*, 2002). The burning woody fuels will also largely determine the hazardous smoke environment to which firefighters are exposed (Pyne *et al.*, 1996; Sullivan *et al.*, 2002; Bertschi *et al.*, 2003; de Souza Costa and Sandberg, 2004; Ottmar *et al.*, 2009).

Woody fuels can burn for long periods of time, sometimes even months after the passage of the fire front. This increases the time and resources needed to patrol and effectively suppress or mop-up a fire (Cheney, 1981; Pyne *et al.*, 1996; Lawson *et al.*, 1997). Acting as a source of fire, burning woody fuels also increase the potential for re-ignition in the days and weeks following fire particularly if woody fuels remain alight near unburnt fuel and a change in fire weather conditions leads to ignition of surrounding fuels and fire build-up (Pyne *et al.*, 1996; Gould, 2003). Therefore, knowing the available woody fuel load, burning potential and rate of consumption is necessary to understand and manage forest fires. For example, fire managers should be aware of particularly heavy woody or dry fuel loads that may considerably increase the difficulty of suppression (Cheney, 1981, 1990a).

2.3.3.2. Fire behaviour

The important contribution by fine fuels (< 0.6 cm in diameter) to frontal flames and forward spread of a fire front is well documented (McArthur, 1967; Cheney, 1990a; Burrows, 2001). Woody fuels are mostly consumed after the flame front has passed and have longer flame residence and burn-out times than fine fuels (Burrows, 2001; Gould *et al.*, 2007). Woody fuels make an important contribution to total energy output, rate of heat release (Martin *et al.*, 1979) and convection column development.

Woody fuels on the forest floor will also directly impact the size, intensity and forward spread of fire (Clements and Alkidas, 1973). Rothermel (1972) reported that large diameter fuels can potentially slow the spread of fire by acting as a barrier to the passage of surface fires. However in piled slash residue, large woody fuels can add significantly to the intensity of the active front and to the length of flames produced (Rothermel, 1972; Cheney, 1990a) increasing fire hazard potential and resistance to control (Brown *et al.*, 2003). In a study of jack pine logging slash at Frontier Lake in Canada, McAlpine (1995) reported a positive correlation between surface fuel consumption and fire spread, particularly at low wind speeds.

Combustion of woody fuels releases large amounts of energy, driving heat and moisture upwards, interacting with the atmosphere above the fire (Potter *et al.*, 2004; Kiefer *et al.*, 2008). As hot air rises, cooler air surrounding is drawn in to take its place (Walker, 1981). The burning rate of surface fuel, including woody fuel, and the stability of the atmosphere above the fire will determine the height of the plume (Walker, 1981). Atmospheric temperature, humidity and surface winds interact to influence the development of a convection column which can have a strong impact on fire behaviour including the potential for downdrafts (Pyne *et al.*, 1996; Tolhurst and Chatto, 1999; Flannigan and Wotton, 2001; Potter *et al.*, 2004).

2.3.3.3. Ecological fire impact and fire severity

Consumption of woody fuels also impacts a variety of first- and second-order fire effects. Heating of tree boles and superficial roots can injure the cambium and result in severe stem wounding, fire scarring and subsequent hollow-butting or potentially stem, root or crown death (Jacobs, 1955; Vines, 1968; Norum, 1976; Ryan and Frandsen, 1991; Swezy and Agee, 1991; McCaw *et al.*, 1997; Stephens and Finney, 2002). Fire also stimulates germination of many Australian species (Gill, 1981; Whelan, 1995; Morrison *et al.*, 1998; Thomas *et al.*, 2007). In Australian eucalypt forests for example, a study of low and moderate intensity experimental fires in jarrah and marri forest in Western Australia by Burrows (1987a) reported considerable damage to jarrah and marri trees (< 35 cm in diameter) due to summer fires. In this study, the incidence and severity of damage to tree boles was attributed in part to the proximity of trees to woody fuel, and damage to these trees was evident even at intensities below 350 kW m^{-1}. Cheney *et al.* (1990b) in their study of the extent of fire damage from burning operations in thinned stands of silvertop ash (*E. sieberi*), reported that the combustion of woody fuels from previous logging operations was the most important cause of fire damage. Similar findings were also reported by Buckley and Corkish (1991) in their study of prescribed burning of thinning slash in a eucalypt regrowth forest in which they reported that old, burning logs were the major source of unacceptably high stem damage. In a study of low to moderate intensity fires in thinning slash fuel in karri regrowth, McCaw *et al.* (1997) reported that woody fuels within 1 m of trees significantly increased the probability of fire-caused tree damage. McCaw *et al.* also reported that the incidence of fire-associated tree damage was directly related to the quantity of fuel consumed and subsequent heat release per unit area. Burrows (2001), in his study of flame residence times and rates of weight loss of eucalypt forest fuel particles, supported this finding, noting that quantity and distribution of woody fuels is likely to have an important impact, not only on the damage to plant stems, but also on the degree of soil heating. Studies of tree mortality and basal injury in North America support these findings for various conifer species (Ryan and Frandsen, 1991; Stephens and Finney, 2002).

The occurrence of fire in Australian eucalypt forests results in the heating of the upper soil profile. This has important implications for the survival of seeds and plants and many micro-organisms dwelling in the soil (Beadle, 1940; Burrows *et al.*, 2002; Thomas *et al.*, 2007). A direct relationship between the amount of fuel consumed and the amount of heat transmitted downward to the soil has been widely reported in Australian and international studies (Alexander, 1982; Johnson and Miyanishi, 1995; Whelan, 1995; Pyne *et al.*, 1996; Burrows, 1999; Odion and Davis, 2000; Burrows *et al.*, 2002; Carvalho *et al.*, 2002; Knapp *et al.*, 2005; Tolhurst *et al.*, 2006). Put simply, the more fuel consumed, the greater the heat impact at a site. This subsequently determines the extent of damage and post-fire recovery.

2.3.3.4. Carbon and smoke emissions

Woody fuels are an important component of a continuous cycle where carbon stocks move between the living forest biomass, dead organic matter, soil and atmosphere. In the context of climate change, it is essential to know the contribution of woody fuels to carbon sinks and greenhouse gas and smoke emissions when they are consumed. This information is necessary for development of management strategies to better meet land management goals and to comply with air quality and emission targets (Gould, 2003). The effect of woody fuel consumption on carbon storage and emissions in the context of climate change was discussed in detail in Section 2.2. In this section, the effect of woody fuels on smoke emissions is discussed.

Exposure to smoke emissions can be hazardous, not only because of the impacts on human heath (particularly respiratory health) but also direct impacts on atmospheric visibility and amenity (McKenzie *et al.*, 2006). Of growing concern, is also the impact on agricultural industries. For instance, Maleknia and Adams (2008) reported that exposure of grapevines to volatile organic compounds in smoke may result in tainted wine and possible financial losses. Air quality can be affected by smoke, both locally exposing firefighters to high concentrations of particulate matter, and also regionally and potentially for hundreds of kilometres downwind from fires (McKenzie *et al.*, 2006), depending on weather factors (e.g. wind direction, inversion strength) and scale of area burned (Sneeuwjagt and Smith, 1995; Wain *et al.*, 2008).

The composition and quantity of smoke emissions is also directly related to the consumption and characteristics of woody fuels such as fuel load, type, chemistry, condition, size distribution, arrangement, moisture content, and the proportion of flaming and smouldering combustion processes (Fahnestock and Agee, 1983; Ottmar *et al.*, 1990; Ward, 2001; Knapp *et al.*, 2005; Tolhurst *et al.*, 2006; Wright and Prichard, 2006; Tham and Bell, 2008). While some of these characteristics may not be easy to identify by fire managers for all fire sites (e.g. woody fuel load), others may be easily determined or estimated using models and can be used by fire and land management agencies to manage the effects of smoke from forest fires (Stocks, 1987; Ottmar *et al.*, 1990; Beese *et al.*, 2006; Wright and Prichard, 2006). Accurately predicting woody fuel consumption is critical in the management of smoke emissions from prescribed fires and wildfires. Despite this, woody fuel consumption is extremely variable and is the largest source of uncertainty in predicting carbon and smoke emissions (Sandberg and Peterson, 1984; French *et al.*, 2004; de Groot *et al.*, 2009).

It is possible to adopt techniques that reduce emissions produced for a given fire. Ottmar *et al.* (2001) suggest that burning in small units will reduce smoke emissions, possibly by increasing combustion efficiency (Brown and Davis, 1973). Also, by creating a mosaic of burned and unburned areas within a prescribed burn perimeter and therefore reducing the potential area burned, the quantity of woody fuel consumed by fire is also reduced (Ottmar *et al.*, 2001). Alternatively, burning when the fuels are wet may reduce the amount of fuel consumed (Ottmar *et al.*, 2001), but may also result in a lower intensity fire with decreased combustion efficiency. This results in a greater proportion of smouldering combustion leading to increased emissions of dark smoke containing large quantities of particulate matter and carbon monoxide (Brown and Davis, 1973; Pyne *et al.*, 1996; Ward, 2001; de Souza Costa and Sandberg, 2004). Brown and Davis (1973) describe how combustion efficiency is higher for a low intensity fire in a dry fuel, that burns with bright yellow flames and with minimal smoke emissions. Further research is required to determine if a known moisture threshold exists above which fire cannot be sustained in woody fuels (Section 2.3.2.1.1), and whether burning when fuels are wet results in lower emissions that would be counteracted by decreased combustion efficiency. Ottmar *et al.* (2001) suggests that even though wet fuels burn less efficiently and produce more emissions, the emissions from a given fire are significantly reduced because so much less fuel is consumed.

Other options to decrease the amount of fuel consumed include burning more frequently to prevent the accumulation of fuels, burning in smaller units to decrease the area burned and scheduling prescribed burns prior to predicted rainfall in the hope that rainfall will stop woody fuels from continuing to smoulder, preventing further consumption (Ottmar *et al.*, 2001). For small fires, it may be easier to rapidly mop-up a fire, again preventing woody fuels from continuing to smoulder and burn (Ottmar *et al.*, 2001) however this would be a costly and impractical exercise for large fires. An alternative technique is to redistribute emissions through meteorological scheduling, by burning when the ventilation index (calculated from the amount of air available for mixing and the speed at which the air is passing) is high and smoke dispersion is good or by avoiding sensitive areas such as large cities or susceptible agricultural areas (Sandberg, 1985; Ottmar *et al.*, 2001; Wain *et al.*, 2008).

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Chapter 3.

Testing woody fuel consumption models for application in Australian southern eucalypt forest fires

3.1. Acknowledgements and contributions

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Jennifer Hollis was the primary author however contributions were made by several co-authors. Stuart Matthews[1,2,3] assisted by preparing code to run the BURNUP model and interpreting the processes and drivers of the model as written in the introduction. Roger Ottmar[4] and Susan Prichard[4] collaborated on checking the CONSUME model equations and outputs. Alen Slijepcevic[5], Neil Burrows[6], Bruce Ward[6], Kevin Tolhurst[7,5,2], Wendy Anderson[8] and Jim Gould[1,2] contributed data collected at the Warra Long Term Ecological Research, Project Aquarius and Tumbarumba woody fuel consumption projects. All co-authors assisted manuscript review.

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3.2. Abstract

Five models for the consumption of coarse woody debris or woody fuels with a diameter larger than 0.6 cm were assessed for application in Australian southern eucalypt forest fires including: CONSUME models for (1) activity fuels, (2) natural western woody and (3) natural southern woody fuels, (4) the BURNUP model and (5) the recommendation by the Australian National Carbon Accounting System which assumes 50% woody fuel consumption. These models were assessed using field data collected as part of the woody fuel consumption project (WFCP) in south-west Western Australia and northern-central Victoria. Three additional datasets were also sourced to increase variability in forest type, fuel complex and fire characteristics. These datasets comprised data from south-west Western Australia collected as part of Project Aquarius, the Warra Long Term Ecological Research site in Tasmania and Tumbarumba in south-eastern New South Wales. Combined the dataset represents a range of fire behaviour characteristic of prescribed burning conditions with a maximum fireline intensity of almost 4000 kW m^{-1}.

Woody fuel consumption was found to be highly variable between sites ranging from 9.1 to 89.9%. Relationships between woody fuel consumption and the primary model drivers were weak (maximum $R^2 = 0.097$). Model evaluation statistics were best for the National Carbon Accounting Systems assumption of 50% with a mean absolute error of 11.1% fuel consumption and minimal bias (0.12). Nonetheless, this assumption does not capture large deviations where woody fuel consumption has been particularly high or low. The BURNUP model yielded the largest level of error when used with natural fuels however its predictive capacity improved when used with large modified fuel loads resulting from clearcut operations.

3.3. Introduction

Coarse woody debris (CWD) defined as downed woody fuel with diameter greater than 0.6 cm, has an important ecological role within Australian forest ecosystems. CWD provides structural complexity and habitat on the forest floor, a source for nutrient cycling and a substrate for many organisms that depend on dead wood for their survival (Woldendorp *et al.*, 2002a; Woldendorp *et al.*, 2002b; Garden *et al.*, 2007). The consumption of CWD in forest fires contributes to several fire behaviour features, including the total energy output and rate of heat release (Byram, 1959; Rothermel, 1993), convection column development (Potter *et al.*, 2004; Potter, 2005), potential for re-ignition and suppression/mop-up difficulty (Gould, 2003) and the thermal and smoke environment to which firefighters are exposed (Pyne *et al.*, 1996; Sullivan *et al.*, 2002; Bertschi *et al.*, 2003; Ottmar *et al.*, 2009). The consumption of woody fuels also impacts a variety of first and second order fire effects such as the degree of soil heating and tree mortality associated with the heating of tree boles and superficial roots (Burrows, 1987a; Pyne *et al.*, 1996; McCaw *et al.*, 1997; Knapp *et al.*, 2005).

CWD is an important component of a continuous cycle where carbon stocks move between the living forest biomass, dead organic matter, soil and atmosphere. In the current context of climate change, it is essential to know CWD contribution to carbon sinks and greenhouse gas and smoke emissions when they are consumed. This information is necessary for the development of management strategies to better meet land management goals and to comply with air quality and emission targets (Gould, 2003). In the dry sclerophyll forests of Australia CWD contributes between 6 and 32% of the above-ground forest biomass (Woldendorp *et al.*, 2002a) of which roughly 50% is composed of carbon (Mackensen and Bauhus, 1999). Disturbances including prescribed fires and wildfires can significantly modify CWD structure and volume with outcomes varying greatly between forest types, fuel complex structures and the conditions under which they are burnt (e.g. season, weather and ignition patterns). This complicates the prediction of CWD consumption and the resulting effect on carbon stocks.

Current estimates for the consumption of CWD or woody fuels in Australian southern eucalypt forests are largely based on average volume consumption for particular forests and fuel/fire types (e.g. slash/regeneration burns, prescribed ecological or fuel reduction burns, wildfires). Estimates are also often determined using McArthur's drought factor calculation (Cheney, 1981; Tolhurst *et al.*, 2006) which employs either the Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968) or Mount's Soil Dryness Index (SDI; Mount, 1972) depending on agreed practice within the State or Territory. Volume consumption in Australian forests has been derived from several studies using pre and post-fire line intersect method (Van Wagner, 1968; Brown, 1974) for woody fuel counts. This includes early work undertaken by Jones (1978) investigating the relationship between fuel removal and fuel conditions in karri *Eucalyptus diversicolor* slash disposal burns. Jones found that woody fuel consumption could not be predicted based on fuel moisture content or KBDI alone. O'Loughlin *et al.* (1982) later conducted a high intensity fire in *E. radiata*, *E. delegatensis* and *E. dalrympeana* forest whereby 50% of the total forest floor fuel load was consumed under a Forest Fire Danger Index of 24 (High to Very High) (McArthur, 1967). McCaw *et al.* (1997) reported that the consumption of woody fuels < 10 cm in karri (*E. diversilcolor*) slash prescribed burns was inversely related to the moisture content of the litter profile and that the total amount of fuel consumed ranged from 31 to 89%. Slijepcevic and Marsden-Smedley (2001) reported that 58-63% of the total weight of organic material and carbon content was released to the atmosphere during regeneration burning of *E. obliqua*, an estimate which is used operationally throughout Tasmania by forest managers. In this study the majority of carbon release was from slash greater than 7 cm in diameter.

Tolhurst *et al.* (2006) undertook detailed research on woody fuel moisture, density, wood decay and their effect on woody fuel consumption in *E. dalrympleana* and *E. radiata* forest in south-eastern New South Wales. The authors found a strong relationship between woody fuel consumption and fire intensity and reported that the greater the degree of decay, the greater the proportion of consumption. Rates of weight loss and burn out time for woody jarrah forest (*E. marginata*) fuels up to 8 cm diameter was determined by Burrows (1994) who established that the rate of weight loss is related to particle diameter. This research was conducted on a load cell platform whereby all fuels were completely consumed. However the author found that the extent of consumption in the field was more variable and depended on fuel dryness, wind speed and fire intensity. Section 8 within the National Carbon Accounting System Technical Report Number 32 titled 'Fire Management in Australian Forests' states that a fuel consumption of 50% of the total fuel load may be a reasonable figure to apply to wildfires under a wide range of burning conditions (Gould and Cheney, 2007).

Collectively, these studies together with educated estimates provide general figures for woody fuel consumption, however they are limited to specific forest types, fuel complexes and fire types and may not transfer well to other southern eucalypt forest fuels. The methods used to establish fuel loads and characterise fire behaviour in each study have varied making comparisons across datasets and the development of a consistent national model difficult. Given the variability in woody fuel consumption rates between and within forest, fuel and fire types, the development of a national model for woody fuel consumption requires more robust figures, especially for slash/regeneration burns and wildfires (Raison and Squire, 2007).

Internationally, several models have been developed to predict woody fuel consumption at the fuel component (size class) and site specific scale. These have the potential to increase understanding and assist prediction of woody fuel consumption in Australian southern eucalypt forests. In the United States these include empirical models (primarily developed using statistical relationships derived from measured woody fuel consumption data) such as CONSUME (Prichard *et al.*, 2005) and the North Idaho Model (Brown *et al.*, 1991), process-based models using simulations of fundamental biological and physical relationships and processes such as Albini's early Burnout model (Albini, 1976a) and combinations of both such as the BURNUP (semi-physical) model based on an improved and calibrated Burnout model (Albini *et al.*, 1995; Albini and Reinhardt, 1995, 1997; Call and Albini, 1997).

Models based on the early work of McRae (1980) are used throughout Canada to predict woody fuel consumption. These are empirical models primarily driven by the Buildup Index (BUI) values of the Canadian Forest Fire Weather Index (Van Wagner, 1987) requiring values for Duff Moisture Code (DMC) and Drought Code (DC). For some of the datasets used in this report, the historical weather data which is required to calculate DMC and DC was not available.

The primary objective of the Woody Fuel Consumption Project (WFCP), initiated in Australia in 2007, includes determining the proportion of woody fuel consumed as functions of fire intensity, Forest Fire Danger Index, KBDI/SDI, fuel type and fuel condition in southern Australian eucalypt forests. The research also includes testing existing woody fuel consumption models to assess their potential for application in Australian southern eucalypt forests which has not previously been conducted. The objective of this paper is to evaluate the predictive capacity of the following five models using woody fuel consumption data collected throughout southern Australian eucalypt forests: (1) CONSUME Activity, (2) CONSUME Western Woody, (3) CONSUME Southern Woody, (4) BURNUP and (5) the Australian National Carbon Accounting System (ANCAS) recommended 50%.

3.3.1. CONSUME Models

In the early 1980s, the Fire and Environmental Resource Application Group (FERA) of the United States Department of Agriculture (USDA) Forest Service, Pacific Northwest Research Station began to develop fuel consumption models by combustion stage for prescribed burn planning in the Pacific Northwest of the United States (Sandberg and Ottmar, 1983). CONSUME Version 1.0 (Ottmar *et al.*, 1993) was released in 1993 and incorporated a set of consumption algorithms formulated from data collected at operational burns. During the 1990's, FERA developed models of fuel consumption by combustion stage for other fuel types and configurations beyond the Pacific Northwest. CONSUME Version 2.1 included calculations for piled and non-piled logging slash (activity fuels) and natural fuels. In addition, it allowed the user to input measured 1000-hr (MEAS-Th), adjusted 1000-hr (ADJ-Th), or NFDRS (Cohen and Deeming, 1985) 1000-hr (NFDRS-Th) lag time fuel moisture values to calculate fuel consumption for activity, non-piled fuels. In 2006 CONSUME 3.0 (Ottmar *et al.*, 2006) was released. This included new consumption algorithms based on recent research on flaming and smouldering combustion phases in various natural fuel types in the United States. The recently released Fuel Characteristic Classification System (FCCS; Ottmar *et al.*, 2007) was also incorporated to make use of its library of fuel loadings, representing fuelbeds throughout North America. CONSUME 3.0 is currently used throughout the United States to predict woody fuel consumption, pollutant emissions and heat release. Ottmar *et al.* (2006) noted that while it is used mostly for forest, shrub and grasslands in North America, it may be applicable to other areas of the world.

The input variables used in each of the CONSUME models are listed in Table 1.

Table 1. Input variables used for the CONSUME and BURNUP models where model usage is indicated by an asterisk (*) or described with more detail.

Input Variable	CONSUME Activity Fuel	CONSUME Natural Western Woody	CONSUME Natural Southern Woody	BURNUP
Fine fuel load	*	*	*	*
Woody fuel load	Sizes[a] 1,2,3,4&5 where 'sound' and 'rotten distinctions are made for sizes 3,4 and 5	Sizes[a] 1,2,3,4&5 where 'sound' and 'rotten distinctions are made for sizes 3,4 and 5	Sizes[a] 1,2,3,4&5 where 'sound' and 'rotten distinctions are made for sizes 3,4 and 5	Sizes[a] 1,2,3,4&5
Woody fuel moisture content	Sizes 1,3 and all logs > 0.6 cm	Size 3	Size3	Sizes 1,2,3,4&5
Area burnt	*			
Wood density				Sizes 1,2,3,4&5
Duff fuel moisture content	*	*	*	*
Duff fuel load				*
Fire intensity				*
Residence time				*
Fire duration	*			
Slope	*			
Mid-flame wind speed	*			*
Air temperature				*

[a] Woody fuel size classes: size 1: 0.60-2.50 cm, size 2: 2.51-7.50 cm, size 3: 7.51-22.50 cm, size 4: 22.51-50 cm, size 5: > 50 cm.

3.3.1.1. CONSUME Activity Fuel Model

CONSUME uses individual algorithms to predict consumption of defined fuel layers (or stratum) and woody fuel size classes (0.64-2.54 cm, 2.54-7.62 cm, 7.62-22.86 cm, 22.86-50.8 cm, > 50.8 cm) within activity fuels (Ottmar *et al.*, 1993). For woody fuels > 7.62 cm in diameter, algorithms for each size class have been determined for both 'sound' and 'rotten' fuel types. These are described below and have been reported by Prichard *et al.* (2005) in the CONSUME Version 3.0 User's Guide.

The CONSUME Activity model assumes that fine fuels < 0.6 cm in diameter and woody fuels 0.6-2.5 cm in diameter are completely consumed during the flaming phase of combustion, regardless of weather or location and there is no patchiness or unburnt areas. The equations for the consumption of fuels 2.6-7.5 cm were derived from fuel consumption theory (Ottmar and Sandberg, 1983), with several of the coefficients determined from a burn study by Ottmar *et al.* (1990) and from fire spread research (Rothermel, 1972).

For large (> 7.6 cm) woody fuels the CONSUME Activity model uses the degree of curing (where wood is considered cured if it has a fuel moisture content less than 60% and/or 3 months of snow free days have passed since harvest), fuel moisture, and consumption of fuels 2.6-7.5 cm in diameter to estimate the diameter reduction (where the diameter reduction is the reduction of the diameter caused by fire of a cylindrical log). Based on the calculated diameter reduction, the model calculates the percent volume reduction of fuels > 2.54 cm, using a quadratic mean diameter (the square root of the arithmetic mean of squared values) of each fuel size class. Percent volume reduction is then multiplied by fuel loading for each large fuel class to estimate fuel consumption. When the fire has been mass (central) ignited, low fuel moisture contents are associated with higher fire intensities as a result of smaller fuels being consumed rapidly (Hall, 1991). This in turn shortens the fire duration whereby large fuels absorb energy resulting in less consumption. The CONSUME Activity model takes this into account by adjusting the predicted diameter reduction for these large fuel sizes proportionally, for example an ‘extreme’ fire intensity will reduce the predicted diameter reduction by 33%.

3.3.1.2. CONSUME Natural Fuel Models

As in Activity fuels, CONSUME uses individual algorithms to predict the consumption of defined fuel layers (or stratum) and woody fuel size classes (0.64-2.54 cm, 2.54-7.62 cm, 7.62-22.86 cm, 22.86-50.8 cm, > 50.8 cm) for natural fuels.

Woody fuel algorithms are divided into three different sets of algorithms based on empirical data from the Boreal, Southern, and Western regions of North America. Due to a lack of data on woody fuel consumption in boreal forests, boreal fuelbeds are treated as Western forests in woody fuel calculations. Woody fuel consumption is predicted for each woody fuel size class based on pre-burn fuel loadings and/or fuel moisture of duff and fuels 2.5-7.6 cm in diameter and 7.6-22.9 cm in diameter (Prichard *et al.*, 2006). For woody fuels > 7.6 cm in diameter, algorithms for each size class have been determined for both ‘sound’ and ‘rotten’ fuel types. The average fuel moisture content of fuels between 7.6-22.5 cm in diameter is by far the most critical variable in determining how much fuel will be consumed (Sandberg and Ottmar, 1983).

3.3.2. BURNUP Model

BURNUP is a process-based model of woody fuel consumption (Albini and Reinhardt, 1995). BURNUP predicts the diameter of fuel classes as a function over time until the fire self extinguishes or all fuel is consumed. Fuel consumption is described as percent mass reduction for each size class at the end of the burn. The model predicts heat output from the burning rates of the fuel components and uses this heat output together with the spatial arrangement of fuels to predict the heat transfer to the fuel components. This determines the burning rates of each fuel component (Albini and Reinhardt, 1995).

BURNUP assumes that heat transfer to an individual fuel particle can be described by a 'fire environment temperature', T_f, which is 'the temperature that an inert object ultimately would achieve if it were kept in the fire environment where T_f is determined' (Albini and Reinhardt, 1995) and is a function of local fire intensity. Heat is transferred between the fuel and its environment by convection and radiation.

Ignition of a fuel particle is modelled as heating of a cylinder with given thermal conductivity, density, and specific heat. Once ignited, the burning rate of the fuel depends on the balance of the rate of heat transfer to the fuel and the amount of energy required to raise the fuel to its pyrolysis temperature.

To simulate the burning of wildland fuels, it is necessary to account for the loading of fuels of different size classes and their spatial arrangement. This is required to take into account the interaction between different burning logs, as fuel elements in close proximity to other logs burn more readily than isolated fuel elements (Anderson, 1990).

The input variables used in the BURNUP model are included in Table 1. The model also uses a number of constants including; heat capacity (1750 J kg^{-1} K^{-1}), thermal conductivity (0.13W m^{-1} K^{-1}), heat content (18676 J kg^{-1}) (Burrows, 1994), ash content (1%), ignition temperature (600K) (Albini and Reinhardt, 1995), and char temperature (650K).

The First Order Fire Effects Model (FOFEM) used widely throughout the United States to predict immediate or 'first-order' effects, employs the BURNUP model to predict woody fuel consumption (Reinhardt *et al.*, 1997). In 2003 the modelling capabilities of the FARSITE fire area simulator (Finney, 1998), were expanded to include combustion of woody fuels and smoke production by also incorporating the BURNUP model (Finney *et al.*, 2003).

3.4. Methodology

Woody fuel consumption in Australian southern forests was assessed as part of the Woody Fuel Consumption Project (WFCP). This included determination of woody fuel consumption under varied prescribed burning conditions at four locations: Wilga, Quillben and Hester blocks in south-west Western Australia and Tallarook State Forest in Victoria (Figure 1 and Appendix C*a*, and C*b*). The range of data available for model evaluation was expanded by using previous Australian field studies including;

- Project Aquarius (Gould *et al.*, 1996): Between 1983 and 1993 the CSIRO Division of Forest Research and the Forest Department of Western Australia collaborated on a field program to study aspects of high intensity forest fire behaviour in jarrah (*E. marginata*) forest. The field study consisted of 32 experimental fires at McCorkhill block in the south-west of Western Australia (Figure 1). Data from only 18 experimental fires where woody fuel consumption was able to be determined have been included in this study.
- Warra Long Term Ecological Research (Warra LTER) (Marsden-Smedley and Slijepcevic, 2001; Slijepcevic, 2001; Slijepcevic and Marsden-Smedley, 2002): The Warra LTER study examined pre-logging, post-logging and post-burn variation in fuel characteristics including the release of carbon during regeneration burning. The field study consisted of 4 prescribed burns including 16 blocks located in Tasmania's southern forests (Figure 1 and Appendix C*c*). One of the prescribed fires was conducted under marginal burning conditions resulting in a very patchy burn. This burn was not used in the analysis. Therefore data from only three burns including eleven blocks are referred to in this study.
- Tumbarumba (Tolhurst *et al.*, 2006): Coordinated by the CSIRO Forestry and Forest Products Division, experiments were conducted as part of the Australian Bushfire Cooperative Research Centre fuel classification and availability project. It consisted of three experimental fires within the Maragle State Forest, Tumbarumba in New South Wales (Figure 1 and Appendix C*d*). One of these fires burnt overnight and had no supporting information on fire behaviour so it has not been included in this study. Field study objectives included quantifying the amount of woody fuel consumed under experimental fire conditions and the effect of fuel moisture, fire intensity, fuel condition and diameter on woody fuel consumption.

A summary of site characteristics for each field study is included in Table 2.

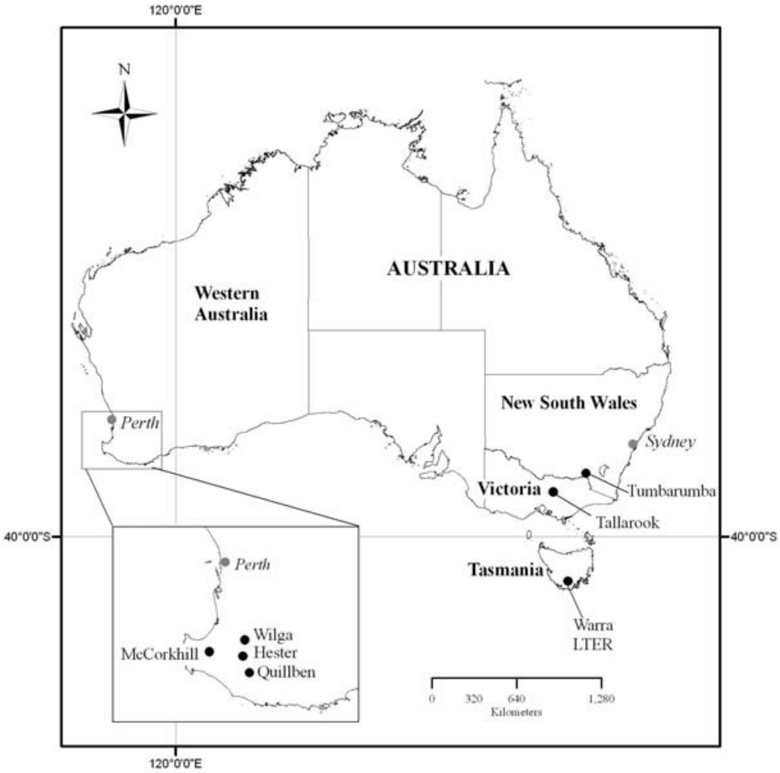

Figure 1. Location of field sites across southern Australia.

Table 2. Summary of site characteristics.

Site	State	Year/s of study	Forest & primary species	Australian climatic zone[a]	Average annual rainfall (mm)
WFCP - Wilga	Western Australia	2007	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	830
WFCP - Quillben	Western Australia	2007	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	1012
WFCP - Hester	Western Australia	2008	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	830
WFCP - Tallarook	Victoria	2008 to 2009	Herb rich foothill forest, *E. globulus*, *E. viminalis*	Temperate (no dry season, warm summer)	595
Project Aquarius	Western Australia	1983	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	1109
Warra LTER	Tasmania	2000	Wet sclerophyll & mixed stringybark, *E. obliqua*	Temperate (no dry season, mild summer)	1080
Tumbarumba	New South Wales	2004	Wet sclerophyll, *E. dalrympleana, E. radiata*	Temperate (no dry season, warm summer)	975

[a] Stern *et al.* (2000).

3.4.1. *Woody fuel assessment and determination of consumption*

The process of compiling different datasets collected using small variations in methodology posed some challenges including inconsistency across field studies in defining woody fuel diameter size classes (Table 3). For this study, all data was re-worked into five diameter size classes adopted by the WFCP which approximate the lag time fuels used in the United States (Fosberg, 1970) to enable comparison with other datasets. This resulted in some minor discrepancies that can be seen across size classes in Table 3. For example, Project Aquarius fuels with diameter 1-2.5 cm were attributed to size class 1 and it was assumed that there would be little change to fuel load outcomes by not including fuel 0.6-1 cm in this size class.

Table 3. Woody fuel size class differentiation across woody fuel consumption datasets with the corresponding lag time for fuels in (*italics)* (Fosberg, 1970).

WFCP size class *(Lag time)*	Size class	Project Aquarius	Warra	Tumbarumba
0.60-2.50 cm *(1h)*	1	1.0-2.50 cm	0.6-2.50 cm	0.6-1.0 cm 1.01-2.50 cm
2.51-7.50 cm *(10h)*	2	2.51-5.00 cm 5.01-7.50 cm	2.51-7.50 cm	2.51-7.50 cm
7.51-22.50 cm *(100h)*	3	7.51-10.0 cm 10.01-15.0 cm 15.01-20.0 cm	7.51-22.50 cm	7.51-22.50 cm
22.51-50 cm *(1000h)*	4	20.01-30 cm > 30 cm[a]	22.51-50 cm	22.51-50 cm
> 50 cm	5	> 30 cm[b]	> 50 cm	> 50 cm

[a] Actual diameters were recorded using only diameters < 50 cm
[b] Actual diameters were recorded using only diameters > 50 cm

For the WFCP sites, Van Wagner's line intersect method (Van Wagner, 1968) was used to calculate pre-fire and post-fire woody fuel load. For size class 1 (Van Wagner, 1968):

$$W = (\Pi^2 / 8 \cdot n \cdot QMD^2 \cdot \rho_p) / L \qquad (1)$$

while Brown's Woody Material formula (Brown, 1974) was used to determine pre-fire and post-fire woody fuel load for size classes 2-5:

$$W = \frac{\Pi^2 \cdot \rho_p}{8L} \sum_i d_i^2 \qquad (2)$$

In Equations (1) and (2) W is the fuel load (Mg ha^{-1}), n is the number of intersecting fuels, QMD is the quadratic mean diameter (cm), d_i is the diameter (cm) of the i^{th} intercept, ρ_p is the wood density (g cm^{-3}), *L* is the length of transect line (m). For the smallest woody fuel size class (0.6-2.5 cm) *QMD* was assumed to be the midpoint of the size class (i.e. 1.55 cm).

Pre-fire and post-fire size class 1 fuels at the Project Aquarius sites were assessed using destructive sampling techniques (Catchpole and Wheeler, 1992) and by assuming that all size class 1 fuel was consumed. Eq. (1) was used to determine pre-fire and post-fire woody fuel loads for sizes 2-4 where QMD was assumed to be the midpoint of each size class. For sizes 4 and 5 (for fuels > 30 cm) where the actual fuel diameter was known, Eq. (2) was used to determine pre-fire and post-fire woody fuel load.

At the Warra LTER site, Marsden-Smedley and Slijepcevic (2001) determined fine and woody fuel loads < 2.5 cm by collecting vegetation within a 1x1 m plot using a hedge-trimmer and/or chainsaw to cut through the fuel array to the soil surface. Thirty samples within each site were sorted into three diameter size classes; 0-0.1 cm, 0.1-0.6 cm and 0.6-2.5 cm and oven-dried to determine biomass. Slijepcevic (2001) incorporated slope and fuel element angle correction factors for calculating woody fuel load of larger diameter size classes (Brown and Roussopoulus, 1974):

$$W = \frac{\Pi^2 \cdot \rho_p \cdot a \cdot s}{8\mathrm{L}} \sum_i d_i^2 \qquad (3)$$

where

$$s = \sqrt{1 + (percentslope/100)^2} \qquad (4)$$

In these equations *a* is the fuel angle correction factor (1.1 for sizes 2.5-7.0 cm, 1.0 for > 7.0 cm (Brown and Roussopoulus, 1974)) and *s* is the slope correction factor. The *QMD* for size classes 2.5-5.0 cm and 5.0-7.0 cm was determined during field sampling, recording diameters within each size class and using Van Wagner's equation to calculate *QMD* (Van Wagner, 1982).

For each of the burns studied, the difference in pre-fire and post-fire woody fuel load was grouped by size class and a percent consumption was determined based on the pre-fire fuel load. After compiling the woody fuel consumption dataset, it was necessary to establish values for each of the input variables for models to be tested. These were mostly established as part of a rigorous sampling effort, but in some instances required modelling or estimation to ascertain a value (e.g. woody fuel moisture content). These variations in methodology are summarised in Table 4.

Table 4. Summary of variations in fuel assessment methodology. Range of conditions (minimum to maximum) in *italics*.

Site	Mean transect length (m)	Woody fuel moisture content (FMC) of size classes	Decay assessment	Wood density
WFCP - Wilga	400	Random sample of log disks using chainsaw then oven-dried to determine FMC	Decay classes 0-4 based on pre-defined assessment criteria (Maser *et al.*, 1988; Whitford and Williams, 2001; Tolhurst *et al.*, 2006). For CONSUME 'rotten' includes decay classes 3- 4 and 'sound' 0-2	Random sample of log disks using chainsaw then submersion method (Technical Association of the Pulp and Paper Industry, 1994)
WFCP - Quillben	400			
WFCP - Hester	389 *(190-400)*			
WFCP - Tallarook	400			
Project Aquarius	584 *(60-1620)*	Random sample of Size class 1 fuels then oven-dried to determine FMC and remaining sizes estimated based on size class 1 FMC and the FMC relationship with diameter at WFCP jarrah (*E. marginata*) sites	Decay was not assessed. For CONSUME decay class was based on the average proportion of 'sound' to 'rotten' found at jarrah (*E. marginata*) sites in the WFCP	Based on the WFCP Quillben site average which has the same fuel age since last fire and similar forest structure i.e. jarrah (*E. marginata*) forest
Warra LTER	45	Hazard stick[a] FMC used for Size 1, then remaining sizes estimated based on Size 1 FMC and the FMC relationship at WFCP sites	Separation into 'sound' and 'rotten' categories based on visual observation	Random sample of at least 20 of each size class by species then submersion method (Technical Association of the Pulp and Paper Industry, 1994)
Tumbarumba	90	Random sample of log disks using chainsaw then oven-dried 'inner' and 'outer' locations of sample, and electronic moisture meter (T-H Fine Fuel Moisture Meter (Chatto and Tolhurst, 1997)) of saw dust generated during the cutting of the sample to determine FMC. Size 1 FMC not sampled so based on linear equation for Diameter v Av Inner + Outer FMC (%) y = 2.0558x + 12.009	Decay classes 1-7 based on pre-defined assessment criteria (Tolhurst *et al.*, 2006). For CONSUME; 'rotten' includes decay classes 1-6 and 'sound' 7	Random sample of log disks using chainsaw then submersion method (Technical Association of the Pulp and Paper Industry, 1994)

[a] Arrays of wood (mostly *Pinus radiata* in Australia) from which fuel moisture can be estimated from the difference in the dry and field weight of the sticks (Eron, 1991).

3.4.2. *Fire behaviour assessment*

In each of the field studies fine fuel (< 0.6 cm or < 1.0 cm for Project Aquarius) moisture content was assessed for the surface (upper 0.6-1 cm of undecomposed litter layer) and the full depth of the litter profile. Fine fuel moisture content was determined by taking periodic fuel samples prior to burning and where possible during burning for fire durations greater than 2 hours. Samples were oven-dried at a nominal temperature of 105ºC for 24 hours to determine moisture content (dry weight basis). Fine fuel load was determined from the full depth of the litter profile and estimated using destructive sampling techniques (Catchpole and Wheeler, 1992). For the purpose of running the CONSUME model, the fine fuel moisture content of the litter profile was used in the absence of data for duff fuel moisture content.

Fireline intensity, I (kW m^{-1}), was calculated as (Byram, 1959):

$$I = H \cdot w \cdot r \tag{5}$$

where H is the low heat of combustion (kJ kg^{-1}), w is the weight of fuel consumed in the active flaming front per unit area (kg m^{-2}) and r is the rate of spread (m s^{-1}). For the Warra silvicultural burns where fuels were ignited using central ignition techniques, the determination of rate of spread and therefore fireline intensity was not applicable and total heat release was calculated to characterise the energy released by each fire (Albini, 1976b). For the purpose of running the BURNUP model, fireline intensity for the Warra burns was calculated using Eq. (5) and based on a modelled rate of spread using *BehavePlus* (Andrews *et al.*, 2008) for heavy slash fuels (fuel model 13; Anderson, 1982).

Techniques for assessing fire behaviour varied by field study and have been summarised in Table 5.

Table 5. Summary of variations in fire behaviour assessment methodology. Range of conditions (minimum to maximum) in *italics*.

Site	Burn & Ignition Type	Mean Rate of Spread (ROS)	Residence Time	Source of weather data
WFCP – Wilga	Silvicultural slash & ecological prescribed burn. Long line > 150 m length	Grid of insulated type K thermocouples with data logger: using the time at which 320° was reached together with visual observations	Insulated type K thermocouple with data logger: using the duration above 320°	On site weather station located in open clearing measuring rainfall, 10m wind, air temperature & relative humidity (RH)
WFCP - Quillben	Ecological & fuel reduction prescribed burn. Long line > 150 m length			Weather station located approximately 500m away in open field measuring rainfall, 10m wind, air temperature & RH
WFCP - Hester	Ecological & fuel reduction prescribed burn. Long line > 150 m length			Weather station located approximately 1km away in open field measuring rainfall, 10m wind, air temperature & RH
WFCP - Tallarook	Ecological & fuel reduction prescribed burn. Long lines and stripping > 150 m length			Weather station located approximately 2km away in open field measuring rainfall, 10m wind, 2m wind air temperature & RH
Project Aquarius	Research. Long line and multiple point ignitions	Periodic mapping with infra red line (IR) scanner & visual observation	Modelled (Nelson, 2003)	Weather station in close proximity measuring rainfall, 10m wind, 2m wind air temperature & RH
Warra LTER	Silvicultural slash / prescribed burn. Central ignition and long line stripping	Not collected. For BURNUP residence time: ROS modelled using *BehavePlus* (Andrews *et al.*, 2008) for heavy slash fuels (fuel model 13; Anderson, 1982)	Modelled (Nelson, 2003)	Localised hand sampling & Geeveston AWS located approximately 22kms SE of site
Tumbarumba	Research. Line ignition, 100 m length	Use of numbered metal tags and visual observations to map fire perimeter periodically	Modelled (Nelson, 2003)	Weather station in close proximity measuring rainfall, 10m open wind, 2m in-forest wind air temperature & RH

3.4.3. *Model evaluation*

Four measures of error were used to evaluate model predictions of woody fuel consumption; mean absolute error (*MAE*), root mean squared-error (*RMSE*), mean bias error (*MBE*) and mean absolute percentage error (*MAPE*) (Makridakis *et al.*, 1998):

$$MAE = \frac{\sum |y_i - \hat{y}_i|}{n} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \tag{7}$$

$$MBE = \frac{\sum (\hat{y}_i - y_i)}{n} \tag{8}$$

$$MAPE = \frac{\sum \left(\frac{|y_i - \hat{y}_i|}{y_i} \right)}{n} \cdot 100 \tag{9}$$

Here y_i and $\hat{y}_i$ are respectively the observed and predicted values for site woody fuel consumption (%).

3.5. Results and Discussion

3.5.1. *Pre-fire fuel load and distribution*

The combined dataset comprised woody fuel loads in two distinct fuelbed types; predominantly natural, unmodified fuelbeds (Quillben, Hester, Project Aquarius & Tumbarumba) and modified fuelbeds that had been recently harvested through selective logging (Wilga) or clear felling (Warra). The pre-fire woody fuel load and distribution by size class were similar across field sites with mostly unmodified fuelbeds. The total average site woody fuel load for these sites was 70 Mg ha^{-1} (st.dev. = 31.3 Mg ha^{-1}, n = 28). The Quillben site had a much higher than average fuel load for fuels in size class 5 (> 50 cm in diameter) contributing to a total woody fuel load of 175 Mg ha^{-1}, over double the average for other sites (Figure 2).

Modified fuelbeds at the Warra LTER sites had higher than average fuel loads in each of the size classes (Figure 2) and a site average fuel load of 599.5 Mg ha^{-1} (st.dev. = 321.7 Mg ha^{-1}, n = 11). In comparison, the woody fuel load remaining on site after selective harvesting at Wilga was only 42.4 Mg ha^{-1}, well below that of the Warra LTER site and likely due to differences in pre-harvest forest structure and harvesting techniques.

Fuels over 22.5 cm in diameter (size classes 4 and 5) accounted for an average over 75% of the total woody fuel load at unmodified fuel sites. At the Warra LTER and Wilga sites with modified fuelbeds, the woody fuels greater than 22.5 cm in diameter contributed over 60% of the total site woody fuel load. This highlights the need for woody fuel consumption models to accurately predict the consumption of woody fuels over 22.5 cm. Within a forest site large diameter fuels are mostly less in number and more scattered than fuel particles of smaller diameter classes. This illustrates that adequate transect lengths are needed to accurately measure large woody fuel loads. Miehs *et al.* (2009) found that transect lengths of at least 450 m for recently burnt sites and 700 m for long unburnt sites should be used to estimate CWD volume.

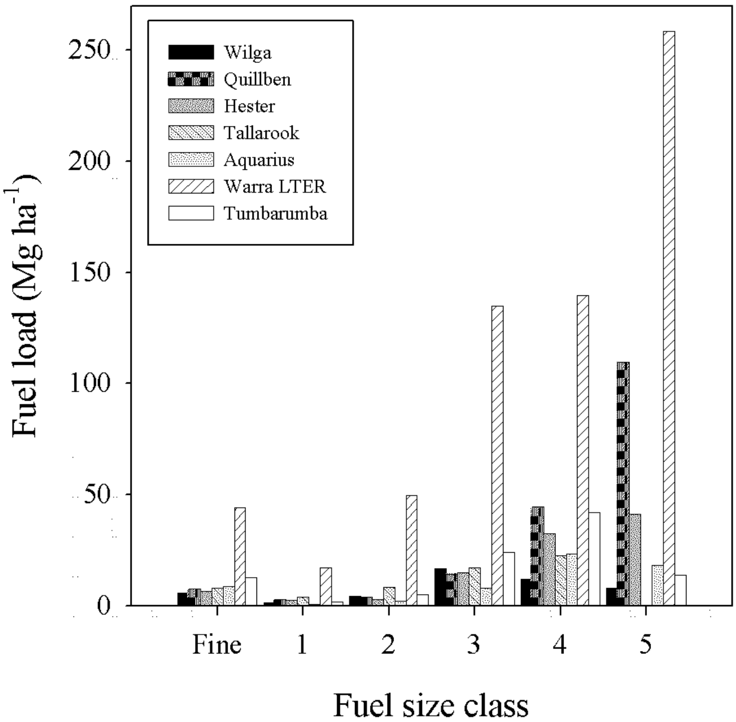

Figure 2. Pre-fire fuel load distribution by size class across the woody fuel consumption field sites where size classes are: fine fuel: < 0.6 cm; 1: 0.6-2.5 cm; 2: 2.51-7.5 cm; 3: 7.51-22.5 cm; 4: 22.51-50 cm; 5: > 50 cm.

3.5.2. Fire behaviour and environment

The range of season and weather conditions and fire behaviour for each of the field sites are presented in Table 6 and additional detail for each burn can be found in Appendix A.

Maximum 10-m open wind speed (U_{10}) for the dataset was 24 km h^{-1} and minimum relative humidity was 20%. Air temperatures ranged from 13°C at the Tallarook autumn burn to 33°C at

Project Aquarius burn number 2002. All field sites were burnt between Low and High Forest Fire Danger Index (FFDI; McArthur, 1973) with the maximum of 18 at the Project Aquarius burn numbers 2001 and 2002. FFDI's greater than 24 (Very High and over) are not represented in this study. The Soil Dryness Index (SDI; Mount, 1972; Burrows, 1987b) ranged from 31 to 163 and the (KBDI; Keetch and Byram, 1968) ranged from 14 to 173 (Table 6 and Appendix A). This shows that a large range of seasonal variation was represented (Burrows, 1987b). Site average woody fuel (d > 0.6 cm) moisture content ranged from 33 to 56% and the surface fine fuel (litter and woody d < 0.6 cm) profile moisture content (PMC) ranged from 8.3 to 71.5% (mean = 21.4%).

Fire behaviour ranged from slow, self extinguishing, patchy, low intensity surface fires to moderate intensity surface fires with spotting behaviour and rates of spread up to 774 m h^{-1}. Fireline intensity ranged from 53 kW m^{-1} at Hester 4 to 3906 kW m^{-1} at Tumbarumba G (Table 6). At the Warra silvicultural burns, heat release ranged from 185 MJ m^{-2} at Warra 8B-5 to 1053 MJ m^{-2} at Warra 8B-3. While fireline intensity wasn't directly applicable to the Warra burns, for the purpose of running the BURNUP model, it was calculated to range between 1014 and 2356 kW m^{-1}. Project Aquarius burns were conducted under dry summer conditions where mean woody fuel moisture content ranged from 33.4 to 38.7% and mostly low wind speeds (Table 6). Only one fire breached containment and all fires were well within the fire intensity range where suppression by ground crews was possible (Loane and Gould, 1986; Hirsch and Martell, 1996). In Australia, intense wildfires have been known to exceed peak fireline intensities of 100,000 kW m^{-1} (Tolhurst, 2009). Thus the dataset represents a limited range of fireline intensity with sites largely being burnt under prescribed burning conditions.

The lack of data representing high fireline intensities limited the model evaluation to low and moderate intensity fires. To obtain high fireline intensity data requires pre-fire and post-fire woody fuel load assessment at either intense wildfire or burns conducted under these conditions. Both are difficult to achieve and are not often part of fire suppression or prescribed burn program objectives. Opportunistic sampling and data collection at locations burnt by high intensity wildfire would be beneficial to both model development and assessment. This is reliant on the identification of burnt and comparative unburnt locations (i.e. comparative sites with same aspect, slope, forest structure and fuel characteristics). Long term coarse woody debris monitoring sites such as the *Forestcheck* (Abbott and Burrows, 2004) sites located in Western Australia presents an option with a good dataset on pre-fire woody fuel loads. However without knowing the future of wildfire locations, dates and fire characteristics, it would be fortuitous to obtain high fire intensity information from these sites.

3.5.3. *Woody fuel consumption*

Percent woody fuel consumption varied greatly between sites and ranged from 9.1% at the Warra LTER 8B-5 site to 89.9% at the Aquarius 15 burn. Using the Anderson-Darling test for normality, no significant departure from a normal distribution was evident (mean = 49.8%, st.dev. = 15.3, n = 39). Table 7 presents a summary of the percentage of woody fuel consumed for each field site (additional information for each burn is presented in Appendix B). Woody fuel consumption also varied greatly at a site level within the Project Aquarius plots where, despite the limited variation in weather conditions and fire behaviour characteristics (Table 6), percent woody fuel consumption ranged between 32.6% at Aquarius 14 and 89.9% at Aquarius 15. There was no clear distinction in the amount of woody fuel consumed between sites characterised by natural, unmodified fuelbeds (Quillben, Hester, Project Aquarius & Tumbarumba) and those recently harvested (Wilga and Warra). Woody fuel consumption (%) at the Hester site (four concurrent burns, i.e. same site, day, time and fuel moisture) ranged from 42.2 – 56.9% with highest woody fuel consumption (56.9%) occurring at Hester 1 which had the highest fireline intensity (678 kW m^{-1}) and the lowest woody fuel consumption 42.2% at Hester 3 (284 kW m^{-1}) and 43.5% at Hester 4 (52.9 kW m^{-1}). This supports the findings of Tolhurst *et al.* (2006) where woody fuel consumption increases with fireline intensity, at least at the lower range of intensities.

Table 6. Summary of weather conditions and fire behaviour characteristics with the range of conditions (minimum to maximum) in *italics*.

Site / Mean Characteristics	*n*	FFDI	RH (%)	T (°C)	U_{10} (km h^{-1})	KBDI	SDI	ROS (m h^{-1})	Residence Time (s)	Fireline Intensity (kW m^{-1})
WFCP - Wilga	1	10	28	25	7.8	17	43	98	94	299
WFCP - Quillben	1	3	69	21	5.5	64	85	52	27	210
WFCP - Hester	4	7.5	57	25	13.7	140	148	105	22	349
		(7-8)	*(48-63)*	*(23-27)*	*(11-17.5)*			*(15-217)*	*(10-40)*	*(53-678)*
WFCP - Tallarook	2	6	50	17	8.6	37	140	52	78	234
		(3-9)	*(34-66)*	*(13-20)*	*(8.2-8.9)*	*(14-60)*	*(136-143)*	*(20-85)*	*(28-127)*	*(76-393)*
Project Aquarius	18	9.6	46	25	5.2	166	140	373	60	1681
		(5-18)	*(20-61)*	*(18-33)*	*(2.5-24)*	*(148-173)*	*(129-163)*	*(153-774)*	*(21-90)*	*(585-3304)*
Tumbarumba	2	11	33	27	7.3	122	115	370	98	2431
		(6-16)	*(20-45)*	*(26-28)*	*(6.5-8)*	*(118-126)*	*(112-118)*	*(122-618)*	*(97-99)*	*(955-3906)*
										Heat Release (kJ m^{-2})
Warra LTER	11	-	67	18	2.5	-	46	-	375	556898
			(52-90)	*(17-19)*	*(2.5-2.5)*		*(31-52)*		*(268-455)*	*(184719-1053203)*

n: sample number; FFDI: Forest Fire Danger Index; RH: relative humidity; T: temperature; U_{10}: 10-m open wind speed; KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; ROS: rate of spread.

Table 7. Summary of field site fuel moisture content (FMC), fuel load characteristics and woody fuel consumption with the range of conditions (minimum to maximum) in *italics*.

Site / mean characteristics	Profile FMC (%)	Woody size class 3 FMC (%)	Total pre-fire fine fuel load < 0.6 cm (Mg ha^{-1})	Total post-fire fine fuel load < 0.6 cm (Mg ha^{-1})	Pre-fire woody fuel load > 0.6 cm (Mg ha^{-1})	Post-fire woody fuel load > 0.6 cm (Mg ha^{-1})	Woody fuel consumption (%)
WFCP - Wilga	11.6	40.8	5.9	0.2	42.3	22.1	47.6
WFCP - Quillben	24.6	33.9	7.8	3.0	175.0	121.7	30.5
WFCP - Hester	16.6	27.3	6.6	0.6	93.8	47.3	49.4
			(6.0-7.0)	*(0.1-1.3)*	*(76-106)*	*(40-62)*	*(42-57)*
WFCP - Tallarook	51.9	43.3	8.1	1.4	52.2	31.6	39.7
	(32.3-71.5)	(37.9-48.6)	*(7.3-8.9)*	*(0.3-2.6)*	*(49-55)*	*(28-36)*	*(36-43)*
Project Aquarius	10.4	34.4	8.8	0.0	60.5	27.1	54.9
	(8.3-13.2)	(33.4-38.7)	*(6.3-12.0)*		*(33-107)*	*(5-54)*	*(33-90)*
Warra LTER	22.7	35.3	44.1	9.0	599.5	336.8	46.4
	(17.0-28.0)	(34-36.6)	*(29.6-53.1)*	*(6.7-10.6)*	*(226-1322)*	*(71-795)*	*(9-69)*
Tumbarumba	11.0	41.9	12.8	0.0	86.3	52.3	44.2
			(12.3-13.3)		*(49-123)*	*(22-83)*	*(33-56)*

3.5.4. Model sensitivity

If any woody fuel consumption model is to perform adequately, an assumption is made that a measurable relationship exists between woody fuel consumption and the most critical variables influencing model predictions. A sensitivity analysis was performed to better understand the effect of input variables on model predictions. This began with the determination of standard conditions for the dataset based on the mean for each variable. The relative effect on consumption was then determined for incremental changes to each variable extending to the limits of the dataset. For fuel size class 3 fuel moisture content, the limitations were extended beyond those of the dataset to what was considered the possible range for field conditions in southern Australian Eucalypt forests. The relative sensitivity of the CONSUME and BURNUP models to their four most influential variables is illustrated in Figure 3*a-d*. In these figures, the steeper the curve, the less sensitive the model is to the variable. For the CONSUME Activity fuel model and Western and Southern natural fuel models, the most influential variable is the fuel moisture content of fuels between 7.5 and 22.5 cm (size class 3). In the BURNUP model, the fuel load of size classes 4, 3, 2 and 5 have the most effect (in order of most to least effect) on model outputs. The standard conditions can be identified by the intersecting point of each variable curve for CONSUME and BURNUP models in Figure 3*a-d*. This point also illustrates the mean consumption outcomes for each of the models while the range for each variable is illustrated by the curve extremities. Model outcomes may go beyond these extremities when more than one variable is varied per simulation.

Observed fuel consumption data was plotted against all primary model variables for our dataset (Figure 4*a-k*) and regression analysis used to examine the relationship between site woody fuel consumption (%) and the variables for each model. R^2 values showed there was little correlation with any of the variables tested (Figure 4*a-k*). The best relationship as determined by the largest R^2 was for the fuel load of the sound (as opposed to rotten) size class 5 fuel (> 50 cm) which explains only 10% of the variation in consumption outcomes (R^2= 0.097) (Figure 4k). This result suggests that model performance based on our dataset and using these as key variables is likely to be poor.

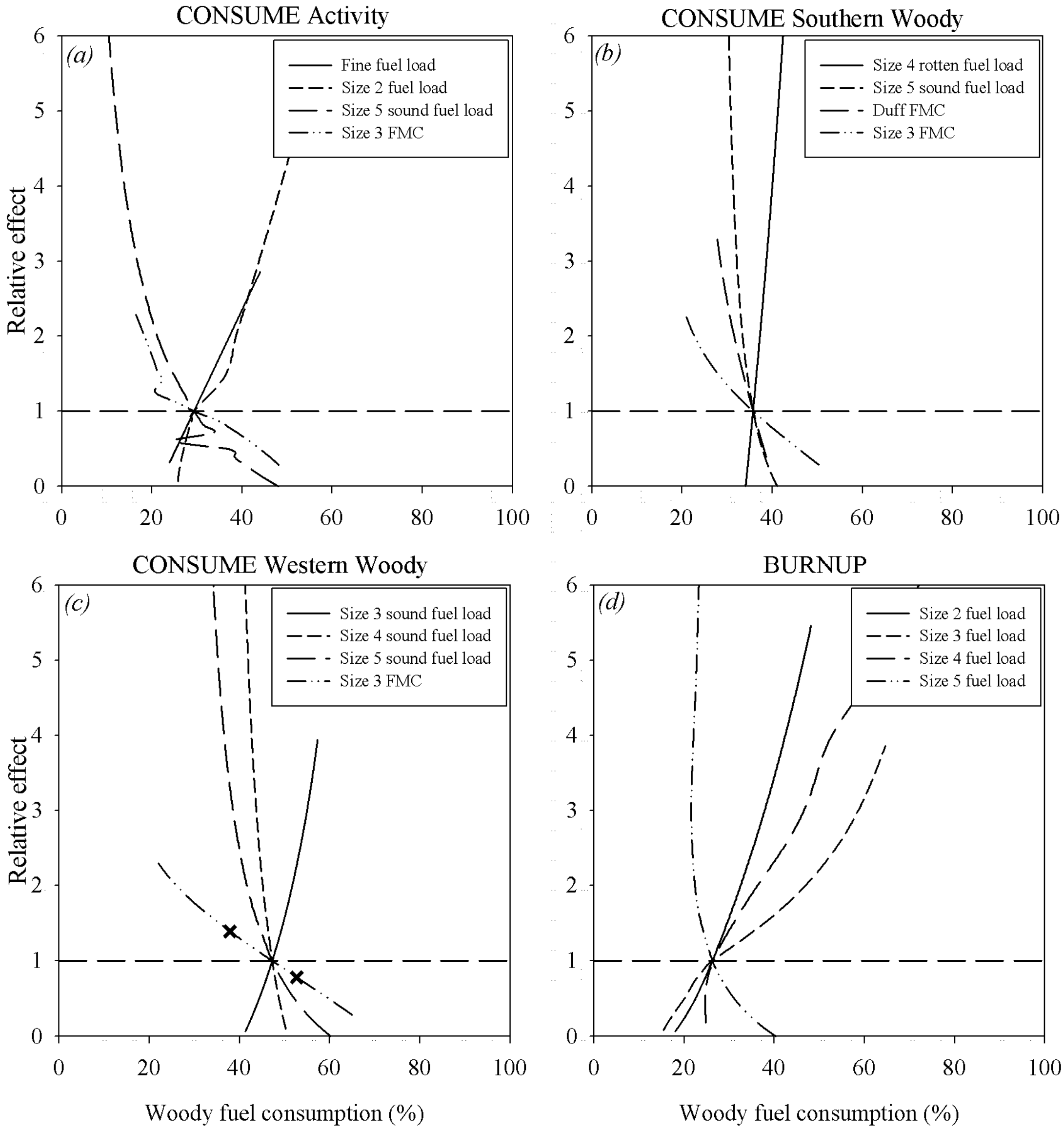

Figure 3*a-d*. Relative sensitivity of the (*a*) CONSUME Activity (*b*) CONSUME Southern Woody (*c*) CONSUME Western Woody and (*d*) BURNUP models to the four most influential variables for each model. Variable effects are bounded by the limits of the field dataset except for size 3 fuel moisture content (%) where the dataset limitations are marked by '**x**' and are normalised on the basis of the mean standard conditions for other input variables.

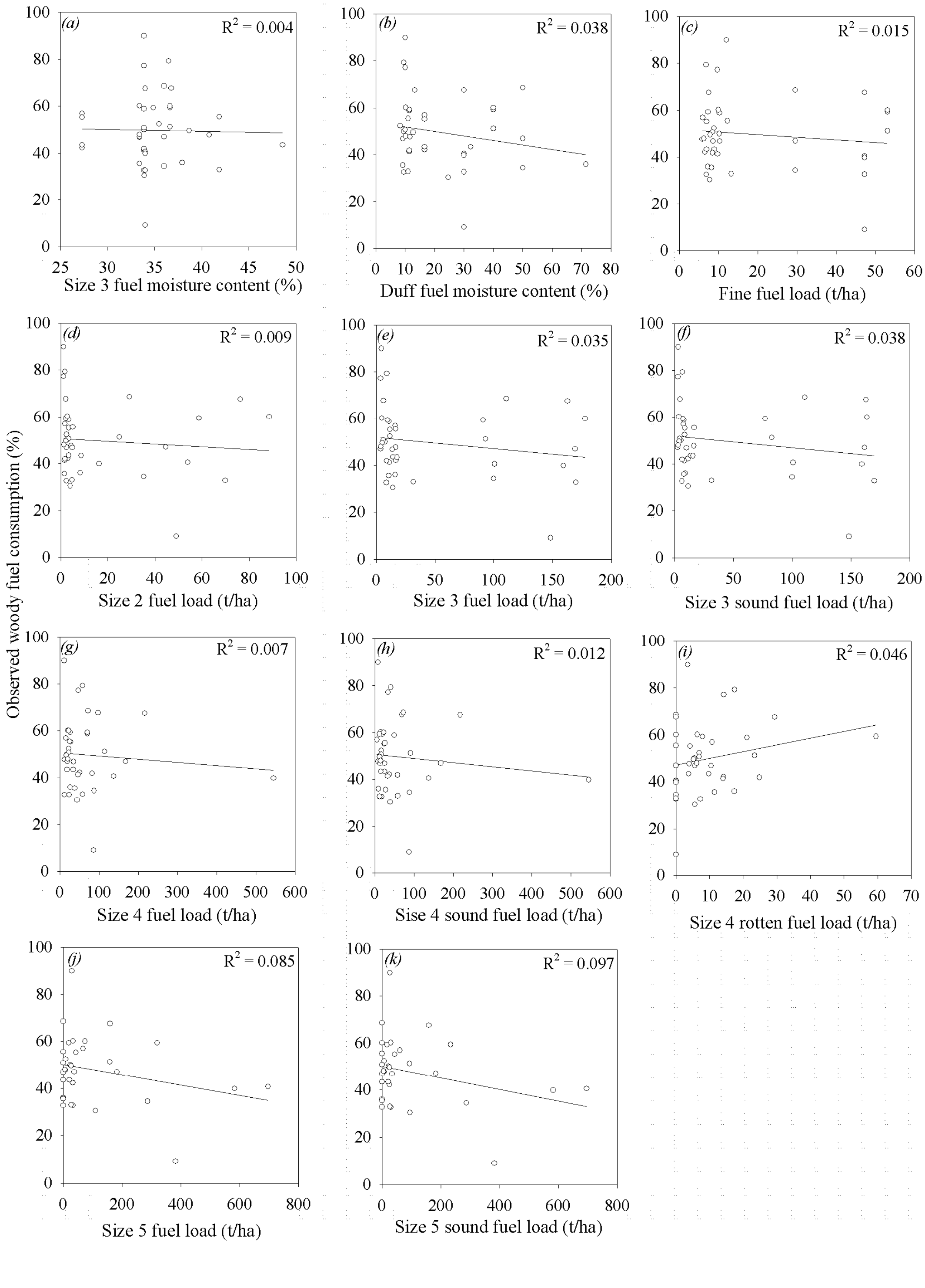

Figure 4*a-k*. Regression relationships of the woody fuel consumption dataset and primary influencing variables for CONSUME and BURNUP models for (*a*) size 3 fuel moisture content (%), (*b*) duff fuel moisture content (%), (*c*) fine fuel load (Mg ha^{-1}) and the woody fuel loads for (*d*) size 2, (*e*) size 3, (*f*) size 3 sound, (*g*) size 4, (*h*) size 4 sound, (*i*) size 4 rotten, (*j*) size 5 and (*k*) size 5 sound where size classes are 1: 0.6-2.5 cm; 2: 2.51-7.5 cm; 3: 7.51-22.5 cm; 4: 22.51-50 cm; 5: > 50 cm.

3.5.5. Prediction of woody fuel consumption

Figure 5*a-e* presents observed versus predicted woody fuel consumption. The statistical measures of performance are listed in Table 8.

The CONSUME Activity and Southern Woody models underpredict observations with biases of 13.1 and 9.3% respectively. The range of predicted consumption of woody fuels for the CONSUME Southern Woody model was between 28.0 and 50.8% while the observed range was much larger and between 9.1 to 89.9%. The CONSUME Western Woody model had very little bias (-1.9%) and a larger range of predicted woody fuel consumption, 38.2 to 76.2%. For each of the CONSUME models a good proportion of predictions were within ±10% of the observed. From 39 observations, this includes 43.6% (17 predictions) for the Activity Fuels model, 51.3% (20 predictions) for the Southern Woody model and 59% (23 predictions) for the Western Woody model. This suggests that the Western Woody model is capturing most of the dynamics of the dataset which is also supported by the model evaluation statistics with a *MAE* of 12.1%. The *MAPE* shows that the CONSUME Southern Woody model has a smaller degree of error (*MAPE* = 30.1% for Southern Woody model, 33.2% for Western Woody model).

The CONSUME models are based on individual equations to predict the consumption of woody fuel by size class, thus the evaluation statistics above combine the outcomes of each equation. By separating the evaluation statistics by size class, the error for each of the size class outcomes and thus the greatest sources of error can be determined. Table 9 shows the *MAE* for each size class across WFCP sites (n = 8). For the Activity fuel model, it is evident that the largest error comes from the size 4 and 5 algorithms with *MAE* of 30.4 and 33.1% respectively. This has resulted in a site woody fuel consumption *MAE* of 18.2%, the largest *MAE* of the CONSUME models, and a *MBE* of 13.1%. This highlights the importance a models ability to predict the consumption of the large fuels d > 22.5 cm. For the Western fuel model, the largest *MAE* was given by the prediction of size 3, sound (38.2%) and rotten (38.2%) fuel equations. This was closely followed by the size 5 rotten fuel equation which gave the largest *MAE* (37.5%) for the Southern model as well.

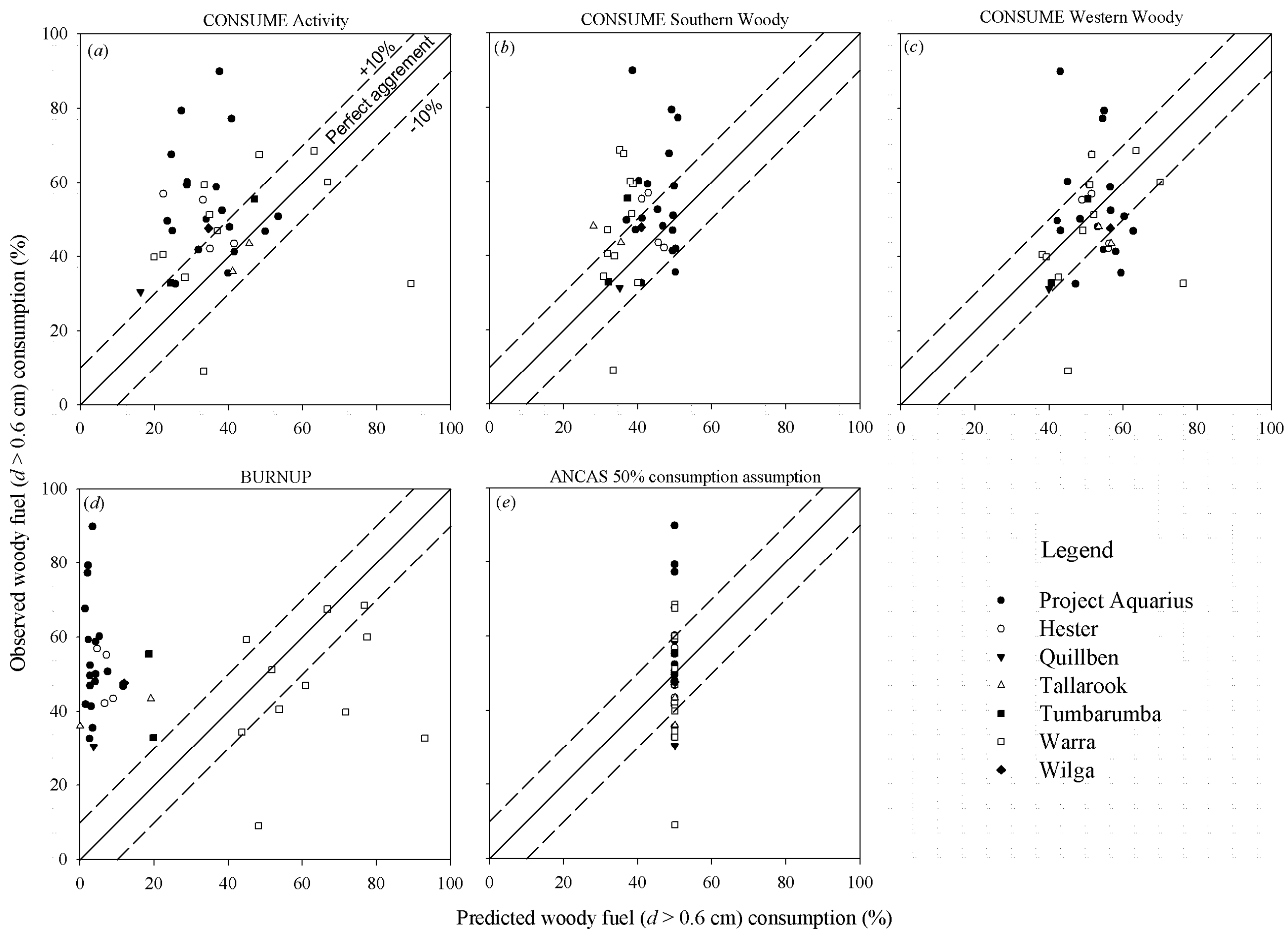

Figure 5*a-e*. Predicted versus observed woody fuel consumption for (*a*) CONSUME Activity, (*b*) CONSUME Southern Woody (*c*) CONSUME Western Woody, (*d*) BURNUP and (*e*) ANCAS assumption of 50% for site woody fuel consumption.

Table 8. Comparison of model error for site woody fuel consumption (%).

	MAE	*MBE*	*RMSE*	*MAPE*
CONSUME Activity	18.20	13.07	23.35	40.40
CONSUME Southern Woody	13.61	9.27	17.23	30.06
CONSUME Western Woody	12.11	-1.94	16.13	33.18
BURNUP *(Aquarius, Tumbarumba & WFCP Data)*	45.16	45.16	47.96	86.99
BURN-UP *(Warra Data)*	19.03	-16.28	25.63	77.49
ANCAS Woody Fuel Consumption = 50% of Fuel Load	11.15	0.12	14.86	31.87

MAE: mean absolute error; *MBE*: means bias error; *RMSE*: root mean square error; *MAPE*: mean absolute percentage error.

Table 9. Mean absolute error values for CONSUME models by size class across WFCP sites (n = 8).

	CONSUME Activity	CONSUME Western Woody	CONSUME Southern Woody
Size class 1	26.70	17.76	17.76
Size class 2	23.39	30.29	14.27
Size class 3	11.88	-	-
Size class 3 SOUND	-	38.21	8.11
Size class 3 ROTTEN	-	38.16	30.16
Size class 4	30.35	-	-
Size class 4 SOUND	-	10.63	10.63
Size class 4 ROTTEN	-	18.25	18.25
Size class 5	33.09	-	-
Size class 5 SOUND	-	16.84	16.84
Size class 5 ROTTEN	-	37.54	37.54

It was evident from Figure 5*d* that two populations existed within the prediction outputs for the BURNUP model. The first contains the modified fuelbeds and silvicultural clearcut fuels at the Warra LTER site which had a mean predicted site consumption of 58.3% and a *MAE* of 19.0%. The second population contains all other field sites which are characterised by smaller fuel loads. These were underpredicted with predicted consumption below 20% (mean = 2.2%, *MAE* = 45.2%). The two populations also become evident when comparing the modelled weight loss through time at the Warra LTER site (Figure 6*a*) with the other sites such as Hester (Figure 6*b*). At the Hester site, the small fuels (size classes 1 and 2: < 7.5 cm in diameter) ignited. However, soon after the size class 1 (0.6-2.5 cm) fuels burn out the size class 2 (2.5-7.5 cm) fuels stopped burning. The larger fuels (size classes 4 or 5: > 22.5 cm in diameter) were not ignited which is likely due to the lack of fuel load to generate sufficient heat flux or duration of heat to ignite larger fuels. In comparison the BURNUP model performs better with the large fuel loads associated with the Warra data. This is due to the generation of sufficient heat flux as a result of the higher fuel loads which then enables ignition and sustaining fire in the larger fuels. The sensitivity analysis indicates that in particular, it is large fuel loads greater than 7.5 cm, and mostly between 22.5 and 50 cm that influence the ability for BURNUP to generate sufficient energy to sustain the combustion of large fuels.

The BURNUP model includes two empirical constants, *K* and *B* that control exchange of heat between fuel elements (Albini and Reinhardt, 1997). For fires in pine forests in North America $K = 3.25$ and $B = -20$. When the *K* and *B* parameters within the model were optimised for each fire, the *MAE* slightly improved to 17.5% for the Warra LTER data and 44.2% for all other sites, an improvement of 1.5 and 0.9% respectively.

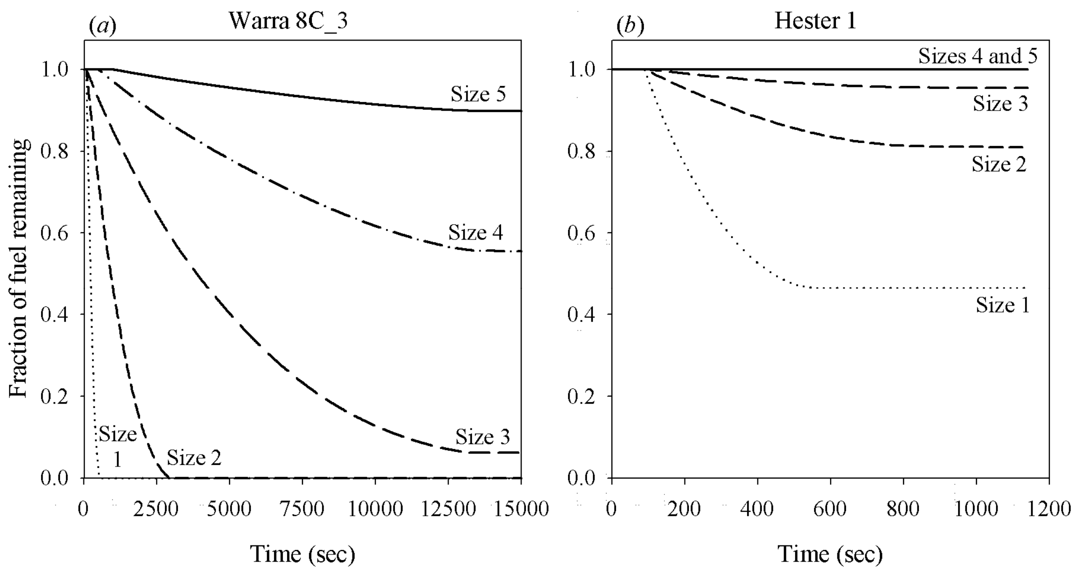

Figure 6*a*-*b*. Time series plots of fuel consumption by size class in the BURNUP model at (*a*) Warra 8C-3 and (*b*) Hester 1 burns.

These model evaluation results should be interpreted with care as the results are based on a dataset where woody fuel consumption varies greatly between and within field sites (Table 7) and is limited to relatively low and moderate intensity prescribed burning conditions (Table 6). Poor model performance for both the CONSUME and BURNUP models could be due to differences between North American and Australian fuels and forest floor structure. An example of these differences relates to wood structure. Australian woody fuels in this study originate largely from eucalypt species, which have different wood density and decay characteristics to those found in North American conifer forests. Ground and surface fuelbed structures are also different in Australian and North American forests. These would influence the heat fluxes generated by the active flame front and lead to distinct ignition and woody fuel combustion outcomes. In a sense, the underlying assumptions relating to ignition and combustion in North American fuels might not be appropriate for eucalypt forests and will influence model performance.

The Australian National Carbon Accounting System assumption of 50% for site woody fuel consumption (Gould and Cheney, 2007) was statistically the best predictor of wood fuel consumption (*MAE* = 11.2%, *MBE* = 0.12% and *RMSE* = 14.9%). While 56.4% of all predictions (i.e. 22 out of 39) were within ±10% of observations, the assumption fails to capture the extremes in woody fuel consumption. For these situations and when associated with relatively high or low model influencing variables, employing the CONSUME Western Woody model to predict woody fuel consumption should decrease the possible error. This includes high or low fuel size class 3 woody fuel moisture content which may be associated with prescribed fires conducted under marginal burning conditions when woody fuels 7.5 – 22.5 cm in diameter are wet or wildfire situations when the woody fuels 7.5 – 22.5 cm in diameter are expected to be at their driest. It also includes high or low 'sound' fuel load for size classes 3, 5 or 5. In the Australian dataset however, the extremes in percent woody fuel consumption were not consistently well predicted by the CONSUME Western Woody model. This is most likely attributed to the inherent variability of the dataset and the weak relationships between woody fuel consumption and the model influencing variables (Figure 4*a-k*).

3.5.6. Model application and use

Currently, there is no clearly defined level of acceptable error for the prediction of woody fuel consumption. As with many fire behaviour phenomena, the degree of acceptable model performance will be determined by the user and the task for which it is being used (Alexander and Cruz, 2006). While many fire managers may not need a high degree of prediction accuracy, the need for reliable predictions has increased with the demand for carbon and greenhouse gas emission inventories. Accurate predictions and an understanding of the key variables affecting the degree of woody fuel consumption will enable fire managers to set burning prescriptions that target predetermined woody fuel attributes and better account for carbon storage and emissions.

The model evaluation statistics show that the highest degree of accuracy would be gained by employing the ANCAS assumption for 50% woody fuel consumption in the majority of fire scenarios. Further data collection and research is required to increase variability within the dataset, particularly variations in mean woody fuel moisture content, high FFDI and high intensity fire behaviour. This will improve model evaluation and assist the development of a woody fuel consumption model suitable for Australian southern eucalypt forest fires.

3.6. Conclusions

The ability to accurately predict woody fuel (d > 0.6 cm) consumption is important for both forest and fire management. Information on coarse woody fuel consumption in Australian southern eucalypt forest fires is scant and the predictive capacity of existent models has been previously unknown.

Model performance against observations of woody fuel consumption in Australian southern eucalypt forests was varied. Model evaluation statistics indicate that the minimum level of error can be achieved by applying a simple model (Gould and Cheney, 2007) which assumes 50% of the woody fuel load at a site is likely to be consumed under the majority of fuel and fire scenarios. While this simple model can be easily interpreted and applied by forest and fire managers, the assumption fails to capture extremes in woody fuel consumption. The CONSUME Activity and Southern Woody models underpredicted observations while the CONSUME Western Woody model had very little bias and a good proportion of predictions (59%) within ±10% of the observed woody fuel consumption. This suggests that while regression relationships of this dataset with the models' primary influencing variables were weak, a model that is largely based on the average fuel moisture content of fuels between 7.6 and 22.5 cm in diameter may have some merit. The BURNUP model showed the greatest overall level of error when used with natural fuels. However its performance improved when applied to heavy modified fuel loads resulting from clearcut operations.

These model evaluation results should be interpreted with care. The results are based on a dataset where woody fuel consumption is highly variable (ranging between 9.1 and 89.9%), limited to relatively low to moderate intensity and mostly prescribed burning conditions. The models were developed for North-American conifer forests. Fundamental differences in fuel particle characteristics (e.g. decay) and fuelbed structure exists between these conifer forests and the eucalypt forests used in this study. This might make the models not fully applicable to Australian forests. Another issue regards whether the woody fuel consumption in Australian southern eucalypt forest fires, particularly prescribed burns, is so variable that the development of an improved model will require an alternative approach that considers distinct underlying assumptions. Further research is required to improve our understanding of the determinant variables and physical processes influencing woody fuel consumption in southern eucalypt forest fires. Such research requires additional data, particularly representing fires burning under higher fire potential and intensities.

3.7. Acknowledgements

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Appendix A. Fire weather and behaviour for field sites.

Burn ID	*RH* (%)	*T* (°C)	U_{10} (km h^{-1})	KBDI	SDI	ROS (m h^{-1})	Residence Time (s)	Fireline Intensity (kW m^{-1})
Wilga	27.5	24.9	7.8	17	42.9	97.7	93.7	299
Quillben	68.5	21.1	5.5	64	84.9	52.2	26.9	210
Hester 1	48.0	27.1	14.0	140	147.5	217.0	10.0	678
Hester 2	56.0	25.1	17.5	140	147.5	104.8	39.5	380
Hester 3	59.0	23.8	12.3	140	147.5	83.7	21.4	284
Hester 4	62.5	23.2	11.0	140	147.5	14.6	15.4	53
Tallarook Sp08	33.9	19.7	8.9	60.0	136	84.6	126.5	393
Tallarook Au09	66.4	13.3	8.2	13.6	143	20.0	28.4	76
Aquarius 3	42.7	26.6	4.3	172.9	162.7	255.8	47.3	912
Aquarius 4-01	48.4	18.7	5.0	166.8	160.8	502.8	64.0	2306
Aquarius 7-01	49.6	23.2	4.4	166.9	134.3	314.5	79.2	1675
Aquarius 7-02	52.2	22.5	4.6	166.9	134.3	529.3	75.7	2691
Aquarius 7-03	50.8	22.9	4.5	166.9	134.3	479.1	65.4	2128
Aquarius 8	47.0	26.4	3.0	165.2	126.7	285.0	58.1	1118
Aquarius 10	52.0	20.0	3.0	169.9	138.2	219.0	21.4	1159
Aquarius 11-01	59.9	25.2	3.9	171.7	140.1	195.7	62.6	864
Aquarius 11-02	60.1	25.0	3.9	171.7	140.1	301.1	72.3	1517
Aquarius 14	52.0	20.0	3.0	169.9	138.2	219.0	21.4	784
Aquarius 15	60.7	25.0	3.9	171.7	140.1	214.5	90.0	1340
Aquarius 17	57.2	17.5	4.4	147.7	146.5	153.0	54.2	585
Aquarius 18	59.0	22.5	24.0	163.5	157.5	153.1	50.8	626
Aquarius 19-01	30.5	26.6	5.7	164.4	128.7	318.8	75.0	1712
Aquarius 19-02	30.5	26.7	6.0	164.1	128.7	680.8	62.3	3044

Burn ID	*RH* (%)	*T* (°C)	U_{10} (km h^{-1})	KBDI	SDI	ROS (m h^{-1})	Residence Time (s)	Fireline Intensity (kW m^{-1})
Aquarius 19-03	30.5	26.7	5.5	164.1	128.7	773.8	58.9	3304
Aquarius 20-01	20.0	32.9	2.5	165.5	132.3	433.7	73.4	2250
Aquarius 20-02	19.9	33.1	2.5	165.5	132.3	681.1	45.2	2237
Tumbarumba E	45.0	26.0	6.5	118.0	112	122.0	99.3	955
Tumbarumba G	20.0	28.0	8.0	126.0	117.5	617.8	96.9	3906
								Heat Release (kJ m^{-2})
Warra 1A-1	90.0	17.0	2.5	-	41	-	266.0	551538
Warra 1A-2	90.0	17.0	2.5	-	52.4	-	266.0	332767
Warra 1A-3	90.0	17.0	2.5	-	52.4	-	266.0	379947
Warra 8B-1	52.0	19.0	2.5	-	52.4	-	388.6	868428
Warra 8B-2	52.0	19.0	2.5	-	52.4	-	388.6	831813
Warra 8B-3	52.0	19.0	2.5	-	52.4	-	388.6	1053203
Warra 8B-4	52.0	19.0	2.5	-	52.4	-	388.5	233956
Warra 8B-5	52.0	19.0	2.5	-	52.4	-	388.6	184719
Warra 8C-1	70.4	17.8	2.5	-	31	-	459.7	703382
Warra 8C-2	70.4	17.8	2.5	-	31	-	459.7	511239
Warra 8C-3	70.4	17.8	2.5	-	31	-	459.8	474887

RH: relative humidity; T: temperature; U_{10}: 10-m open wind speed; KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; ROS: rate of spread.

Appendix B. Field site fuel moisture content (FMC), fuel load characteristics and woody fuel consumption outcomes.

Burn ID	Mean profile FMC (%)	Size 3 (7.5-22.5 cm) FMC (%)	Mean log FMC (%)	Total pre-fire fine fuel load (Mg ha^{-1})	Total post-fire fine fuel load (Mg ha^{-1})	Pre-fire woody fuel load > 0.6 cm (Mg ha^{-1})	Post-fire woody fuel load > 0.6 cm (Mg ha^{-1})	Site consumption (%)	Woody fuel consumption (%)	Carbon release (Mg ha^{-1})
Wilga	11.6	40.8	38.7	5.9	0.2	42.3	22.1	53.7	47.6	10.1
Quillben	24.6	33.9	37.3	7.8	3.0	175.0	121.7	31.8	30.5	26.7
Hester 1	16.6	27.3	32.9	6.0	0.1	103.9	44.8	59.2	56.9	29.6
Hester 2	16.6	27.3	32.9	7.0	0.4	88.9	39.8	58.1	55.2	24.5
Hester 3	16.6	27.3	32.9	6.5	0.5	106.2	61.5	45.1	42.2	22.4
Hester 4	16.6	27.3	32.9	7.0	1.3	76.3	43.2	46.6	43.5	16.6
Tallarook Sp08	32.3	48.6	34.5	8.9	0.3	48.9	27.7	51.7	43.4	10.6
Tallarook Au09	71.5	37.9	55.5	7.3	2.6	55.4	35.5	39.3	36.0	10.0
Aquarius 3	9.5	36.5	37.7	6.9	0.0	69.3	14.3	81.2	79.3	27.5
Aquarius 4-01	8.3	35.5	36.7	8.8	0.0	46.0	21.9	60.1	52.4	12.0
Aquarius 7-01	11.4	33.9	35.1	10.3	0.0	85.5	35.2	63.2	58.8	25.1
Aquarius 7-02	11.4	33.9	35.1	9.8	0.0	59.8	35.1	49.6	41.3	12.4
Aquarius 7-03	11.4	33.9	35.1	8.6	0.0	93.7	54.5	46.7	41.9	19.6
Aquarius 8	13.2	36.8	38.0	7.6	0.0	106.6	34.5	69.8	67.6	36.0
Aquarius 10	9.6	33.9	35.1	10.2	0.0	54.0	27.0	58.0	50.0	13.5
Aquarius 11-01	10.0	33.9	35.1	8.5	0.0	32.8	16.2	60.9	50.7	8.3
Aquarius 11-02	10.0	33.9	35.1	9.7	0.0	52.8	12.0	80.8	77.2	20.4
Aquarius 14	9.6	33.9	35.1	6.9	0.0	68.9	46.4	38.7	32.6	11.2
Aquarius 15	10.0	33.9	35.1	12.0	0.0	47.0	4.7	92.0	89.9	21.1
Aquarius 17	11.5	34.9	36.1	7.4	0.0	57.8	23.5	63.9	59.3	17.1
Aquarius 18	12.7	38.7	39.9	7.9	0.0	52.2	26.3	56.2	49.6	12.9
Aquarius 19-01	9.2	33.4	34.6	10.4	0.0	54.1	28.8	55.3	46.8	12.7

Burn ID	Mean profile FMC (%)	Size 3 (7.5-22.5 cm) FMC (%)	Mean log FMC (%)	Total pre-fire fine fuel load (Mg ha^{-1})	Total post-fire fine fuel load (Mg ha^{-1})	Pre-fire woody fuel load > 0.6 cm (Mg ha^{-1})	Post-fire woody fuel load > 0.6 cm (Mg ha^{-1})	Site consumption (%)	Woody fuel consumption (%)	Carbon release (Mg ha^{-1})
Aquarius 19-02	9.2	33.4	34.6	8.6	0.0	63.2	33.5	53.3	46.9	14.8
Aquarius 19-03	9.2	33.4	34.6	8.2	0.0	50.9	32.8	44.5	35.6	9.0
Aquarius 20-01	10.2	33.4	34.6	10.0	0.0	62.2	24.8	65.7	60.2	18.7
Aquarius 20-02	10.2	33.4	34.6	6.3	0.0	32.6	17.0	56.4	48.0	7.8
Warra 1A-1	27.0	36.0	37.2	29.6	6.7	579.2	307.2	48.4	47.0	136.0
Warra 1A-2	27.0	36.0	37.2	29.6	6.7	226.2	71.2	69.6	68.5	77.5
Warra 1A-3	27.0	36.0	37.2	29.6	6.7	524.1	343.8	36.7	34.4	90.1
Warra 8B-1	17.0	34.0	35.2	47.3	10.6	633.6	205.9	68.2	67.5	213.9
Warra 8B-2	17.0	34.0	35.2	47.3	10.6	1006.6	598.4	42.2	40.5	204.1
Warra 8B-3	17.0	34.0	35.2	47.3	10.6	1321.5	795.0	41.1	39.8	263.3
Warra 8B-4	17.0	34.0	35.2	47.3	10.6	270.0	181.6	39.4	32.7	44.2
Warra 8B-5	17.0	34.0	35.2	47.3	10.6	684.5	622.4	13.5	9.1	31.0
Warra 8C-1	28.0	36.6	37.8	53.1	8.5	558.7	227.1	61.5	59.3	165.8
Warra 8C-2	28.0	36.6	37.8	53.1	8.5	381.3	152.5	62.9	60.0	114.4
Warra 8C-3	28.0	36.6	37.8	53.1	8.5	408.6	199.3	55.0	51.2	104.7
Tumbarumba E	11.0	41.9	47.2	13.3	0.0	123.3	82.7	39.4	32.9	20.3
Tumbarumba G	11.0	41.9	47.2	12.3	0.0	49.3	22.0	64.4	55.5	13.7

Appendix C Photos illustrating the forest and fuels for (*a*) jarrah (*E. marginata*) forest at Hester block (*b*) Tallarook State Forest (*c*) Warra LTER site and (*d*) Maragle State Forest, Tumbarumba.

Chapter 4.

The effect of fireline intensity on woody fuel consumption in southern Australian eucalypt forest fires

4.1. Acknowledgement and contributions

The work presented in this chapter occurred as a result of this PhD research and was accepted for publication during the course of candidature:

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Jennifer Hollis was the primary author however contributions were made by several co-authors. Wendy Anderson[1] developed model code, assisted data analysis and prepared much of the methodology relating to construction of Generalised Linear Models. Lachie McCaw[2,3] and Miguel Cruz[4] assisted result interpretation. Neil Burrows[5], Bruce Ward[2], Kevin Tolhurst[6,3] and Jim Gould[4,3] contributed data collected at Aquarius and Tumbarumba woody fuel consumption projects. All co-authors assisted manuscript review.

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4.2. Summary

The relationship between woody fuel consumption and fireline intensity was assessed using data collected at controlled fires and wildfires in south-western Western Australia, central Victoria and south-eastern New South Wales. The combined dataset consisted of fires in a range of dry eucalypt forests. Weather conditions and fire behaviour varied from slow, self extinguishing prescribed burns to intense, fast-moving fires burning under conditions of extreme fire danger. Fireline intensity ranged from 50 kW m^{-1} to more than 31000 kW m^{-1}. Woody fuel consumption ranged from 31% to 100%, and generally increased with fire intensity. Percentage consumption was highest for small woody fuels where diameter was between 0.6 cm and 2.5 cm. Fireline intensity had a statistically significant, positive relationship with the proportion of woody fuel consumed by both controlled fires and wildfires. Two generalised linear models (GLM) describing woody fuel consumption as a function of fireline intensity were developed, one applicable to the prescribed fire environment (with fireline intensities typically less than 750 kW m^{-1}) and the other to the full range of fireline intensity. The prescribed burning model produced the best fit and lowest error statistics.

The findings of this research have important practical implications for the management of fire to reduce fuel loads, maintain habitat and manage carbon stocks in fire-prone eucalypt forests. The woody fuel consumption models presented may assist the assessment of potential climate change impacts on coarse woody debris in Australian southern eucalypt forests. The results of this research suggest that predicted changes to fire regimes and fire intensity associated with climate change in southern Australia could result in greater woody fuel consumption and carbon release during bushfires and a reduction in woody fuel loads in dry eucalypt forests. Use of low intensity prescribed fires may provide a practical way of managing woody fuel stocks to achieve particular land management objectives.

4.3. Introduction

Woody fuels, also referred to as coarse woody debris (CWD), are an important component of the fuel complex in eucalypt forests but have received much less attention than the fine fuels (< 0.6 cm in diameter) which contribute directly to forward movement of the fire (Cheney, 1990a; Pyne *et al.*, 1996; Gould *et al.*, 2007). Woody fuels typically comprise most of the surface fuel load within eucalypt forests and form the major proportion of surface fuels consumed by fire. Unlike fine fuels, woody fuels burn mostly after the passage of the fire front. Consumption of woody fuels on the forest floor greatly influences post-frontal fire behaviour including the rate of heat release and total energy output (Byram, 1959; Rothermel, 1993) as well as convection column development (Potter *et al.*, 2004; Kiefer *et al.*, 2008). Woody fuel consumption will also largely determine the radiant heat and smoke environment to which firefighters are exposed (Sullivan *et al.*, 2002). Woody fuels can burn for long periods of time, sometimes even months after the passage of the fire front, increasing difficulty of fire suppression and mop-up (Cheney, 1981; Lawson *et al.*, 1997) and the potential for re-ignition following the fire (Pyne *et al.*, 1996; Lawson *et al.*, 1997). Combustion of woody fuel plays a significant role in determining first-order fire effects, through soil heating and tree mortality associated with the heating of tree boles and superficial roots (Burrows, 1987a; Cheney, 1990a; Johnson and Miyanishi, 1995; Whelan, 1995; McCaw *et al.*, 1997).

CWD support many functions and processes within Australian forest ecosystems. They have an essential role in contributing to biological diversity and ecosystem processes (Harmon *et al.*, 1986; Grove and Meggs, 2003; Woldendorp and Keenan, 2005) and have been described as being among the most important of biological legacies within disturbed forests (Franklin and MacMahon, 2000). CWD strongly affect the spatial pattern of biota distribution and the rate of post-disturbance recovery of biodiversity (Lindenmayer, 2009). Recognition of their ecological value has contributed to their increasing prominence in forest management strategies throughout Australia (Williams and Faunt, 1997; Woldendorp *et al.*, 2002; Woldendorp and Keenan, 2005).

Woody fuels are also an important component of the forest carbon cycle, persisting for many decades in forest biomass, dead organic matter and soil before being released to the atmosphere, either slowly through decay or rapidly through combustion when burnt in a forest fire. The contribution by woody fuels to carbon sinks, greenhouse gas and smoke emissions is important in the context of climate change, and in the application of management practices to meet land management goals that comply with air quality and emission targets (Gould, 2003). Any fire may consume woody fuels, thereby contributing to carbon emissions (Apps *et al.*, 2006), but there may not be the equivalent reduction in surface woody fuel load. Following fire, newly fallen trees and branches are often transferred from the standing biomass to the downed woody fuel load (Waterworth and Richards, 2008). The resulting woody fuel load may be as high as the pre-fire woody fuel load depending on variables such as species, stand structure, fire behaviour (e.g. fire intensity, residence time) and termite damage, consequently adding to the complexity of predicting the effect of fire on woody fuel dynamics.

Australian fire behaviour and regimes are closely related to climate and meteorological conditions including temperature, humidity, wind speed and diurnal and seasonal patterns of fuel dryness and ignition probability (Luke and McArthur, 1977; Cheney, 1981; McCaw *et al.*, 2003). Climate change projections for southern Australia, which include rising annual mean temperatures as well as local variations in rainfall patterns with longer dry periods broken by heavier rainfall events (CSIRO and BoM, 2007; Lucas *et al.*, 2007) could modify fire regimes. This includes changes to fire frequency, size, intensity and the length of the fire season including the period suitable for prescribed burning (Lucas *et al.*, 2007). Climate change has the potential to increase the area burnt by wildfires (Amiro *et al.*, 2001; Gould and Cheney, 2007), thereby increasing greenhouse gas emissions linked to biomass combustion. Understanding the effects that these changes could have on the amount and quality of CWD and improving predictive ability for woody fuel consumption and the resulting implications for carbon stocks and cycles within a forest ecosystem is becoming increasingly important.

The objective of the present paper is to investigate the relationship between fireline intensity and woody fuel consumption for experimental/prescribed fires (n = 28) and wildfires (n = 5) across different Australian eucalypt forests. We tested the hypothesis that fireline intensity is a significant variable in determining the proportion of woody fuel consumed by fire and that the proportion of woody fuel consumed by fire increases with increasing fireline intensity.

4.3.1. Woody fuel consumption and fireline intensity

Byram (1959) defined fireline intensity as the rate of energy released per unit length of flame front. Fireline intensity I (kW m^{-1}) is widely used by the fire community to characterise the active flaming zone, and is calculated as:

$$I = H \cdot w_a \cdot r \quad (1)$$

where H is the low heat of combustion (kJ kg^{-1}), w_a is the fuel consumed in the active flaming front (kg m^{-2}), and r is the fire rate of spread (m s^{-1}). This simple measure of fire intensity is directly related to flame size (Alexander, 1982) and provides a quantitative description that can be used to evaluate the effect of fire on ecosystem components.

Defining and quantifying fireline intensity is particularly difficult for complex burn patterns which may result, for example, from multiple ignition points or ring ignitions that are commonly used in prescribed burn operations. These burn patterns can lead to stationary fires with mass fire behaviour (McRae and Flannigan, 1990) and are characterised by significant heat release and extreme turbulence for which the concept of a moving flame front is not applicable. McArthur and Cheney (1966) and Cheney (1990b) suggest total heat release as a more appropriate descriptor of fire energy release in such situations. Total heat release, H_A (kJ m^{-2}), is calculated as:

$$H_A = H \cdot w \quad (2)$$

where w is the total amount of fuel consumed (kg m^{-2}) (Albini, 1976).

The effect of fireline intensity on woody fuel consumption has been widely reported in literature but the conclusions from different studies are not consistent. This has resulted in uncertainty about the effect of fireline intensity, and particularly the difference in woody fuel consumption between high-intensity wildfires and low-intensity prescribed burns. Some Australian research has shown that the proportion of woody fuels consumed by fire will increase with increasing fire intensity. Hamilton *et al.* (1991) reported that only 13.6% of woody fuels were consumed by a low-intensity (200-250 kW m^{-1}) prescribed burn in *Eucalyptus obliqua* forest in Victoria. However, this was probably because the burn was patchy and a large proportion of total biomass came down from overstorey post-burn and contributed to the post-fire fuel load. McArthur and Cheney (1966) found a positive relationship between fireline intensity (ranging from 230 to 3900 kW m^{-1}) and woody fuel consumption in prescribed burns in thinned *Pinus radiata* stands. Similarly Tolhurst *et al.* (2006) reported a strong positive relationship between fire intensity (ranging between 585 and 3304 kW m^{-1}) and woody fuel consumption for wet sclerophyll forest of *E. dalrympleana* and *E. radiata* near Tumbarumba, NSW. Burrows (2001) reported that woody fuel consumption was dependent on the intensity of fire through the litter fuel as well as fuel dryness and wind speed.

Positive relationships between woody fuel consumption and fire intensity have also been reported in several North American studies. Fahnestock and Agee (1983), using data from prescribed fires (Fujimori *et al.*, 1976; Grier, 1976; Grier and Logan, 1977; Grier *et al.*, 1981) and their own data estimated that snag and downed log consumption in western Washington wildfires would be 20% in moderate-intensity fires and 30% in high-intensity fires. Youngblood *et al.* (2008) argued that aggressive burning prescriptions are likely to result in greater amounts of fuel consumption in dry conifer forests in north-eastern Oregon than less intense, surface fires. Others studies have demonstrated how changes to the seasonal and weather variables that influence both fuel moisture and fire behaviour (including the intensity of fire) will also affect woody fuel consumption. For example, in a study analysing fire behaviour through immature jack pine stands in Ontario, Canada, Stocks (1987) reported that the amount of fuel available for combustion and the consumption of ground and surface fuels correlated well with the Build Up Index (BUI) of the Canadian Fire Weather Index (FWI) System (Van Wagner, 1987). Sparks *et al.* (2002), in their study of season-of-burn influences on fire behaviour and fuel consumption in restored shortleaf pine-grassland communities, reported that the proportion of fuel consumed was significantly less in growing-season fires than in dormant-season fires due in part to the fireline intensity being greater in the latter. In a study on Vancouver Island in British Columbia, Beese *et al.* (2006) also reported differences in woody fuel consumption between low-severity spring burns and high-severity fall burns. While their study demonstrated substantial differences in woody fuel consumption due to seasonal differences, particularly in fuel moisture, the authors also concluded that woody fuel consumption increased significantly with increasing fire severity. Most recently, a study of woody fuel consumption in Canadian boreal forest fires by de Groot *et al.* (2009) showed that high-intensity surface fires (around 4400 kW m^{-1}) resulted in greater consumption of forest fuel than low-intensity fires (between 15 and 390 kW m^{-1}). The process-based BURNUP model (Albini and Reinhardt, 1995) used to predict woody fuel consumption in the FARSITE fire area simulator (Finney, 2004) incorporates a positive effect of fire intensity and residence time on the consumption of woody fuels.

In contrast, several authors have reported that the proportion of woody fuels consumed by fire decreases with increasing fire intensity. Hall (1991) compared fuel consumption between mass-ignited high-intensity fires and moderate-intensity fires in logging slash, and concluded that high-intensity fires consume less woody fuel than lower-intensity fires. Hall's study has been widely cited (Ottmar *et al.*, 1993; Tinker and Knight, 2000; Ottmar *et al.*, 2001; Wright and Prichard, 2006) and its conclusions have been incorporated into the CONSUME model of woody fuel consumption for activity fuels (logging slash) (Prichard *et al.*, 2005). Hall argued that high-intensity fires had a faster rate of flaming consumption and that this reduced the duration of heat supplied to wood, therefore influencing the rate of woody fuel consumption. While the findings of Hall (1991) have been influential in research and model development, the method used to define and measure fire intensity was subjective. Hall (1991) did not measure fire intensity per se but categorised fires according to ignition method, namely mass-ignition (high-intensity burns) versus strip ignition (low-intensity burns). Taylor and Sherman (1996), in their report on biomass consumption and smoke emissions from contemporary and prehistoric wildland fires in British Columbia, estimated that the proportion of woody fuel consumed decreased with increasing fire intensity, with 85% of woody fuels consumed in a surface crown fire and only 60% in a crown fire. This estimation was based on data collected during experimental fires (Quintilio *et al.*, 1977; Brown and DeByle, 1989; Alexander *et al.*, 1991; Quintilio *et al.*, 1991 and unpublished data from the Canadian Forest Service).

Other studies have reported no significant difference in woody fuel consumption under varying fire intensities. For example, Tinker and Knight (2000) found no significant differences in post-fire woody fuel loads following crown fires and those following intense surface fires. In slash hazard reduction burns of longleaf pine, Hough (1968) reported no difference in woody fuel consumption between backfires and headfires. Due to a distinct difference between backing versus headfire rates of spread, this result indicates that woody fuel consumption is not affected by fire intensity in this fuel type. Sandberg and Ottmar (1983), in their study of slash burning and fuel consumption in the Douglas-fir subregion, did not measure fire intensity or rate of spread because they assumed that these would have no effect on woody fuel consumption.

4.4. Methods

Woody fuel consumption resulting from wildfires and prescribed fires in Australian southern eucalypt forests was assessed as part of the Woody Fuel Consumption Project (WFCP) between 2007 and 2010. Field studies were conducted within prescribed burns in dry sclerophyll jarrah forest (*Eucalyptus marginata*) at Wilga, Quillben and Hester blocks in south-western Western Australia and herb-rich foothill forest (*E. globulus* and *E. viminalis*) at Tallarook State Forest in Victoria (Figures 1 and 2). At the Hester site, four concurrent fires were conducted to assess the effect of fireline intensity on woody fuel consumption. The relative influence of other variables including fuel moisture and drought condition on fuel consumption is therefore minimal compared to other fires in the dataset. Consumption of woody fuel was also measured at locations burned by two high-intensity bushfires: the 2005 Pickering Brook fire in Western Australia (Cheney, 2010) and the 7th February 2009 Kilmore East fire in northern-central Victoria (Cruz *et al.*, 2010). Sampling within the Pickering Brook fire was conducted in jarrah forest at the Occidental block site. Four sites were sampled within the Kilmore East fire, namely, Burgan Track, Healesville West, Upper Plenty and Pheasant Creek (Figures 1 and 3). These sites were located in herb-rich foothill forest; a medium to tall open forest primarily consisting of *E. radiata*, *E. dives* and *E. obliqua*.

The dataset was expanded by including field data collected during previous experimental studies in Western Australia and New South Wales. Data for jarrah forest were available from 18 plots burnt at McCorkhill block during Project Aquarius, a study of high intensity forest fire behaviour in south-western Western Australia (Gould *et al.*, 1996). Data for wet sclerophyll forest of *E. dalrympleana* and *E. radiata* in the Maragle State Forest, near Tumbarumba were available from three experimental fires conducted in 2004 (Tolhurst *et al.*, 2006) (Figures 1 and 2).

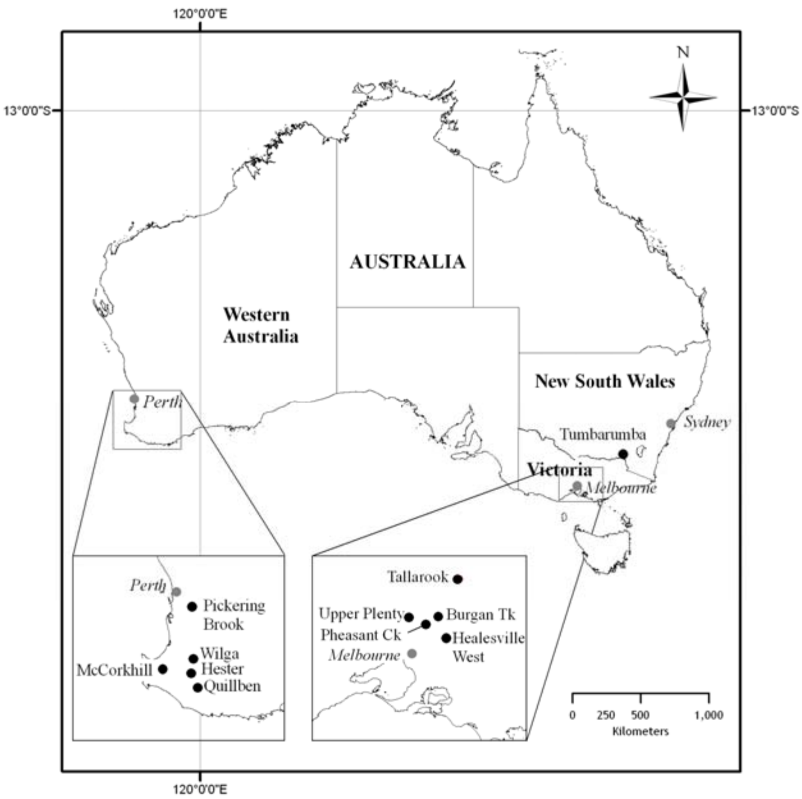

Figure 1. Location of woody fuel consumption research sites across Australia including Wilga, Quillben, Hester, McCorkhill (Project Aquarius) and the Occidental (Pickering Brook) wildfire in Western Australia, Tallarook and sites from the Kilmore East (Black Saturday) wildfires in Victoria (including Burgan Track, Healesville West, Upper Plenty and Pheasant Creek) and Tumbarumba in New South Wales.

Figure 2. Photos illustrating the forest and fuels for (*a*) Hester block (*b*) Tallarook State Forest (*c*) McCorkhill block and (*d*) Maragle State Forest, Tumbarumba.

4.4.1. Fuel assessment and determination of consumption

The dataset compiled for the present analysis arises from three distinct studies. The WFCP categorised woody fuels into five distinct diameter size classes that approximate the moisture time-lag response of fuels by Fosberg (1970). Small methodological variations between the studies required a rearrangement of the woody fuel size classes to attain consistency between studies and allow further analysis. Woody fuel load data from the McCorkhill block (Project Aquarius) and Tumbarumba (Tolhurst *et al.*, 2006) were re-classified into the five diameter size classes adopted for the WFCP, resulting in some minor inconsistency between size classes (Table 1).

Table 1. Woody fuel size class differentiation across woody fuel consumption datasets, with the corresponding lag time for fuels in (italics) (Fosberg, 1970).

	WFCP	Project Aquarius	Tolhurst *et al.* (2006)
Size class (lag time)	Woody fuel diameter (cm)		
1 *(1-hr)*	0.60-2.50	1.0-2.50	0.6-1.0 1.01-2.50
2 *(10-hr)*	2.51-7.50	2.51-5.00 5.01-7.50	2.51-7.50
3 *(100-hr)*	7.51-22.50	7.51-10.0 10.01-15.0 15.01-20.0	7.51-22.50
4 *(1000-hr)*	22.51-50	20.01-30 > 30[a]	22.51-50
5	> 50	> 30[b]	> 50

[a] Actual diameters were recorded only for diameters < 50 cm.
[b] Actual diameters were recorded only for diameters > 50 cm.

For the WFCP sites, Van Wagner's (1968) line intersect method was used to calculate pre-fire and post-fire woody fuel load of the smallest size class (size 1: 0.6-2.5 cm) while Brown's (1974) woody material formula was used to determine pre-fire and post-fire woody fuel load for all fuels > 2.5 cm in diameter. For size class 1 (0.6-2.5 cm) the quadratic mean diameter (QMD) was assumed to be the midpoint of the size class (i.e. 1.55 cm). Mean wood density for each site was determined from a random sample of log disks. Wood density for each log disk was determined by the submersion method (Technical Association of the Pulp and Paper Industry, 1994). No wood samples were collected for the McCorkhill block, Pickering Brook and Kilmore East fire sites. Average wood density determined for the WFCP Quillben site was used for Project Aquarius and Pickering Brook sites due to similarities in fuel age and jarrah forest type. For the Kilmore East fire sites, the average wood density for the nearby Tallarook State Forest was used.

Pre-fire and post-fire size class 1 fuels at McCorkhill block fires were assessed using destructive sampling techniques (Catchpole and Wheeler, 1992) and by assuming that all size class 1 fuel was consumed. The line intersect method was used to determine pre-fire and post-fire woody fuel loads for sizes classes 2 to 4 where QMD was assumed to be the midpoint of each size class. For sizes 4 and 5 (greater than 30 cm) where fuel particle diameter was known, Brown's (1974) woody material formula was used to determine woody fuel load pre-fire and post-fire. For each of the fires, the difference in pre-fire and post-fire woody fuel load was grouped by size class and a percent consumption was determined based on the pre-fire fuel load.

At the Occidental site (Pickering Brook fire), pre-fire and post-fire woody fuel loads were determined using the line intersect method. For Kilmore East fires, woody fuel consumption was determined by comparing pairs of burnt and unburnt sites (Figure 3). Unburnt sites were chosen to represent pre-fire conditions at sites burnt by extreme fire behaviour during the 7th February 2009 Black Saturday fires in Victoria. Unburnt sites were typically matched to reflect characteristics of the burnt sites including: forest and fuel type, stand structure, fuel age, slope and aspect. A further constraint in pairing unburnt-burnt sites was to minimise the distance between sites (mean = 1.9 km). Pre-fire woody fuel load at each burnt site was then assumed to be equivalent to the woody fuel load at its corresponding unburnt site. Transect lengths to determine pre-fire and post-fire woody fuel load varied between field studies and sites and are reported in Table 2. Fine fuel (litter) load was determined from the full depth of the litter profile using destructive sampling techniques (Catchpole and Wheeler, 1992).

Figure 3. Healesville West comparative pair sites of the Kilmore East February 2009 wildfire in Victoria: (a) representative of long unburnt pre-fire conditions and (b) post-fire March 2010.

4.4.2. Fire behaviour assessment

In each of the experimental studies fine fuel (< 0.6 cm in diameter, or < 1.0 cm for the McCorkhill block) moisture content was measured for the surface (upper 0.5-1 cm of undecomposed litter layer) and the full depth of the litter profile. Samples for fuel moisture were taken prior to burning and where possible during burning for fire durations > 2 h. No fuel moisture measurements were conducted during the Kilmore East and Pickering Brook fires. For these fires, fine fuel moisture content was estimated using Matthews (2006) fine fuel moisture model.

Techniques for assessing fire rate of spread varied by field study and are summarised in Table 2. Fireline intensity was calculated for all fires using Eq. 1 where H was assumed to be 18,676 kJ kg^{-1} (Burrows, 1994) and w_a was the loading of the surface fine fuels consumed in flaming combustion.

4.4.3. Statistical methods

Prescribed fires in southern Australian eucalypt forests are mostly conducted at intensities below 750 kW m^{-1} (Cheney *et al.*, 1992). Above this range, the intensity of the fire may result in unacceptable damage to the forest stand and difficulty containing fire within control lines due to spotting (McArthur, 1962). For this reason, the woody fuel consumption dataset was divided into two groups based on a fireline intensity threshold of 750 kW m^{-1} for the prescribed burning environment. Data collected within the WFCP prescribed fires provided the greatest level of control over data collection (e.g. the ability to analyse the consumption of individual woody fuel particles and size classes) compared to the other sources; therefore the greatest degree of accuracy and confidence in woody fuel consumption outcomes was in the WFCP dataset. So, for the prescribed range of burning conditions, data were analysed first within the WFCP subset, including analysis within size classes, and later extended to the whole dataset.

A generalised linear model (McCullagh and Nelder, 1989) was used to model the proportion of woody fuel consumed in response to fireline intensity. This involved constructing a quasi-likelihood function (Collett, 2003) where the dependence of the conditional mean of y (μ say) at a fixed value of x is specified as:

$$g(\mu) = b_0 + b_1 x, \tag{3}$$

where $g(.)$ is called the link function, and b_0 and b_1 are regression coefficients. Regression coefficients are estimated by the method of maximising the likelihood using iteratively weighted least squares. For data in the form of proportions a reasonable assumption is that the conditional variance of y given x (written as $\mathrm{var}(y \mid x)$) is given by:

$$\mathrm{var}(y \mid x) = \phi v(p) \quad where \quad v(p) = p(1 - p), \tag{4}$$

where p is the mean proportion consumed for a given x, and $\phi \geq 1$ is a scaling parameter. The variance of y is in the same form as for binary data but increased by ϕ, that is y has a quasi-binary distribution.

The commonly used link function, the logit function $g(\mu) = p/(1 - p)$, was used, so the proportion consumed was modelled as:

$$p = 1/\left(1 + \exp\{-(b_0 + b_1 x)\}\right). \tag{5}$$

Table 2. Summary of variations in mean transect length, burn and ignition type, mean rate of spread and source of weather data. Range of conditions (minimum to maximum) in *italics*.

Site	Mean transect length (m)	Burn & Ignition Type	Mean Rate of Spread (ROS)	Source of weather data
WFCP – Wilga	400	Silvicultural slash & ecological prescribed burn. Long line > 150 m length	Grid of insulated type K thermocouples with data logger: using the time at which 320°C was reached together with visual observations	On site weather station located in open clearing measuring rainfall, 10m wind, air temperature & relative humidity (RH)
WFCP - Quillben	400	Ecological & fuel reduction prescribed burn. Long line > 150 m length		Weather station located approximately 500m away in open field measuring rainfall, 10m wind, air temperature & RH
WFCP - Hester	389 *(190-400)*	Ecological & fuel reduction prescribed burn. Long line > 150 m length		Weather station located approximately 1km away in open field measuring rainfall, 10m wind, air temperature & RH
WFCP - Tallarook	400	Ecological & fuel reduction prescribed burn. Long lines and stripping > 150 m length		Weather station located approximately 2km away in open field measuring rainfall, 10m wind, 2m wind air temperature & RH
McCorkhill	584 *(60-1620*)	Research. Long line and multiple point ignitions	Periodic mapping based on infra red line (IR) scanner & visual observations	Weather station in close proximity measuring rainfall, 10m wind, 2m wind air temperature & RH
Pickering Brook fire	200	Wildfire	Field observation, photographs and satellite imagery during and after fire to map fire perimeter periodically	Perth Airport (30 kms north-west of fire), Bickley (13km north) and Wandering (50km south-east) automatic weather stations
Tumbarumba	90	Research. Line ignition, 100 m length	Use of numbered metal tags and visual observations to map fire perimeter periodically	Weather station in close proximity measuring rainfall, 10m open wind, 2m in-forest wind air temperature & RH
Kilmore East fire	400	Wildfire characterised by short and long range spotting	Field observation and satellite imagery[a] to map fire perimeter periodically	Coldstream or Kilmore Gap automatic weather stations

[a] Based on Cruz *et al.* (2010).

Models were fitted using the software R (R Development Core Team, 2008).

Model fit was assessed using several goodness-of-fit statistics: mean absolute error (*MAE*), root mean squared error (*RMSE*) and mean absolute percentage error (*MAPE*) (Makridakis *et al.*, 1998). For a non-dimensional standardised measure of goodness-of-fit, Effron's pseudo R^2 (Effron, 1978) was used in preference to other pseudo R^2 measures based on likelihood because the likelihood in the quasi-binomial model is not fully specified. Formulae for error and goodness-of fit-statistics are:

$$MAE = \frac{\sum_i (y_i - \hat{y}_i)}{n} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum_i (y_i - \hat{y}_i)^2}{n}} \tag{7}$$

$$MAPE = \frac{\sum \left(\frac{|y_i - \hat{y}_i|}{y_i} \right)}{n} \cdot 100 \tag{8}$$

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y}_i)^2} \tag{9}$$

where y_i is the observed value of y, $\hat{y}_i$ is the predicted value of y, $\bar{y}_i$ is the mean value of y, and n is the number of observations. Note that even though Effron's pseudo R^2 (Eq. 8) has the same formula as that of the R^2 for ordinary least squares it does not have the same meaning in the sense of proportion of explained variation in the model. Effrons's R^2 is used here as an indicator of comparative fit.

Diagnostic analysis was carried out using the plot(glm.model) command in R. This gives a plot of residuals versus fitted values to assess the form of the model, a normal quantile plot of the standardised deviance residuals, a plot of the square root absolute standardised deviance residuals versus fitted values to assess the error model, and a plot of the standardised Pearson residuals versus leverage to identify points of high leverage (see Davidson and Snell (1991) for further details).

4.5. Results

4.5.1. Pre-fire fuel load distribution

Pre-fire woody size class distribution and fuel load were variable between field sites (Figure 4) with an average pre-fire woody fuel load of 66 t ha^{-1} (st.dev. = 34 t ha^{-1}, n = 33). Pre-fire woody fuel load was greatest at Quillben (175 t ha^{-1}) due to the large contribution made by size class 5 fuels (110 t ha^{-1} cf. average of 22 t ha^{-1} for the full dataset). Wilga had the lowest pre-fire woody fuel load (42 t ha^{-1}) of the jarrah forest sites probably due to recent selective timber harvesting. Pre-fire woody fuel loads were relatively small (< 30 t ha^{-1}) at Pickering Brook, Burgan Track, Healesville West and Upper Plenty with the last having the lowest pre-fire woody fuel load in the dataset (13 t ha^{-1}) and lacking fuels > 7.5 cm. Woody fuels > 50 cm diameter were absent at Tallarook, Pickering Brook and Burgan Track.

On average, fuels > 22.5 cm in diameter (size classes 4 and 5) accounted for over 75% of the total woody fuel load across all sites, while fuels in the largest size class (> 50 cm; size class 5) typically comprised more than 35%. On average, woody fuels > 7.5 cm in diameter (size classes 3, 4 and 5) accounted for 91% of the total woody fuel load.

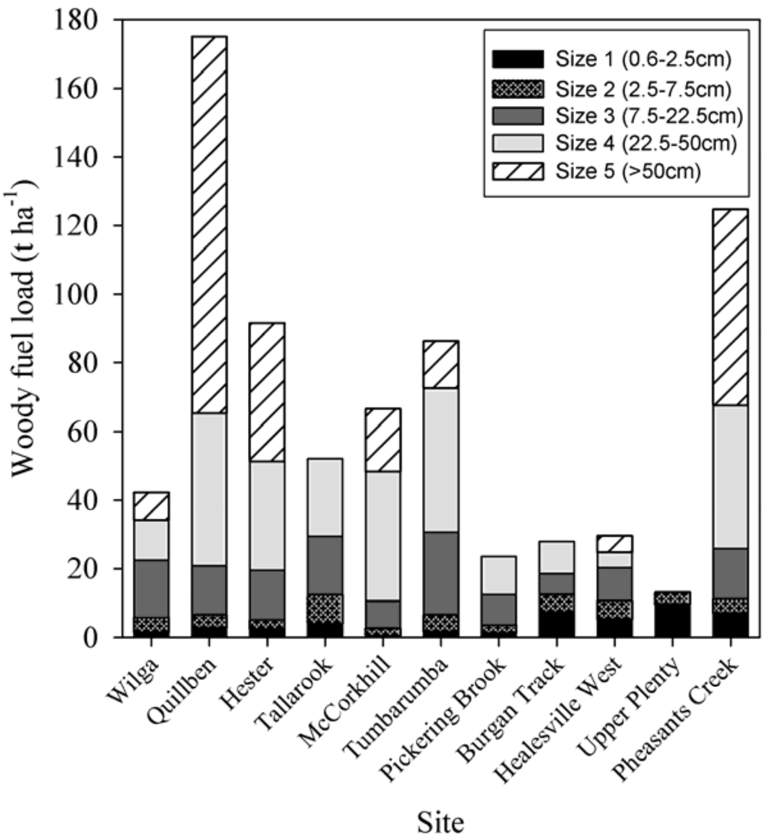

Figure 4. Pre-fire woody fuel load distribution by size class.

4.5.2. *Fire behaviour and environment*

Fire behaviour ranged from slow, self-extinguishing surface fires to very high-intensity wildfires with abundant spotting behaviour and rates of spread up to 7620 m h^{-1} (Figure 5). Consumption of fine, surface fuels ranged between 4.6 and 13.3 t ha^{-1}. A wide range of the Forest Fire Danger Index (FFDI: McArthur, 1967) is represented in the dataset with the maximum FFDI of 155 recorded at Kilmore Gap Automatic Weather Station during the Kilmore East wildfire at the approximate time when the fire burnt the Upper Plenty site. Fireline intensity ranged from 53 kW m^{-1} at Hester 4 plot to 31,625 kW m^{-1} at the Upper Plenty site within the Kilmore East wildfire (Table 3). Figure 5 illustrates the distribution of fireline intensity, with most data (85%) corresponding to intensities < 4000 kW m^{-1} which are normally associated with experimental and prescribed fires. Mean woody fuel consumption was 51% (st. dev. = 14.3 , *n* = 28) for experimental and prescribed fire sites and 90% (st. dev. = 9.1 , *n* = 5) for wildfires.

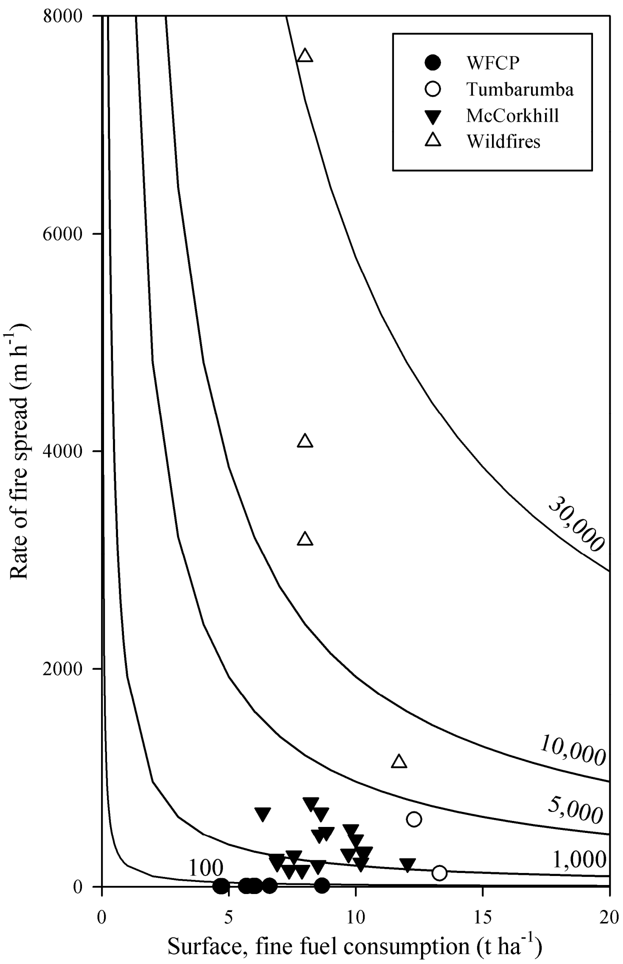

Figure 5. Distribution of fuel consumption (flaming combustion) and rate of fire spread in relation to Byram's (1959) fireline intensity (kW m^{-1}) for the woody fuel consumption dataset.

Table 3. Summary of fuel age and mean fire behaviour characteristics across burn sites. Range across multiple fires (minimum to maximum) in *italics*. For Pickering Brook and Kilmore East wildfires, characteristics describe the period when woody fuel transects were burnt by the active flaming front.

Site / Mean characteristics	*n*	Fuel age (years since last fire)	RH (%)	*T* (°C)	U_{10} (km h^{-1})	KBDI	SDI	FFDI	ROS (m h^{-1})	*I* (kW m^{-1})
WFCP: Wilga	1	17	28	25	8	17	43	10	100	299
WFCP: Quillben	1	17	69	21	6	64	85	3	52	210
WFCP: Hester	4	17	56	25	14	140	148	8	105	349
			(48-63)	*(23-27)*	*(11-18)*		*(148-148)*		*(15-217)*	*(53-678)*
WFCP: Tallarook	2	37	50	17	9	37	140	6	52	234
			(34-66)	*(13-20)*	*(8-9)*	*(14-60)*	*(136-143)*	*(3-9)*	*(20-85)*	*(76-393)*
McCorkhill	18	6	46	25	5	166	139	10	373	1681
			(20-61)	*(18-33)*	*(2.5-24)*	*(148-173)*	*(129-163)*	*(5-18)*	*(153-774)*	*(585-3304)*
Pickering Brook fire	1	9	25	27	28	142	166	25	1133	6877
Tumbarumba	2	> 20	33	27	7	122	115	11	370	2431
			(20-45)	*(26-28)*	*(6-8)*	*(122-122)*	*(112-118)*	*(6-16)*	*(122-618)*	*(955-3906)*
Kilmore East fire	4	43	22	36	42	96	144	74	4515	18738
		(26-52)	*(10-35)*	*(28-41)*	*(28-63)*			*(18-155)*	*(3180-7620)*	*(13198-31625)*

n: sample number; RH: relative humidity; *T*: temperature; U_{10}: 10-m open wind speed; KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; FFDI: Forest Fire Danger Index; ROS: rate of spread; *I*: fireline intensity.

Moisture content of woody fuels (diameter, *d* > 0.6 cm) measured during experimental fires ranged from 33% at Hester to 56% at the Tallarook autumn fire (Table 4). Reliable measurements of woody fuel moisture content were not available for McCorkhill block fires, Pickering Brook and Kilmore East wildfires. Fine fuel (litter) profile moisture content (PMC) ranged from 2% to 72% (mean = 14%) (Table 4). The dataset included observations from fires in spring, summer and autumn with Soil Dryness Index (SDI; Mount, 1972; Burrows, 1987b) ranging from 43 to 166 mm and Keetch Byram Drought Index (KBDI; Keetch and Byram, 1968) from 17 to 173 (Table 3).

Table 4. Summary of fuel moisture conditions and fuel consumption outcomes across fire sites. Range across multiple fires (minimum to maximum) in *italics*.

Site / Mean characteristics	PMC (%)	WMC (%)	Pre-fire woody load (*d* > 0.6 cm) (t ha^{-1})	Post-fire woody load (*d* > 0.6 cm) (t ha^{-1})	Woody fuel consumption (%)
WFCP: Wilga	12	39	42	22	48
WFCP: Quillben	25	37	175	122	31
WFCP: Hester	17	33	94 *(76-106)*	47 *(40-62)*	49 *(42-57)*
WFCP: Tallarook	52 *(32-72)*	45 (35-56)	52 *(49-55)*	32 *(28-36)*	40 *(36-43)*
McCorkhill	10 *(8-13)*	not measured	61 *(33-107)*	27 *(5-54)*	55 *(33-90)*
Pickering Brook fire	7[a]	not measured	22	2	91
Tumbarumba	11	47	86 *(49-123)*	52 *(22-83)*	44 *(33-56)*
Kilmore East fire	1.9[a] *(1.6-2.1)*	not measured	49 *(13-125)*	8 *(0-25)*	90 *(80-100)*

[a] Determined using Matthews (2006) fine fuel moisture model.
PMC: Profile fine fuel (litter) moisture content; WMC: woody fuel (*d* > 0.6 cm) moisture content.

Table 5. Simple correlation coefficient (Pearson *r*) matrix for fire environment and behaviour variables in the woody fuel consumption dataset (*n* = 33).

	pw_W (%)	*I*	SMC (%)	U_2 (km h^{-1})	FFDI	PMC (%)	SDI	WMC (%)	KBDI
pw_W (%)	1	0.672**	-0.680**	0.657**	0.611**	-0.445**	0.365*	-0.195	0.037
I		1	-0.697**	0.868**	0.778**	-0.384*	0.165	-0.026	-0.232
SMC (%)			1	-0.560**	-0.565**	0.827**	-0.208	0.477(*)	-0.21
U_2 (km h^{-1})				1	0.897**	-0.268	0.187	0.223	-0.371*
FFDI					1	-0.296	0.095	-0.133	-0.237
PMC (%)						1	-0.059	0.608**	-0.515**
SDI							1	-0.177	0.478**
Wfmc (%)								1	-0.537**
KBDI									1

***** Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.
pw_W: woody fuel (*d* > 0.6 cm) consumption; *I*: Fireline intensity (kW m^{-1}); SMC: Surface fine fuel (litter) moisture content ; FFDI: Forest Fire Danger Index; U_2: 2-m in forest wind speed; PMC: Profile fine fuel (litter) moisture content; SDI: Soil Dryness Index; WMC: woody fuel (*d* > 0.6 cm) moisture content; KBDI: Keetch Byram Drought Index.

4.5.3. *Woody fuel consumption and fireline intensity*

Woody fuel consumption varied greatly between sites and ranged from 31% at Quillben to 100% at Healesville West within the Kilmore East wildfire (Table 4). The proportion of woody fuels consumed was significantly ($P < 0.01$) correlated with fireline intensity ($r = 0.67$). Both these variables were significantly negatively correlated with fine fuel moisture content and profile fuel moisture content, and significantly positively correlated with understorey wind speed (U_2) and FFDI (Table 5). Woody fuel consumption also varied considerably within sites; for example at the McCorkhill block fires the proportion of woody fuel consumed ranged between 33% and 90%, despite limited variation in weather conditions and fire behaviour characteristics (Table 3).

Woody fuel consumption at Hester ranged from 42% at Hester 3 (284 kW m^{-1}) to 57% at Hester 1 which also had the highest fireline intensity (678 kW m^{-1}). Hester 4 (52.9 kW m^{-1}) had the lowest fireline intensity and only slightly more woody fuel consumed than at Hester 3 (44%). The range of conditions for WFCP fires was limited to prescribed burning conditions where there was minimal variation in fireline intensity and no fireline intensity > 678 kW/m. Woody fuel consumption at WFCP prescribed fire sites ranged from 31% at Quillben to 57% at Hester 1 (mean = 44%, $n = 8$).

Regression analysis using the generalised linear model (GLM) described above for the WFCP prescribed fires showed that fireline intensity was a significant predictor ($P = 0.047$) of the proportion of woody fuel consumed (pw_W) and that the relationship was positive (Figure 6; Table 6). Goodness-of-fit statistics for this model are in Table 7. Regression diagnostics were satisfactory, but the number of observations was small ($n = 8$).

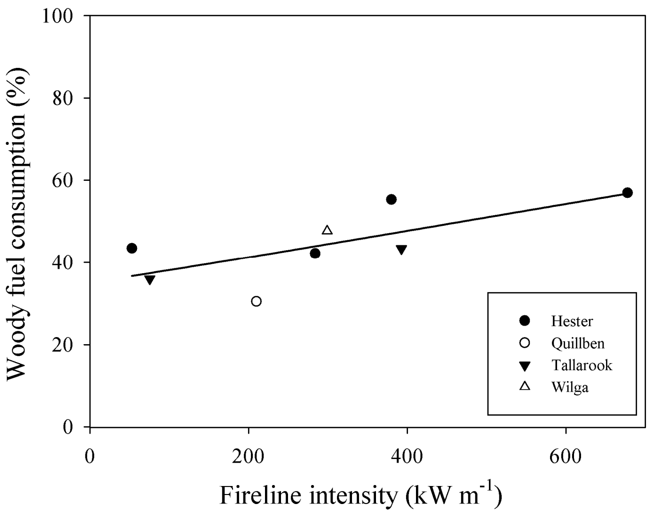

Figure 6. Woody fuel consumption (%) versus fireline intensity for the Woody Fuel Consumption Project (WFCP) prescribed fire sites. The GLM is overlaid.

GLMs were used to analyse the proportion of each size class consumed within WFCP prescribed fires. Analysis showed that the slope parameter of each GLM varied between 0.001 (size class 4) and 0.003 for size class 5 (P = 0.185) and that the effect of fireline intensity on the consumption of size class 5 fuels was the most pronounced of all sizes (R^2 = 0.40) (Table 6). The sample size available for analysis however, does not allow us to draw conclusive results. GLM analyses also showed that the slope b_1 did not vary significantly with size class (P = 0.62). With the same slope for all size classes, the intercept was found to vary significantly with size class (p = 0.0009) and a parallel GLM model grouped by size class was fitted to the data (Figure 7). The diagnostics were satisfactory. When the proportional consumption of size classes were compared, it was found that the consumption in size class 1 was significantly greater than in all other size classes for a given intensity. The analysis showed that the proportional consumption of size classes 2 to 5 could possibly be grouped, but grouping reduced the R^2 value of 0.43 to 0.39 and such simplification would reduce the predictive power.

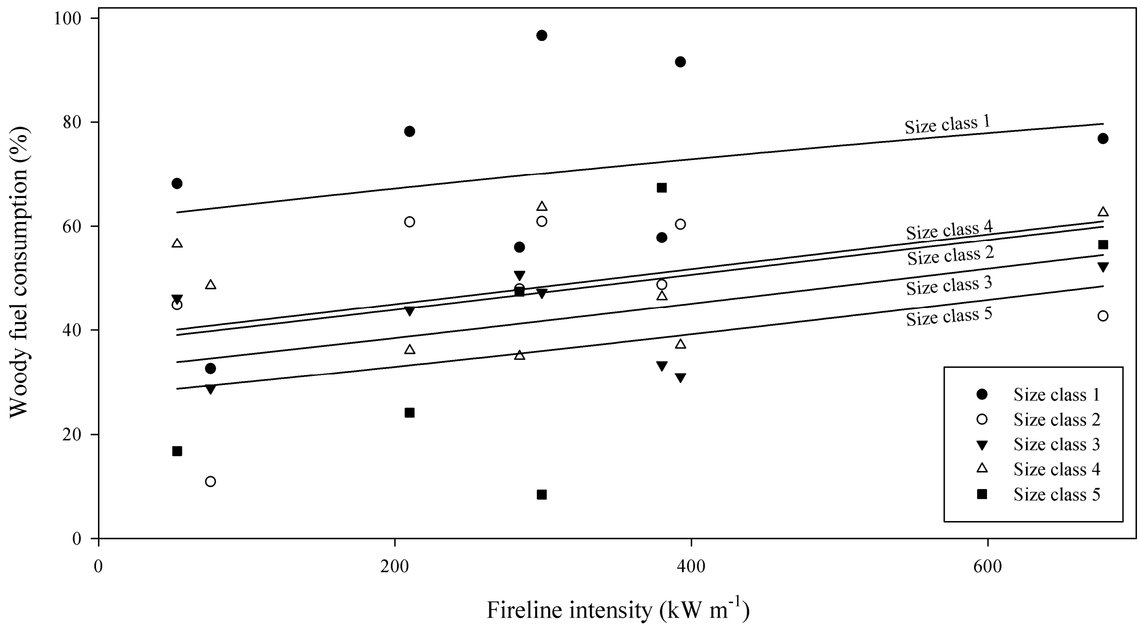

Figure 7. Woody fuel consumption (%) versus fireline intensity by size class for the Woody Fuel Consumption Project (WFCP) prescribed fire sites. The GLM grouped by size class is overlaid.

Adding data from McCorkhill and Tumbarumba fires to the analysis increased the scatter of woody fuel consumption outcomes (Figure 8). Analysis of the combined controlled fire dataset considering fires up to a fireline intensity of 4000 kW m^{-1} found no significant effect of fireline intensity on woody fuel consumption (P = 0.737, R^2 < 0.01, n = 28). No difference in outcomes was apparent between multiple-point ignition and line ignition types (Figure 8). Woody fuel consumption appeared to increase steadily up to a point around 700 kW m^{-1} after which data became increasingly scattered. The proportion of woody fuel consumed demonstrated a significantly increasing relationship (P = 0.013, R^2 = 0.57, n = 10) with fireline intensity up to 750 kW m^{-1} (Figure 9).

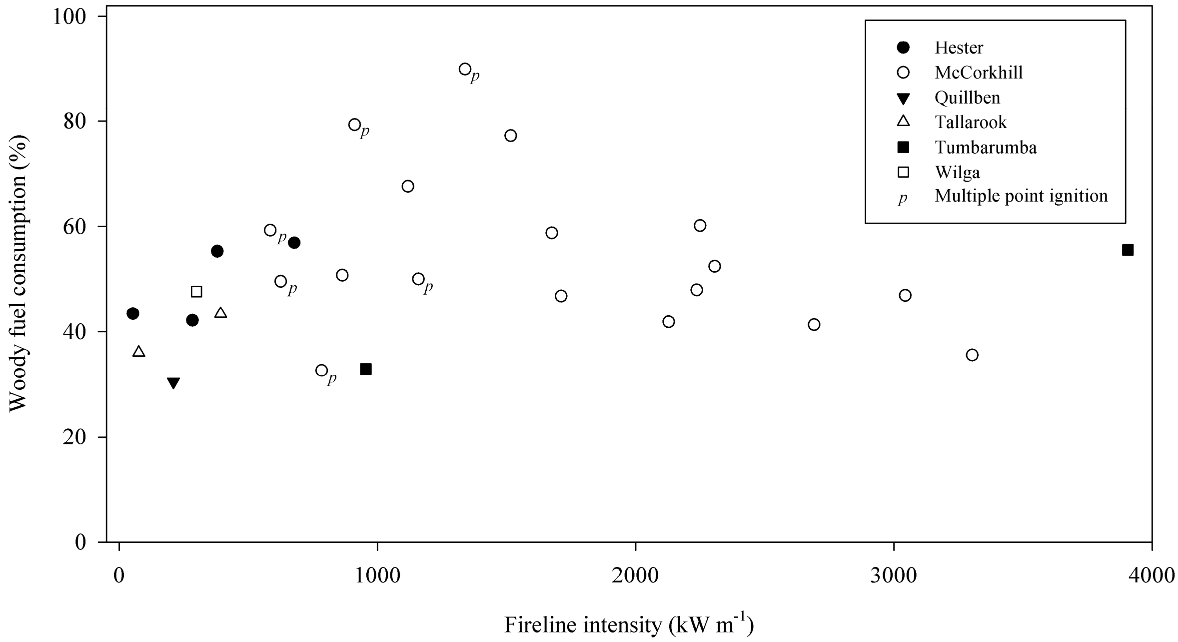

Figure 8. Woody fuel consumption (%) versus fireline intensity for all controlled burn sites.

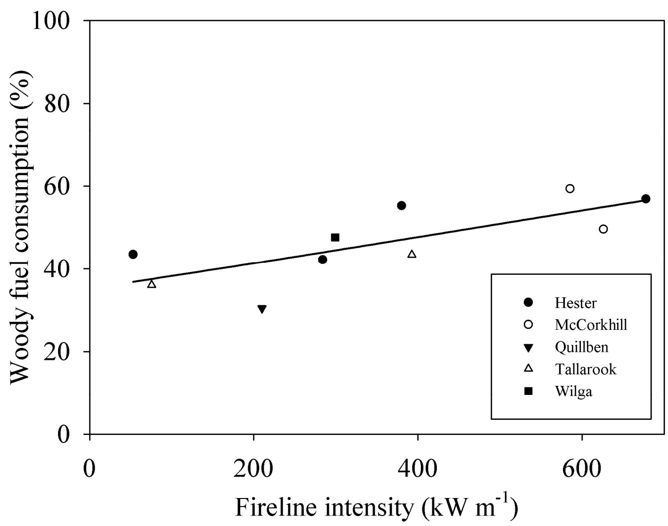

Figure 9. Woody fuel consumption (%) versus fireline intensity for all controlled burn sites where fireline intensity is less than 750 kW m^{-1}. The GLM is overlaid.

Figure 10 shows the effect of fireline intensity on woody fuel consumption across the complete dataset. GLM analysis considering the full dataset identifies fireline intensity as a significant predictor of woody fuel consumption (P < 0.001, R^2 = 0.50, n = 33). The varying quality of the datasets and lack of more wildfire data made assessing the diagnostics difficult, but the standardised deviance residuals exhibited some skewness, indicating a problem with the error model (probably due to non-homogeneity of variance for the different data sets).

This relationship was improved by removing data from McCorkhill block fires ($P < 0.001$, $R^2 = 0.85$, $n = 15$) and the resulting model is illustrated in Figure 10 by a dashed line. Based on the goodness-of-fit statistics, this GLM demonstrates the strongest relationship between woody fuel consumption and fireline intensity (Table 6) and reduces the degree of error when compared to the full dataset (Table 7).

Not surprisingly the model with the smallest level of error was that given by using the WFCP prescribed fires (*MAE* = 4.59, *RMSE* = 5.79 and *MAPE* = 11.43), followed closely by the controlled fire GLM where $I < 750$ kW m^{-1} (Table 7). The largest degree of error was found for the GLM considering the WFCP dataset and modelling consumption separately by size class (*MAE* = 12.46, *RMSE* = 14.5 and *MAPE* = 38.78).

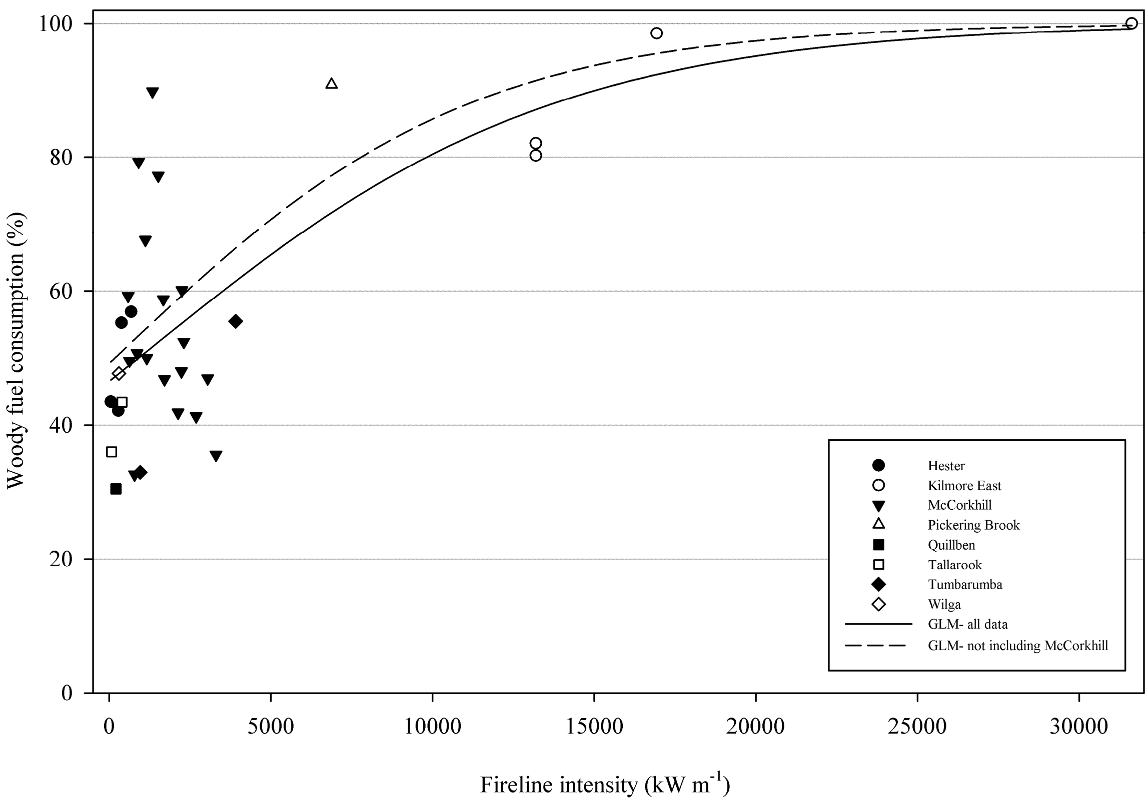

Figure 10. Woody fuel consumption (%) versus fireline intensity for all fires including wildfires.

Table 6. Parameter estimates for the generalised linear models for the proportion of woody fuel consumed.

Size class	Coefficient	Estimate	Standard error	P (> |t|)	R^2
		WFCP prescribed burn sites (Figure 6)			
	b_0	-0.6150	0.1851	0.016	0.52
	b_1	0.0013	0.0005	0.047	
		WFCP controlled burn sites by size			
1	b_0	0.2162	0.6328	0.744	0.19
	b_1	0.0022	0.0010	0.314	
2	b_0	-0.4212	0.4596	0.395	0.10
	b_1	0.0010	0.0010	0.460	
3	b_0	0.5015	0.2624	0.105	0.09
	b_1	0.0006	0.0007	0.477	
4	b_0	0.2185	0.3304	0.533	0.05
	b_1	0.0005	0.0009	0.617	
5	b_0	-1.6058	0.7763	0.107	0.40
	b_1	0.0032	0.0032	0.185	
		WFCP prescribed burn sites by size, constant slope[1] *(Figure 7)*			
1	b_0	0.4457	0.3041	0.152	0.43
2	b_{02}	-0.9617	0.3468	0.009	
3	b_{03}	-1.1851	0.3489	0.002	
4	b_{04}	-0.9184	0.3466	0.012	
5	b_{05}	-1.4254	0.3804	0.001	
	b_1	0.0014	0.0006	0.031	
		Controlled burns where I < 750 kW m^{-1} (Figure 9)			
	b_0	-0.6075	0.1678	< 0.001	0.57
	b_1	0.0013	0.0004	0.013	
		All fires (Figure 10)			
	b_0	-0.1416	0.1292	0.282	0.50
	b_1	0.0002	< 0.0001	< 0.001	
		All fires except McCorkhill (Figure 10)			
	b_0	-0.3220	0.147	0.0479	0.85
	b_1	0.0002	< 0.0001	< 0.001	

[1] $g(\mu) = b_0 + b_{02} \cdot S2 + b_{03} \cdot S3 + b_{04} \cdot S4 + b_{05} \cdot S5 + b_1 \cdot I$

where $S_2 \ldots S_5$ are dummy variables. If size class = 2, S_2 = 1, otherwise S_2 = 0; if size class = 3, S_3 = 1, otherwise S_3 = 0; etc.

Table 7. Model statistics for the proportion of woody fuel consumed.

Model	*n*	*MAE*	*RMSE*	*MAPE*
WFCP controlled burn sites (Figure 6)	8	4.59	5.79	11.43
WFCP controlled burn sites by size (Figure 7)	38	12.16	14.5	38.78
Controlled burns where I < 750 kW m^{-1} (Figure 9)	10	4.80	5.74	11.24
All fires (Figure 10)	33	10.53	13.8	20.37
All fires except McCorkhill (Figure 10)	15	7.12	9.00	13.96

n: number of observations.

4.6. Discussion

Our analysis supports the hypothesis that fireline intensity is a significant variable in determining woody fuel consumption and that woody fuel consumption increases with increasing fireline intensity. This result is consistent with the findings of McArthur and Cheney (1966), Burrows (2001) and Tolhurst *et al.* (2006). The relationship between woody fuel consumption and fireline intensity was strongest for the dataset which excluded the McCorkhill block. This may be due to unquantified variation in field sites and data collection techniques, including techniques to determine mean rates of spread that are critical for calculation of fireline intensity. Error was minimised by applying the GLM to the controlled fire dataset where the fireline intensity was < 750 kW m^{-1}. Within the range of conditions typically associated with prescribed burning, the positive relationship between woody fuel consumption and fireline intensity demonstrated in this study can provide guidance for forest and fire managers seeking to achieve particular woody fuel consumption outcomes. For example, prolonged heating due to consumption of woody fuels that may damage stems, tree boles and superficial roots and result in considerable volatilisation of nitrogen (O'Connell and McCaw, 1997) can be reduced by targeting conditions that support lower fireline intensity.

The findings of our study contrast with those of Hall (1991) and Taylor and Sherman (1996) who reported that woody fuel consumption decreases with increasing fire intensity. Hall argued that the faster rate of flaming consumption would reduce the duration of heat supplied to wood. While this may be true for low-intensity fires burning under marginal conditions, this assumption is questionable for heavy fuel loads and mass-ignition methods used by Hall (1991), where residence times were not a limiting factor (observed to be between 1 and 2 h). The assumption also fails to recognise that higher intensity fires tend to involve more fuels in combustion processes through feed-back mechanisms (McArthur and Cheney, 1966; Gill and Moore, 1990), hence for heavy fuel beds higher intensity would result in longer residence times. Contrasting findings are also likely to be due to different measures of fire intensity. While our analyses were based on fireline intensity, Hall (1991) determined fire intensity based on ignition method and so comparisons between studies may not be appropriate. Confusion surrounding usage of the term ‘fire intensity’ is relatively common (Keeley, 2009), and in this case, highlights the importance of clearly defining the measure of fire intensity in studies of fire behaviour.

More than 75% of woody fuels at our sites was comprised of material > 22.5 cm in diameter, reflecting the importance of larger size classes (4 and 5) in determining the proportion of woody fuels consumed at a site. Given this, the significant relationship between fireline intensity and the proportion of woody fuels consumed at a site can be attributed mostly to the consumption of large woody fuels. GLM analysis of the proportion of woody fuel consumption in each of the size classes showed that while fireline intensity was not significant in determining the consumption of woody fuels of any particular size class, the R^2 (0.40) for fuels > 50 cm in diameter (size 5) was the largest of all sizes and not considerably weaker than those of the *controlled burn* (R^2 = 0.52) or *all fires* (R^2 = 0.50) models presented in Table 6. The lack of significance may be attributed to the limited sample number and further analysis will be improved by using a broader dataset recording accurate consumption by size class. The relationship with large woody fuels may be due in part to larger proportional consumption of fine and small woody fuels (associated with higher fireline intensities) being required to ignite and consume fuels > 50 cm in diameter. Surface characteristics may also affect the ease of ignition; for example, deep cracks in the outer surface of a log may favour ignition by providing places where embers can lodge. At low fire intensities, the Hester 4 fire (53 kW m^{-1}) resulted in minimal (17%) consumption of woody fuels > 50 cm, possibly due to the limited energy quantity released by the fine, surface fuels.

The relationship between consumption of large, woody fuels and fireline intensity is important because large woody fuels contribute significantly to carbon release when consumed and have an essential role in contributing to biological diversity and ecosystem processes. Some rare and threatened insects such as the blind velvet worm are specific to logs > 50 cm in diameter (Mesibov and Ruhberg, 1991; Warren and Key, 1991) and hollow-nesting mammals such as the chuditch (*Dasyurus geoffroyii*) rely on large logs that contain hollows of a particular size and shape (Faunt, 1992; Williams and Faunt, 1997). Management of plants and animals reliant on woody debris habitat should address the negative effects of fires of high fireline intensity on post-fire woody fuel load, and consider the benefits of fires of low fireline intensity to minimise reduction of the woody fuel load, particularly for large woody fuels. Large-diameter fuels are less frequent and more scattered than smaller particles, making it important to employ sampling methods suitable for accurately assessing woody fuels throughout their full size range. Miehs *et al.* (2009) recommended that transect lengths to estimate woody fuel volume should be at least 450 m in recently burnt sites and 700 m in long unburnt sites to estimate woody fuel volume.

Only a small proportion (15%) of our data was collected under wildfire conditions of very high fireline intensity. In the case of the Kilmore East wildfire, there is considerable uncertainty in our estimate of fireline intensity because calculations are based on forward rate of spread of the fire which was not accurately measured, and was complicated by short- and long-distance spotting. Data analysis and the shape of the GLM are highly influenced by these wildfire data points. While only a small proportion of our data represent very high fireline intensity, the fuel consumption models developed in this study are broadly consistent with observations of researchers and fire managers across southern Australia (N.P. Cheney, CSIRO, pers.comm. 2010; A. Slijepcevic, DSE, pers.comm. 2010). Our calculation of fireline intensity for each fire was based on surface, fine fuels consumed in the active flaming front and did not include near-surface, elevated, bark and canopy fuels due to uncertainties quantifying their relative fuel load and contribution to the active flaming front. Because of this, our calculations are likely to have underestimated fireline intensity, particularly for the Pickering Brook and Kilmore East wildfires where the fuel load consumed during flaming consumption was likely to have been higher.

The CONSUME models for predicting woody fuel consumption in North America are driven mostly by fine and woody fuel loads, and duff and woody fuel moisture content. The CONSUME model for activity fuels (logging slash) incorporates the findings of Hall's (1991) study where high-intensity fires consume less woody fuel than lower-intensity fires (Prichard *et al.*, 2005; Ottmar *et al.*, 2006). In the BURNUP model, also used in the United States, woody fuel consumption is driven mostly by woody fuel load (Albini and Reinhardt, 1995) and incorporates the positive effect of fire intensity and residence time on the consumption of woody fuels. Hollis *et al.* (2010) reported a *MAE* between 12% and 18% for the CONSUME models when applied to Australian southern eucalypt fuels and between 19% and 45% for the BURNUP model depending on whether the fuels were modified. Our analyses show that, in Australian southern eucalypt forests, a woody fuel consumption model that is positively affected by fireline intensity (i.e. the fuel consumed in the active flaming front as well as rate of fire spread) may be more accurate and reduce error when predicting woody fuel consumption compared to applying the CONSUME or BURNUP models or a simple model (Gould and Cheney, 2007) which assumes 50% of the woody fuel load at a site is likely to be consumed under most fuel and fire scenarios. Using a model based entirely on fireline intensity resulted in improved levels of error with a *MAE* between 5% and 11% depending on which model was used (Table 7). Many of the variables correlated with woody fuel consumption in our dataset also influence fireline intensity, including fine fuel moisture, wind speed and FFDI. These variables are auto-correlated in our dataset and their relative effect on woody fuel consumption is difficult to isolate. Further analysis and additional data from well-designed experiments would assist in better defining these complex relationships.
A better understanding of the relationship between woody fuel consumption and fireline intensity would be achieved by increasing the dataset to include additional fires with medium and high fireline

intensity. Ideally, fuel consumption should be quantified by pre-fire and post-fire assessments, but this is difficult to achieve in cases of unplanned fire, and high-intensity fire experiments are both costly and difficult to implement. Opportunistic sampling and data collection at locations burnt by high-intensity wildfire is reliant on the identification of comparable burnt and unburnt pairs of sites matched for pre-fire biogeographic and fuel hazard characteristics. Wildfires will therefore remain an important but fortuitous source of data. Long-term monitoring of changes to woody fuel volume and condition is being undertaken as part of the *Forestcheck* project in the jarrah forest of Western Australia (Abbott and Burrows, 2004) and is expected to provide valuable insights into the effect of fires on the dynamics of woody fuel.

Climate change has the potential to affect fire regimes by modifying fire intensity. It is well established that fireline intensity influences fire patchiness and the proportion of fine fuels consumed (Hargrove *et al.*, 2000; Gould *et al.*, 2007). The two GLMs presented in this manuscript provide woody fuel consumption model options for studies assessing the potential impact of climate change on CWD in Australian southern eucalypt forests. Analyses based on our dataset suggest that changes to fireline intensity will affect woody fuel consumption and subsequently carbon release, with longer and more severe (drier) fire seasons leading to increased consumption of woody fuels. For example, increased occurrence of summer bushfires would tend to increase the proportion of woody fuel consumed and hence reduce the quantity of woody fuel over time. Woody fuels are an important carbon sink and provide habitat for a diverse biota in many southern Australian eucalypt forests, making reductions of woody fuels, particularly large logs, potentially detrimental to conservation. This may be moderated to some extent, at least in the short term, by contributions of woody fuel resulting from post-fire branch fall, tree mortality and fall of snags, but further research is needed to identify the factors that influence the post-fire accumulation of downed woody timber and to quantify their effects.

4.7. Conclusions

Data from well-instrumented experimental and prescribed fires and high intensity wildfires support the hypothesis that woody fuel consumption increases with increasing fireline intensity in eucalypt forests of southern Australia. Two GLMs describing woody fuel consumption as a function of fireline intensity were developed, one applicable to the prescribed or controlled fire environment (with fireline intensities typically < 750 kW m^{-1}) and the other to the full range of fireline intensity. The prescribed burning model produced the best fit and lowest error statistics, partially because uncertainties in pre-fire fuel loading and fireline intensity were minimised by the experimental methods. Including interaction between variables and additional wildfire data representing medium and high fireline intensities may improve analysis and confidence in this hypothesis.

The positive relationship between woody fuel consumption and fireline intensity may be a valuable consideration for forest and fire managers when preparing prescribed fire prescriptions. Specified woody fuel consumption outcomes as well as levels of soil and stem heating may then be achieved by targeting conditions that result in an appropriate fireline intensity. The woody fuel consumption models developed will also assist the assessment of climate change impacts on CWD in Australian southern eucalypt forests.

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Chapter 5.

Behind the flaming zone: Predicting woody fuel consumption in eucalypt forest fires in southern Australia

5.1. Acknowledgements and contributions

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Jennifer Hollis was the primary author however contributions were made by several co-authors. Stuart Matthews[1,2,3] assisted with statistical techniques, particularly the principal components analysis. Wendy Anderson[4] assisted data analysis and statistical techniques, particularly generalised linear modelling. Miguel Cruz[1] assisted result interpretation. Neil Burrows[5] contributed data collected at Project Aquarius. All co-authors assisted manuscript review.

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5.2. Abstract

Pre-fire woody fuel (diameter > 0.6 cm) structure and its consumption by fire were measured at experimental/prescribed fires and high intensity wildfires in eucalypt forests in southern Australian in order to better understand and model the dynamics of woody fuel consumption. Two approaches were used in model development: (1) a fire or plot level analysis, based on a dataset which includes the proportion of the pre-fire woody fuel load consumed at each fire; and (2) a stage level analysis, based on a dataset where woody fuel consumption was measured at a woody fuel particle level (i.e. pre-fire and post-fire diameter). For the plot level analysis a generalised linear model (GLM) approach identified the Forest Fire Danger Index (FFDI) as the best predictor of the proportion of woody fuel consumed, with an R^2 of 0.58 and mean absolute error of 10%. The stage level analysis recognised the various combustion stages through which a burning woody particle would pass, but failed to develop an accurate model that predicted the ignition, partial and full consumption of woody fuels based on fuel, fire behaviour and environmental variables. Analysis showed that consumption of woody fuel particles is highly variable and that variation in fire behaviour potentially has a greater impact on woody fuel consumption, than does variation in fuel characteristics (e.g. state of decay, fuel suspension and interactions with other fuel particles). The FFDI GLM provides forest and fire managers with a tool to manage woody fuel consumption objectives and may assist fire managers with forecasting post-frontal fire behaviour. The FFDI GLM may also assist forest and fire managers to better meet land management goals and to comply with air quality and emission targets.

5.3. Introduction

In Australian eucalypt forests, fire management is driven by the need to minimise the impact of wildfires on human life and property, reduce the occurrence and severity of large wildfires on natural values and protect, regenerate and conserve biota (Burrows and Abbott, 2003; Forest Fire Management Group, 2007). To achieve fire management objectives, prescribed fire programs are conducted throughout Australian southern eucalypt forests that result in the combustion and removal of woody biomass.

Woody fuels (diameter, d > 0.6 cm), which are also referred to as coarse woody debris (CWD) in many ecological studies, have an essential role in Australian forest ecosystems supporting many ecological functions and processes and contributing to biological diversity (Harmon *et al.*, 1986; Grove and Meggs, 2003; Woldendorp and Keenan, 2005). Consumption of woody fuels in forest fires also contributes to several important features relating to fire behaviour, fire suppression and firefighter safety (Rothermel, 1993; Gould, 2003; Potter *et al.*, 2004) as well as greenhouse gas and smoke emissions (Pyne *et al.*, 1996; Ottmar *et al.*, 2009). Therefore, the ability to accurately predict woody fuel consumption is essential in the skilful planning of prescribed fires (Fahnestock and Agee, 1983; Brown *et al.*, 1985). Fire prescriptions are often complicated due to the need to accommodate trade-offs between conflicting management objectives (e.g. habitat and carbon management versus fuel load reduction) and require a detailed knowledge of woody fuel characteristics (Martin *et al.*, 1979; Ottmar *et al.*, 2001; Beese *et al.*, 2006). Accurate prediction of woody fuel consumption is also essential for managing the long-term effects of wildfire and prescribed fire programs on woody fuels.

The proportion of woody fuel burnt in eucalypt forest fires in southern Australia varies a great deal and is influenced by a myriad of variables (Sullivan *et al.*, 2002; Tolhurst *et al.*, 2006; Hollis *et al.*, 2011), many of which are correlated. For the most part, factors influencing woody fuel consumption have been identified; however, their relative effect on consumption in the southern eucalypt forests of Australia remains poorly established.

Hollis *et al.* (2010) tested various models (Albini and Reinhardt, 1995; Prichard *et al.*, 2005; Gould and Cheney, 2007) for application in Australian southern eucalypt forests. Models developed for forest types in the United States yielded large errors, whereas a simple model that assumes that 50% consumption of woody fuels at a site irrespective of burning conditions (Gould and Cheney, 2007) resulted in the lowest errors (mean absolute error of 11.1% and bias of 0.12%). While this model minimised error for the southern eucalypt dataset, this simple constant value does not help to explain deviations where woody fuel consumption has been observed to be particularly high (> 75%) or low (< 25%) due to variability in burning conditions.

Hollis *et al.* (2011) investigated the relationship between fireline intensity and woody fuel consumption across different Australian eucalypt forest fires and found that fireline intensity was a significant variable in determining the proportion of woody fuel consumed by fire and that the proportion of woody fuel consumed by fire increases with increasing fireline intensity. While Hollis *et al.* (2011) provide a generalised linear model that can be used to predict woody fuel consumption the use of a model based on fireline intensity would require the estimation of fine fuel consumption and rate of spread. The need to estimate these quantities can introduce further error and uncertainty in the prediction of woody fuel consumption so an alternative model is sought to meet the needs of fire managers.

The purpose of this study was to develop an empirically based model for woody fuel consumption in Australian southern eucalypt forest fires using data collected under a wide range of burning conditions at experimental/prescribed fires and wildfires.

5.3.1. Combustion type and phases

Woody fuels are chemically complex substances, composed mostly of cellulose, hemicellulose and lignin (Browning, 1963; Brown and Davis, 1973; Luke and McArthur, 1977). During a forest fire, woody fuels react with oxygen, through the oxidation process of combustion, to form carbon dioxide, water vapour and produce large amounts of heat (Byram, 1959). Combustion efficiency can be described as the overall oxidation capacity or conversion of carbon to carbon dioxide under a given set of weather and fuel conditions (Ward and Hardy, 1991; Ward, 2001). Complete combustion results in the production of water and carbon dioxide; however, in forest fires the combustion of woody material is rarely complete or fully efficient. As a result of incomplete or inefficient combustion, carbon monoxide is the major carbonaceous product (Ward, 2001).

Due to their larger size and thermal inertia, woody fuel ignition lags behind the leading edge of the flame front. This time lag will depend on the fire intensity and the characteristics of the woody fuel, for example the moisture content, presence of fissures or bark and chemical composition. Ignition can occur seconds after the passage of the ignition interface or minutes after the passage of the active flame front due to post-frontal combustion of compacted litter, woody and duff fuels (Cheney, 1990; Finney, 1999). Woody fuels undergo three phases of combustion in a moving forest fire. In both prescribed fires and wildfires, these phases compete for available fuel and often exist simultaneously, contributing to a diversity of combustion products (Byram, 1959; Brown and Davis, 1973; Ward, 2001; Carvalho *et al.*, 2002).

5.3.1.1. Phase 1: drying and preheating

The drying and preheating phase starts as the flame front approaches woody fuel particles. At this stage the surface temperature of a woody fuel particle is raised mostly through radiation (Byram, 1959; Brown and Davis, 1973; Pagni and Peterson, 1973). The magnitude of preheating will depend essentially on flame size. Simultaneously, as the flaming front approaches, advection from the plume and direct flame contact will further raise temperature and drive off moisture from the woody fuel surface and generation of flammable hydrocarbon gases begins (Albini and Reinhardt, 1995; Silvani and Morandini, 2009). If the source of heat is withdrawn, drying and preheating will not be self-sustaining (Luke and McArthur, 1977). This phase may be referred to as ‘ignitability’ or ‘ignition delay time’: the time before ignition when heat without flame is applied to fuel (Anderson, 1970). Others have referred to it as the ‘ignition time’ which also includes the period of initial combustion (Gill *et al.*, 1978).

5.3.1.2. Phase 2: ignition and flaming combustion

Ignition of hydrocarbon gases supplies additional heat and links the preheating phase with the next phase of flaming combustion (Byram, 1959; Brown and Davis, 1973; Gill *et al.*, 1978). Flames propagate through the fuel bed and become attached to the outer surface of woody fuels immersing them into a flaming environment (Clements and Alkidas, 1973; Albini and Reinhardt, 1995). Important to woody fuel ignition is the concept of flame front residence time. Flame front residence time, or reaction time, is used to describe the duration of flaming combustion at a fixed location on the fuelbed (Fons *et al.*, 1962; Nelson, 2003). This will determine the time a woody fuel particle spends immersed in the flame. When the combination of duration and heating is sufficient to raise the mass of fuel to ignition temperature (about 320°C is usually assumed (Sussot, 1984)) and fuel/air ratio is appropriate, then woody fuels will ignite (Clements and Alkidas, 1973). Once ignited, burning woody fuels produce water vapour and carbon dioxide, releasing heat and providing energy to bring additional fuel to ignition (Anderson, 1970; Clements and Alkidas, 1973; Shafizadeh *et al.*, 1977; Pyne *et al.*, 1996). This reaction is self-sustaining (Luke and McArthur, 1977) and in the absence of oxygen, pyrolysis works to break down fuels (Ward, 2001). Pyrolysis may follow one of two different pathways depending on fuel characteristics and temperature conditions. Under high temperatures (between 280-340°C) pyrolysis results in the production of levogluosan which is particularly volatile (Shafizadeh, 1968; Ward, 2001). Under low-temperature conditions (between 200-280°C) pyrolysis results in the dehydration of cellulose and the formation of char (Byram, 1959; Shafizadeh, 1968; Ward, 2001; Benkoussas *et al.*, 2007).

5.3.1.3. Phase 3: smouldering and glowing combustion

In this phase, when the vapours produced earlier have been consumed (Luke and McArthur, 1977), the charcoal deposited on fuel is burnt at a relatively slower rate by surface oxidation in glowing combustion (Byram, 1959; Brown and Davis, 1973; Sussot *et al.*, 1975). If heat is conserved on the fuel’s reacting surface, glowing combustion will continue (Drysdale, 1998). After the fuel surface has released enough volatile matter, smouldering combustion proceeds (Carvalho *et al.*, 2002). The smouldering combustion phases can produce large quantities of particulates and carbon monoxide (Ward, 2001). Residual charcoal will continue to burn away leaving only mineral ash (Luke and McArthur, 1977) until the point of extinction when the combustion process is no longer able to be sustained (Pyne *et al.*, 1996). Combined, these phases influence the ‘flammability’ of woody fuels (Anderson, 1970).

5.3.2. Variables affecting woody fuel consumption

Published studies, both laboratory and field based, were reviewed to identify variables influencing consumption of woody fuels, and these are summarised in 13 groups in Table 1.

Woody fuel moisture content has been reported as being one of the most important variables influencing woody fuel ignitability, rate of combustion and the amount of consumption (Byram, 1959; Gill *et al.*, 1978; Walker, 1981; Harrington, 1982; Chandler *et al.*, 1983; Albini and Reinhardt, 1997). Woody fuel moisture content is one of the primary variables driving many woody fuel ignition and consumption models (Sandberg, 1985; Albini and Reinhardt, 1997; Call and Albini, 1997; Prichard *et al.*, 2005). Natural variation of woody fuel moisture content, both within a fuel particle and between fuels is particularly large. Tolhurst *et al.* (2006) reported a large variation in the moisture content from the exterior to the core of downed eucalypt woody fuel. Byram (1959) reported a large variation between woody fuels, for example the fuel moisture content of fine twigs may range from as little as 2% to over 200% in large, punky (decayed) logs after prolonged rainfall. Variability in woody fuel moisture makes modelling and defining the relationship between woody fuel consumption and moisture content extremely difficult (Brown *et al.*, 1985; Tolhurst *et al.*, 2006). For example, Brown *et al.* (1985) failed to find a relationship between woody fuel moisture characteristics and woody fuel consumption. McCaw *et al.* (1997) were also unable to find a clear relationship between the proportion of woody fuel consumed within individual fractions of the fuel bed and their respective moisture contents in thinning slash in regrowth stands of karri (*Eucalyptus diversicolor*).

The lack of a clearly established link between the moisture content of woody fuels and the forward spread of a moving fire (McArthur, 1967; Rothermel, 1972; Gould *et al.*, 2007a), coupled with the time consuming and onerous nature of sampling (Fosberg *et al.*, 1981; Harrington, 1982), has discouraged collection of woody fuel moisture data in Australian fire behaviour studies. This limits our understanding and ability to investigate the effect of moisture on woody fuel consumption.

While some variables including pre-fire fuel load and fire size are required to calculate the amount of woody fuel consumed in a fire, and are expected to be correlated with this total value, it is not clear whether they have a causal effect on the proportion (or fraction) of fuel consumed (Smithson, 2000). For example, throughout North America it has been widely reported that total woody fuel consumption is strongly correlated with pre-fire fuel loadings, but this is not necessarily true of percentage consumption. This includes studies by: Norum (1976) in experimental fires in mature Douglas-fir (*Pseudotsuga menziesii*) and western larch (*Larix occidentalis*) stands; Quintilio *et al.* (1977) in Canadian upland jack pine (*Pinus banksiana*); Brown *et al.* (1985) in slash and non-slash prescribed fires comprising mixture of western larch, Douglas-fir, ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and grand fir (*Abies grandis*); Quintilio *et al.* (1991) in spring fires in a semimature trembling aspen (*Populus tremuloides*) stand in central Alberta; Prichard *et al.* (2006) in prescribed burns of ponderosa pine forests; Wright and Prichard (2006) in prescribed fires in big sagebrush ecosystems and most recently de Groot *et al.* (2009) in Canadian boreal forests.

Several studies have reported that higher pre-fire woody fuel loads will increase interaction between burning fuel elements and influence the rate of burning and heat release of a fire (Byram, 1959; Shafizadeh *et al.*, 1977; Shafizadeh, 1978; Albini and Reinhardt, 1997). Brown *et al.* (1985) reported that the proportion of consumption of woody fuels with a diameter less than 7.5 cm, is affected by pre-fire fuel loading where consumption was consistently high for pre-fire fuel loads over 22.4 Mg ha^{-1} and considerably less for lighter loads. This supports theory driving the process-based woody fuel consumption model BURNUP (Albini and Reinhardt, 1995), which yielded the lowest level of error when used with large (heavy) modified fuel loads resulting from clearcut operations (Hollis *et al.*, 2010). McArthur and Cheney (1966) suggested that the burnout time or residence time of a fire will depend in part on the quantity of fuel that is available for combustion. While the available fuel may only be a fraction of the total fuel load, the quantity of available fuel will generally increase with increasing woody fuel load through feedback mechanisms. An increase in fuel available for combustion will then support a longer fire duration, more effective heat transfer and increased rate of drying (McArthur and Cheney, 1966), which will further increase the amount of fuels susceptible to ignite.

Table 1. Variables that have been identified as affecting combustion processes and consumption of woody fuels during forest fires (in chronological order).

Author/s	Species / forest type	Country	FMC	*Disturbance*	*Fine fuels*	*Arrangement*	*Wood density*	*Decay*	*Diameter*	*Residual char*	*Woody load*	*Bark*	*Fire size*	*Fire intensity*	*Environment*
Byram (1959)	General forest fuels	US	x				x		x		x				x
McArthur and Cheney (1966)	Thinning slash, silvertop ash (*E. seiberi*)	Au							x		x			x	
Hough (1968)	Slash-longleaf pine	US	x												
Anderson (1969)	Mixed conifer forest	US							x						
Anderson (1970)	General forest fuels	US					x								
Brown and Davis (1973)	General forest fuels	US					x			x			x		
Clements and Alkidas (1973)	Laboratory experiments, white fir (*Abies concolor)*	US							x						
Sussott *et al* .(1975)	Natural forest fuels	US						x							
Norum (1976)	Larch (*Larix occidentalis*) / Douglas-fir stands (*Pseudotsuga menziesii*)	US	x		x			x	x						
Martin *et al.* (1979)	United States forest fuels	US							x						
Luke and McArthur (1977)	Australian forest fuels	Au			x										
Shafizadeh *et al* .(1977)	Laboratory experiments, mixed conifer species	US									x				
McRae (1980)	Mixed conifer forest slash	Ca													x
Walker (1981)	General Australian vegetation	Au	x				x								
Harrington (1982)	Ponderosa pine	US	x												
O'Loughlin *et al.* (1982)	Mountain gum (*E. dalrympleana*), *E. pauciflora*, narrow-leaf peppermint (*E. radiata*), *E. dives* & *E. Delegatensis*	Au							x						
Chandler *et al.* (1983)	General forest fuels		x						x						
Fahnestock and Agee (1983)	Mixed conifer forest	US												x	
Sandberg and Ottmar (1983)	Douglas-fir and western hemlock (*Tsuga heterophylla*) slash	US	x												
Brown *et al.* (1985)	Mixed conifer	US	x	x				x	x						
Sandberg (1985) [a]	Douglas-fir and western hemlock	US	x												
Ottmar (1987)	Logging slash in red alder (*Alnus rubra*)	US	x	x											
Stocks (1987)	Immature jack pine	CA	x												
Kauffman and Martin (1989)	Mixed conifer forests	US						x							x
Reinhardt *et al.* (1989)	Mixed conifer logging slash	US	x												
Anderson (1990)	Laboratory experiments, mixed conifer species	US	x			x			x						
Cheney (1990)	Silvertop ash (*E. sieberi*)	Au	x						x						
Ottmar *et al*. (1990) [a]	Douglas-fir and western hemlock clearcut units	US	x												
Buckley and Corkish (1991)	Heaped and broadcast residues in thinned eucalypt regrowth	Au		x											
Hall (1991)	Mixed conifer forest	US												x	
Hamilton *et al.* (1991)	Stringybark (*E. obliqua)*	Au											x	x	

Author/s	Species / forest type	Country	FMC	*Disturbance*	*Fine fuels*	*Arrangement*	*Wood density*	*Decay*	*Diameter*	*Residual char*	*Woody load*	*Bark*	*Fire size*	*Fire intensity*	*Environment*
Hawkes and Taylor (1993)	Mixed conifer forest	Ca						x							
Burrows (1994)	Jarrah forest (*E. marginata)*	Au							x						
Albini and Reinhardt (1995) [a]	Natural forest fuels	US				x			x		x				
Taylor and Sherman (1996)	Canadian forests	Ca												x	
Albini and Reinhardt (1997) [a]	Natural forest fuels	US	x									x			
Call and Albini (1997) [a]	Immature jack pine	US	x						x						
Lawson *et al.* (1997)	Boreal forest	Ca													x
McCaw *et al.* (1997)	Thinning slash, karri (*E. diversicolor*)	Au			x										
Finney (1999)	General forest fuels	US			x										
Tolhurst and Cheney (1999)	Victorian eucalypt forests	Au						x							
Tinker and Knight (2000)	Lodgepole pine	US													x
Burrows (2001)	Jarrah forest	Au							x					x	x
Marsden-Smedley and Slijepcevic (2001)	Stringybark	Au	x												
Carvalho *et al.* (2002)	Laboratory experiments, *(Machaerium anguwtifolium)*	Br													x
Skinner (2002)	Forests of southwest Oregon and California	US						x							
Sparks *et al.* (2002)	Shortleaf pine (*Pinus echinata*)	US												x	
Sullivan *et al.* (2002)	Australian eucalypt forests	Au					x								
Finney *et al.* (2003)	General forest fuels	US												x	
Knapp *et al.* (2005)	Mixed conifer forest	US	x				x	x							x
Prichard *et al.* (2005)[a]	Mixed forest fuels	US	x						x					x	
Beese *et al.* (2006)	Mixed conifer forest	Ca	x											x	x
Prichard *et al.* (2006) [a]	Ponderosa pine	US			x										
Schroeder *et al.* (2006) [a]	Lodgepole pine , spruce and Douglas-fir	Ca	x								x				
Tolhurst *et al.*(2006)	Mountain gum and narrow-leaf peppermint	Au	x					x	x					x	
Wright and Prichard (2006)	Big sagebrush (*Artemisia tridentate*)	US	x										x		x
Benkoussas *et al.* (2007)	Wildland fuels								x						
Youngblood *et al.* (2008)	Mixed conifer forest	US												x	
de Groot *et al.* (2009)	Boreal forests	CA												x	x
Uzoh and Skinner (2009)	Mixed conifer forest	US						x							

[a] Usage of variable in woody fuel consumption model. *Country*: Au: Australia; US: United States; Ca: Canada; Br: Brazil. *Variable names:* FMC: woody fuel moisture content; Disturbance: forest management and disturbance effects; Fine fuels: surface and near-surface fine fuels; Arrangement: woody fuel spacing, arrangement and continuity; Wood density: wood density, species and chemical composition; Decay: woody fuel decay; Diameter: woody fuel diameter; Woody load: pre-fire woody fuel load; Bark: presence or absence of bark; Fire size: fire size and patchiness; Fire intensity: fire intensity and duration; Environment: environmental conditions including weather and seasonally affected variables such as temperature, relative humidity, precipitation and wind speed.

5.4. Methodology

The Woody Fuel Consumption Project (WFCP) began in 2007 with the objective being to better understand and model woody fuel consumption in eucalypt forests in southern Australia and included sites in several different eucalypt forest types (Figure 1).

Woody fuel consumption was assessed within prescribed fires in herb-rich foothill forest (*E. globulus* and *E. viminalis*) at Tallarook State Forest in Victoria and dry sclerophyll jarrah forest (*E. marginata*) at Wilga, Quillben and Hester blocks in south-west Western Australia (Figure 1). Woody fuel consumption was also measured opportunistically at two locations previously burnt by high intensity bushfires; the Kilmore East wildfire on Black Saturday 7th February 2009 in northern-central Victoria (Cruz *et al.*, 2010) and the 2005 Pickering Brook wildfire in Western Australia (Cheney, 2010). To complement this dataset, data from two experimental studies of woody fuel consumption were used: (1) in wet sclerophyll forest of *E. dalrympleana* and *E. radiata* in the Maragle State Forest, near Tumbarumba, New South Wales (Tolhurst *et al.*, 2006) and (2) in jarrah forest at McCorkhill block burnt in a study of high intensity forest fire behaviour (Project Aquarius) in south-west Western Australia (Gould *et al.*, 1996). All sites were natural forest systems influenced by historical selective timber harvesting except for the Wilga WFCP site in Western Australia which had been recently selectively harvested for sawlogs. A summary of characteristics for each of the sites are included in Table 2.

5.4.1. Assessment of woody fuel load and consumption

Methodology to assess wood fuel load and proportional consumption at WFCP sites has been described in detail by Hollis *et al*. (2010) and Hollis *et al*. (2011). The following methodology is therefore a brief summary.

At WFCP sites, Van Wagner’s (1968) line intersect method was used to determine pre-fire and post-fire woody fuel load for size class 1 fuels (0.6-2.5 cm in diameter) where the quadratic mean diameter (QMD) was assumed to be the midpoint of the size class (i.e. 1.55 cm). Brown’s (Brown, 1974) woody material formula was used to determine pre-fire and post-fire woody fuel load for all other fuels greater than 2.5 cm in diameter. Transect lengths were mostly 400 m, except at Hester where they ranged from 190 to 400 m. Data from the other field studies was re-worked into the five diameter size classes adopted by the WFCP (Hollis *et al.*, 2010) which approximate the lag time fuels used in the United States (Fosberg, 1970).

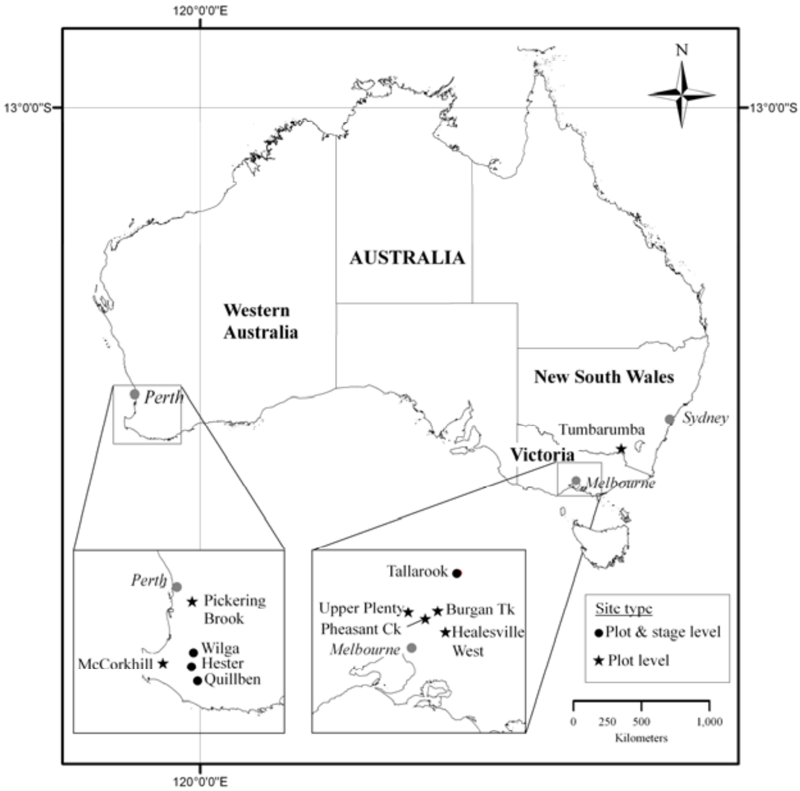

Figure 1. Location of field sites across southern Australia.

Table 2. Summary of site characteristics, adapted from Hollis *et al.* (2010).

Site	State	Year/s of study	Forest & primary species	Australian climatic zone[a]	Average annual rainfall (mm)
WFCP - Wilga	Western Australia	2007	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	830
WFCP - Quillben	Western Australia	2007	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	1012
WFCP - Hester	Western Australia	2008	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	830
WFCP - Tallarook	Victoria	2008-2009	Herb rich foothill forest, *E. globulus*, *E. viminalis*	Temperate (no dry season, warm summer)	595
Pickering Brook	Western Australia	2005-2009	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and hot summer)	1097
Project Aquarius	Western Australia	1983	Dry sclerophyll, *E. marginata*	Temperate (distinctly dry and warm summer)	1109
Tumbarumba	New South Wales	2004	Wet sclerophyll, *E. dalrympleana, E. radiata*	Temperate (no dry season, warm summer)	975
Kilmore East	Victoria	2009-2010	Herb rich foothill forest, mixed eucalypt	Temperate (no dry season, warm summer)	between 657-705

[a] Stern *et al.* (2000).

At McCorkhill, pre-fire and post-fire size class 1 fuels were assessed using destructive sampling techniques (Catchpole and Wheeler, 1992). Pre-fire assessment of size class 1 fuels at Pickering Brook were also based on destructive sampling methods, however no post-fire sampling was carried out. Visual inspection, coupled with the results from other summer wildfires in dry eucalypt forests supported the assumption that all post-fire size class 1 fuels were consumed. For all other fuels greater than 2.5 cm in diameter the line intersect method (Van Wagner, 1968) or Brown's woody material formula (Brown, 1974) were used to determine pre-fire and post-fire woody fuel load. Average transect length for McCorkhill was 584 m and varied from 60 to 1620 m, while transect length at the Pickering Brook fire site was 200m.

At the Kilmore East fire sites, a comparative pair of burnt and unburnt sites was used to determine woody fuel consumption. This was done by selecting unburnt sites that best represented pre-fire conditions at four sites burnt during the Black Saturday fires, namely Burgan track, Healesville West, Upper Plenty and Pheasant Creek sites. Site characteristics including forest and fuel type, stand structure, fuel age, slope and aspect were matched as closely as possible. It was then assumed that the woody fuel load at the unburnt site was equivalent to the pre-fire woody fuel load at the corresponding burnt site. Transect length at Kilmore East fire sites was 400 m.

For each plot, differences in pre-fire and post-fire woody fuel load were grouped by size class and the proportion of woody fuel consumed (pw_W) was determined based on pre-fire fuel load. For the present study we model the proportion of woody fuel consumed rather than the quantity of fuel consumed, to allow the effect of fuel load on consumption to be identified.

5.4.2. Woody fuel characterisation

All woody fuels (d > 0.6 cm) encountered along each transect were characterised by scoring the degree of decay, amount of bark, arrangement and relationship with other fuels, amount of suspension and degree of charring (Table 3, Appendix A). Each fuel was photographed pre-fire and post-fire and where possible, wood species was also indentified.

5.4.3. Woody fuel moisture content and woody density

At each WFCP prescribed fire site moisture content was determined from random sample of woody fuels representing a wide variety of fuel characteristics. Disks approximately 5 cm wide were cut from each log or branch using a chainsaw, measured for diameter and labelled with an identifying number. While on site, each piece of woody fuel was characterised using scores for decay, bark, arrangement, suspension and charring described in Section 2.2. (Table 3, Appendix A). Where possible, the species of wood was also indentified. Disks were photographed, put into sealed plastic bags and placed in a cool, sheltered position to prevent dehydration.

In the workshop each disk was cut into vertical and horizontal sections approximately 5 cm wide and then cut into cubes approximately 5 cm x 5 cm x 5 cm (Figure 2). Each of these sub-sampled cubes was labelled to show its position (top, bottom, left or right) and profile (outer to inner) in the disk. Cubes were weighed (wet-weight) and then dried at 105ºC for at least five days (Matthews, 2010) then re-weighed to determine fuel moisture content (FMC) on a oven-dry basis where FMC= (wet-weight - dry-weight)/dry-weight. Cubes were subsequently used to determine wood density ($Density_{W}$) using the submersion method (Technical Association of the Pulp and Paper Industry, 1994). The average woody FMC of each disk was calculated as the mean of the various cubes. This was considered to be the woody particle’s average moisture content. FMC for each size class was then calculated by partitioning fuel particles according to their size and calculating the average value. The average FMC for a plot (FMC_{W}) was then determined by averaging each woody fuel size class at a plot.

Variation in moisture content within each woody fuel sample was visualised as a polar contour plot using Matlab R 2010a software (The MathWorks Inc., TMWI, 2010). Contours were calculated using two dimensional interpolation assuming that the log was round and that the wood-cube samples were on a 5 cm x 5 cm grid (Tate, 2010, personal communication).

Reliable measurements of woody fuel moisture content were not available for experimental fires at McCorkhill or wildfires at Pickering Brook and Kilmore East.

Table 3. Scores used to characterise the degree of woody fuel decay, amount and type of bark, arrangement and relationship with other fuels, suspension and degree of charring.

Characteristic	0	1	2	3	4
Decay[a]	• Solid, cross-section maintaining original shape • Bark intact and mostly attached • Minor branches, twigs or stems may be present and intact • Original colour • Sapwood hard, brown • Fissures and cracks absent • Heartwood hard	• Solid with cracks present, slight fissuring (1-2 cm deep, 8-10 cm apart) due to age • Bark usually absent • Possible branch stubs, no twigs or stems • Sapwood can be scuffed by boot, grey • Original colour fading • Heartwood predominantly hard	• Surface decaying with cracks and fissuring (3-4 cm deep) due to age • Bark absent • Sapwood is predominantly decayed and crumbly, easily broken away by hand • Brach stubs absent • Heartwood can be broken away • Partial collapse is present • Maintaining size integrity	• Surface decaying with cracks and fissuring (5-7 cm deep) due to age • Furrows may be present. • Bark absent • Sapwood is decayed and missing on parts of the log • Loss of shape and collapse is present, possibly some solid wood present • Original colour faded	• Log has decayed and collapsed due to age • Bark and Sapwood are completely absent • Less than 25% of original shape remains • Heartwood is rotten, can be easily kicked away. • Log is predominantly blocky, punky, brown decayed wood • Live vegetation may be growing out of decayed wood
Bark[b]	• No bark present	• Very little bark is present • Smooth trunk • Bark is tightly held • No ribbons or bark • Bark may be charred from pervious fire and is tightly held on whole trunk	• A limited amount of bark is present • A large proportion of the log may be charred • Fibrous bark is held tightly to the log • Tight bark is long unburnt	• Significant amounts of bark are present • Less than 50% of the log may be charred • The are significant amounts of bark loosely held • Bark is fibrous and stringy or ribbony	• Very large amounts of bark are present • Large amounts of loosely held bark • Bark is fibrous or stringy • Bark is weakly attached or easily dislodged • Does not occur on platy or smooth gum species
Arrangement	• Predominantly discontinuous fine fuel layer • Bare earth with little or no fine fuels (< 0.6 cm)	• Predominantly continuous fuel layer • Minimal layer of fine fuels touching fuel • Fuel positioned in	• Continuous, established layer of fine fuels surrounding fuel • Fuel positioned in isolation with no same	• Continuous, established layer of fine fuels surrounding fuel • Fuel positioned touching or within it’s diameter’s	• Continuous, established layer of fine fuels surrounding the fuel • Fuel positioned touching and/or within it’s

Characteristic	0	1	2	3	4
	touching • Fuel positioned in isolation with no woody fuels touching or close by	isolation with no woody fuels touching or close by	size class woody fuels touching	distance from another woody fuel of the same size or smaller	diameter's distance from other woody fuels of the same size class or greater • Commonly occurs in silvicultural logging areas with piles or heaps of slash residue
Suspension	• Fuel completely grounded • The full length of the fuel is in contact with the ground	• Fuel mostly grounded • Parts of the fuel are elevated and are not in contact with the ground; however most of the log is in contact with the ground	• Fuel mostly elevated on support points • Mostly less than 10 cm above the ground (Buckley and Corkish, 1991)	• Fuel elevated on support points • Mostly greater than 10 cm above the ground (Buckley and Corkish, 1991)	N/A
Charring	• Fuel has no char	• Fuel is slight charred. • A thin layer of charcoal covers part of the fuel	• Fuel is heavily charred. • A thick residual layer of charcoal covers the majority of the fuel	N/A	N/A

[a] Adapted from Tolhurst *et al.* (2006), Maser *et al.* (1988) and Whitford and Williams (2001).
[b] Adapted fuel hazard assessment techniques from McCarthy *et al.* (1999) and Gould *et al.* (2007b).

Figure 2. Wood disks were cut into vertical and horizontal sections, then into cubes representing each profile of the woody disk. The samples in this Figure were from log number 10 at the Hester site and consisted of A and B profiles.

5.4.4. Weather, fine fuel moisture and fire behaviour assessment

Methodology to assess fine fuel moisture and fire behaviour has been described for each site in detail by Hollis *et al*. (2010) and Hollis *et al*. (2011). The following methodology is therefore a brief summary.

Surface fine fuel moisture content (SMC: moisture content of the top 0.6-1 cm of undecomposed litter layer) and profile fine fuel moisture content (PMC: full depth of the litter profile) were sampled at each of the WFCP, Tumbarumba and McCorkhill sites prior to burning and where possible during the fire (for fire durations mostly greater than 2 h). Fine fuel samples included all fuel < 0.6 cm in diameter except at McCorkhill where fine fuels were < 1.0 cm. Fine fuel moisture content was not assessed at the Kilmore East and Pickering Brook wildfires; however estimates were made using Matthews (2006) fine fuel moisture model.

Rate of spread was measured at each of the WFCP sites using a grid of insulated type K thermocouples with data logger placed at 25 m grid intervals. The time at which the fire crossed pre-determined grid points was assumed to be the moment thermocouple temperatures reached 320°C. Arrival times for the flame front were cross-referenced and checked with recorded visual observations. At Pickering Brook and Kilmore East wildfires, rates of spread were determined from periodic maps of the fire perimeter based on witness statements, photographic and video recordings, and infrared (IR) line scanner images. For the McCorkhill experimental fires rates of spread were derived from sequential fire perimeters mapped with an IR line scanner (Gould *et al.*, 1996). At Tumbarumba, progress of the fire perimeter was marked with numbered metal tags, supplemented by visual observations.

Prescribed fires were mostly ignited using long line ignitions (> 150 m in length) and multiple point ignitions at McCorkhill. Pre-fire climate data and weather conditions during the fire were sourced from nearby Bureau of Meteorology, Automatic Weather Stations (AWS) and in the WFCP sites, from on-site (or nearby) portable weather stations measuring, rainfall, 10-m open wind speed (U_{10}), 2-m in-forest wind (U_2: at Tallarook, McCorkhill and Tumbarumba) air temperature (T) and relative humidity (RH).

5.4.5. Data analysis and model development

Two different approaches and data subsets have been used to determine the effect of variables on woody fuel consumption and in model development; (1) plot level woody fuel consumption and (2) stage level woody fuel consumption.

5.4.5.1. Plot level woody fuel consumption

Assessment of woody fuel consumption at a plot level was based on a dataset which includes the measured proportion of woody fuel consumed at each fire as determined from the pre-fire woody fuel load (e.g. Wilga pw_W = 47.6%).

From a wide search of published studies, 13 groups of variables were identified that potentially influence the consumption of woody fuels in Australian forest fires (Table 1). Within these groups, 62 individual variables were identified as potential predictor variables (Appendix *B*) and used to create generalised linear models (GLM: McCullagh and Nelder, 1989) for the total proportion of woody fuel consumed, p, as well as the proportions for each size class. The GLM approach used was based on a quasi-likelihood function (Collett, 2003) with the use of the logit function, $g(\mu) = p/(1-p)$, as the link function. The proportion of woody fuel consumed was modelled as:

$$p = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k)}} \quad (1)$$

where x_i is the ith predictor variable and β_i is the ith regression coefficient, $i = 1,...k$. Models for plot (i.e. fire) level consumption were fitted using the software R (R Development Core Team, 2008). Correlated variables (Pearson linear correlation coefficient, r) in the dataset were identified and correlated combinations were subsequently avoided in model development. Model selection was based on the largest reduction in deviance (McCullagh and Nelder, 1989), highest Effron's pseudo R2 values (Effron, 1978) and minimum levels of mean absolute error (MAE) and root mean squared error (RMSE) (Willmott, 1982).

5.4.5.2. Stage level woody fuel consumption

Assessment of woody fuel consumption at the stage level was based on a dataset where woody fuel ignition and consumption was measured at a particle level using line intersect methods (Van Wagner, 1968; Brown, 1974) (i.e. based on pre-fire diameter and post-fire diameter). Only sampling techniques at WFCP prescribed fires allowed analysis of individual woody particle consumption and so other datasets were not used in stage level analysis. For example, post-fire diameters measured at McCorkhill were recorded without reference to pre-fire diameter, thus giving a total pre-fire and post-fire woody fuel load but not enabling analysis of individual proportional consumption.

Combustion phases for woody fuel consumption have been well documented and described in literature as (1) drying and preheating, (2) ignition and flaming combustion and (3) glowing and smouldering combustion (Section 1.1 – Combustion types and phases). The majority of research defining these broad phases has been conducted within controlled laboratory environments where all three combustion phases can be recorded using video and mass-loss measurements (Ward, 2001; Carvalho *et al.*, 2002). In a field experiment it is not possible to completely monitor the combustion progress of a fuel particle as it burns, but using line intersect 461 data it is possible to classify the final state of individual woody fuels by breaking the data into four binary response categories (Fig. 3): (S1) whether the fuel particle was exposed to fire, (S2) whether the fuel particle ignited, (S3a) whether combustion was sustained resulting in partial consumption and (S3b) whether combustion was sustained resulting in full consumption.

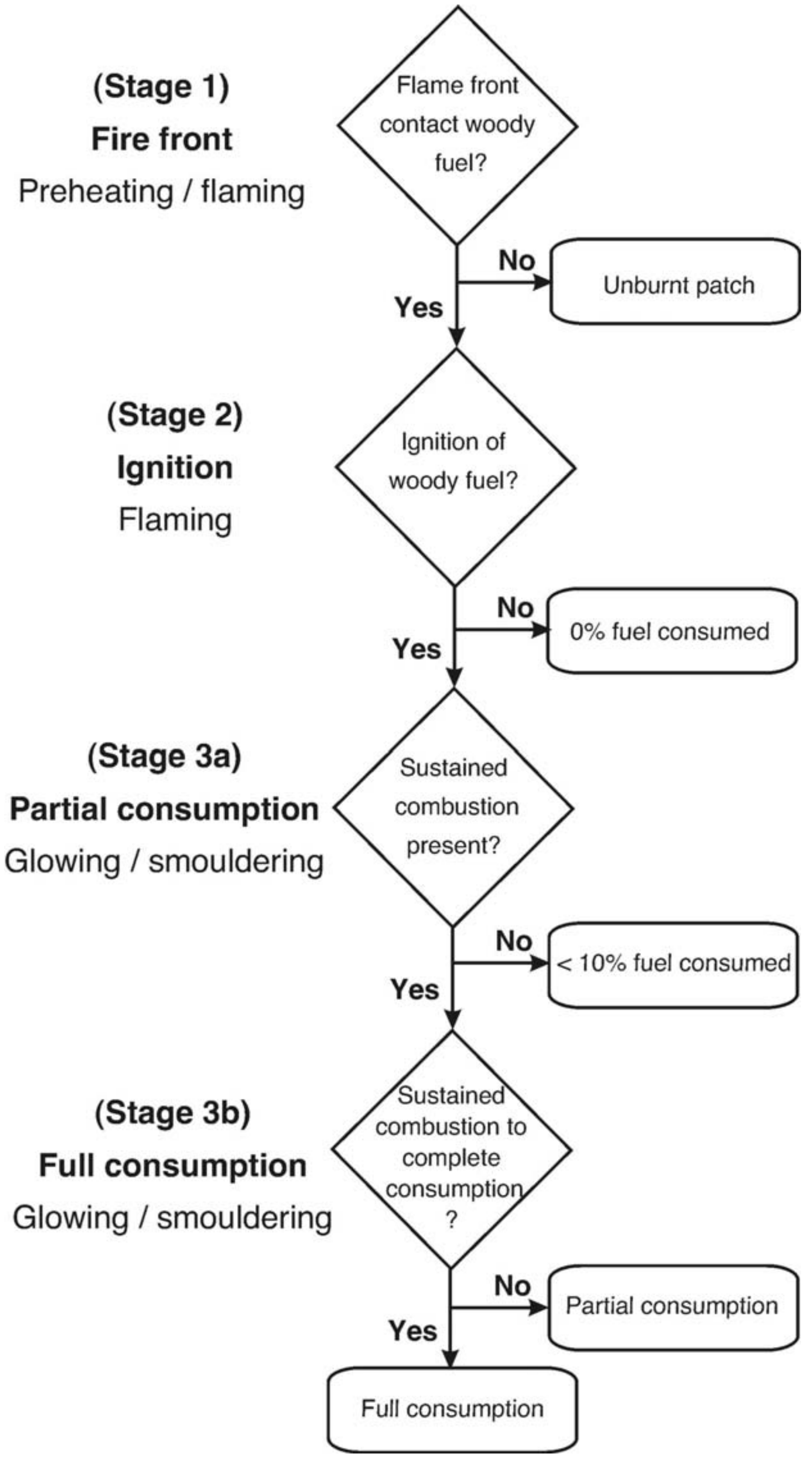

Figure 3. Process map for four binary woody fuel combustion stages.

Generalised linear mixed models (Broström, 2009) were used to assess the effect of the same 62 individual variables used for the analysis of plot level consumption (Section 2.4.1) on the probability of a woody fuel particle reaching each combustion stage. This included analysis using subsets of the dataset based on size class. Each woody particle had nine variables that were specific to it and 53 variables that were specific to that fire (Appendix B).

We attempted to construct models to predict;

(i) whether woody fuels particles ignited given they were exposed to flame (S2) and

(ii) whether they were partially or fully consumed given that they sustained combustion (S3a and S3b).

Fraction of logs exposed to flame (S1) was not modelled, as this is a property of the moving fire, i.e. patchiness. Full consumption of woody fuels (S3b) is derived trivially from S3a. *(i)* was modelled as a binomial process using the 62 measured variables as fixed effects and 'site' as a random effect. *(ii)* was modelled as a continuous variable with the same variables as *(i)* but using a quasi-likelihood distribution with logit link and variance proportional to $\mu(1-\mu)$.

To avoid numerical problems caused by significant correlation amongst the 62 measured variables, principal components analysis (PCA: R Development Core Team, 2008) was used to produce a set of orthogonal variables. The set of variables was transformed using scaled, centered PCA, and the set of principal components (PC) was truncated after cumulative fractional variance of 99.99% was achieved.

5.5. Results

5.5.1. Pre-fire fuel load and distribution

The woody fuel load at each site originated mostly from natural fall of branches and trees, and is likely to have been influenced by historical selective timber harvesting. Most sites had some larger woody fuels that had been previously cross-cut with a saw. The Wilga WFCP site in Western Australia had been recently harvested for sawlogs. Across the entire dataset, pre-fire woody fuel load ($Load_W$) varied from 13 Mg ha^{-1}at the Upper Plenty site which lacked fuels greater than 7.5 cm, to 175 Mg ha^{-1} at the Quillben site (av. = 66 Mg ha^{-1}, st. dev. = 34 Mg ha^{-1}, n = 33) (Table 4). Woody fuel loads were small (< 30 Mg ha^{-1}) at Pickering Brook, Burgan Track and Healesville west. At the Wilga recently harvested site, the woody fuel load was 42 Mg ha^{-1}. The largest, woody fuels (size class 5, d > 50 cm) were absent from Tallarook and at Pickering Brook and Burgan Track wildfire sites.

On average, 75% of the total woody fuel load within each plot was made up of size class 4 and 5 woody fuels (d > 22.5 cm) while size class 5 (d > 50 cm) fuels alone typically made up more than 35%. Less than 10% of the total woody fuel load on each site was made up of size class 1 and 2 fuels (d < 7.5 cm).

5.5.2. *Range of fire weather and fire behaviour conditions*

The plot level woody fuel consumption dataset represented a wide range of fire weather and fire behaviour conditions are represented. Surface, fine fuel (litter) profile moisture content (PMC) ranged from 2% at the Kilmore East wildfire to 72% at the Tallarook autumn fire, with a dataset mean of 14% (Table 4). Wind speeds (measured at 10-m in the open) ranged between 3 and 63 km h^{-1}. The maximum Forest Fire Danger Index (FFDI: McArthur, 1967) reached during the flaming combustion period for each fire ranged from 3 to 155 respectively for the Tallarook autumn fire and Kilmore East wildfire (Kilmore Gap Automatic Weather Station; Cruz *et al.* (2010)) at the approximate time when the fire burnt the Upper Plenty site. Fire behaviour ranged from slow moving (15 m h^{-1}), patchy fires that self-extinguished to wildfires characterised by long range spotting behaviour and rates of spread up to 7.6 km h^{-1} and fireline intensity up to 31,625 kW m^{-1} (Table 5). In the stage level dataset, fire weather and fire behaviour conditions were limited to a smaller range and were typical of low intensity prescribed burning conditions. The average fireline intensity was 297 kW m^{-1} (ranging from 53-678 kW m^{-1}) and FFDI ranged from 3 to10, representing only low-moderate FFDI values. Summer-like conditions characteristic of severe wildfires were not represented in the stage level analysis of data.

For both plot level and stage level woody fuel consumption datasets, observations included fires in spring, summer and autumn; however only the Quillben site was burnt in early summer in the stage level dataset. For both datasets, a relatively wide range of Soil Dryness Index (SDI; Mount, 1972; Burrows, 1987) and Keetch Byram Drought Index (KBDI; Keetch and Byram, 1968) are represented (Table 5). Surface, fine fuel (litter) profile moisture content (PMC) ranged from 2% at the Kilmore East wildfire to 72% at the Tallarook autumn fire (mean = 14%) (Table 4).

A summary of fire weather and behaviour conditions for both the site level and stage level datasets are included in Table 5. Additional detail for each site has been presented by Hollis *et al.* (2010) and Hollis *et al.* (2011).

Table 4. Summary of field site fuel moisture content (FMC), fuel load characteristics and woody fuel consumption with the range of conditions (minimum to maximum) in *italics*.

Site / mean characteristics	PMC (%)	FMC_{W} (%)	Size class 1 FMC (%)	Size class 2 FMC (%)	Size class 3 FMC (%)	Size class 4 FMC (%)	Size class 5 FMC (%)	Fuel age (years since last fire)	$Load_{ff}$ ($Mg\ ha^{-1}$)	$Load_{W}$ ($Mg\ ha^{-1}$)	Post-fire woody load (d > 0.6 cm) ($Mg\ ha^{-1}$)	pw_{W} (%)
WFCP - Wilga	11.6	42[d]	NM	17	41	44	64	17	5.9	42.3	22.1	47.6
		(6-74) *n*=59		*(6-52)* *n*=9	*(11-74)* *n*=32	*(19-64)* *n*=14	*(41-74)* *n*=4					
WFCP - Quillben	24.6	37	11	37	34	60	64	17	7.8	175.0	121.7	30.5
		(8-104) *n*=88	*(8-13)* *n*=24	*(12-26)* *n*=28	*(14-62)* *n*=18	*(18-104)* *n*=15	*(60-75)* *n*=3					
WFCP - Hester	16.6	41[d]	NM	23	27	44	69	17	6.6	93.8	47.3	49.4
		(14-92) *n*=65		*(15-43)* *n*=5	*(14-60)* *n*=39	*(23-92)* *n*=17	*(40-84)* *n*=4		*(6.0-7.0)*	*(76-106)*	*(40-62)*	*(42-57)*
WFCP - Tallarook	51.9	46	27	34	38	70	87	37	8.1	52.2	31.6	39.7
	(32.3-71.5)	*(14-160)* *n*=206	*(14-97)* *n*=40	*(19-108)* *n*=44	(16-108) *n*=75	*(22-160)* *n*=45	*(66-108)* *n*=2		*(7.3-8.9)*	*(49-55)*	*(28-36)*	*(36-43)*
Pickering Brook fire	7[a]	NM	NM	NM	NM	NM	NM	9	13[b]	22	2	91
Project Aquarius	10.4	NM	NM	NM	NM	NM	NM	6	8.8	60.5	27.1	54.9
	(8.3-13.2)								*(6.3-12.0)*	*(33-107)*	*(5-54)*	*(33-90)*

Site / mean characteristics	PMC (%)	FMC_W (%)	Size class 1 FMC (%)	Size class 2 FMC (%)	Size class 3 FMC (%)	Size class 4 FMC (%)	Size class 5 FMC (%)	Fuel age (years since last fire)	$Load_{ff}$ (Mg ha^{-1})	$Load_W$ (Mg ha^{-1})	Post-fire woody load (*d* > 0.6 cm) (Mg ha^{-1})	pw_W (%)
Tumbarumba	11.0	55[d]	NM	19	42	86	74	> 20	12.8	86.3	52.3	44.2
		(11-245) *n*=154		*(11-68) n=55*	*(11-118) n=59*	*(14-245) n=37*	*(51-91) n=3*		*(12.3-13.3)*	*(49-123)*	*(22-83)*	*(33-56)*
Kilmore East fire	1.9[a]	NM	NM	NM	NM	NM	NM	43	11[c]	49	8	90
	(1.6-2.1)							*(26-52)*		*(13-125)*	*(0-25)*	*(80-100)*

Source of data: Hollis *et al.* (2010).
PMC: Profile fine fuel (litter) moisture content; FMC_W: plot average of sizes 1-5 woody fuel (*d* > 0.6 cm) moisture content; FMC: fuel moisture content; *n*: sample number (where known); $Load_{ff}$: pre-fire fine fuel load (*d* < 0.6 cm); $Load_W$: pre-fire woody fuel load (*d* > 0.6 cm); pw_W: proportion of woody fuel (*d* > 0.6 cm) consumption (%); NM: Not measured.
[a] Determined using Matthews (2006) fine fuel moisture model.
[b] Determined using Table 6.8 of Sneeuwjagt and Peet (1998).
[c] Determined using Gould *et al.* (2007b).
[d] FMC_W based only on size classes 2-5.

Table 5. Summary of mean fire weather and fire behaviour characteristics for site level and stage level woody fuel consumption datasets. Range within dataset (minimum to maximum) in *italics*.

Site	*n*	RH (%)	*T* (°C)	U_{10} (km h^{-1})	KBDI	SDI	FFDI	ROS (m h^{-1})	*I* (kW m^{-1})
Plot level dataset	33	43	26	12	136	136	18	828	3616
		(10-69)	*(13-41)*	*(3-63)*	*(14-173)*	*(43-166)*	*(3-155)*	*(15-7620)*	*(53-31625)*
Stage level dataset	8	53	22	11	89	125	7	84	297
		(28-69)	*(13-27)*	*(6-18)*	*(14-140)*	*(43-148)*	*(3-10)*	*(15-217)*	*(53-678)*

n: sample number; RH: relative humidity; *T*: temperature; U_{10}: 10-m open wind speed; KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; FFDI: Forest Fire Danger Index; ROS: rate of spread; *I*: fireline intensity.

5.5.3. Woody fuel moisture and characteristics

At a plot level, the moisture content of woody fuels (d > 0.6 cm) exhibited large variability within and between size classes (Table 4). There was limited variation in the average woody fuel moisture content between plots (FMC_W ranging from 37% at the Quillben site to 55% at Tumbarumba) but the sample range at each site was highly variable. For example, while the plot average (FMC_W) at Tumbarumba was 55%, the 154 samples used to determine the plot average varied from 11% to 245%, a range of 234%. At the plot level, the dataset showed an expected trend of increasing fuel moisture content with increasing diameter (Table 4).

Detailed sampling of the moisture content profile within woody fuel samples showed large variability between woody fuels of similar characteristics. Fuel moisture profiles for three jarrah disks taken from logs at the Hester site in the autumn 2008 are shown in Figure 4. These disks had d > 35 cm (size classes 4 and 5), were in the early stages of decay (decay classes 1 and 2); and were partially suspended above the ground (suspension classes 1 and 2). Photographs and corresponding moisture contour plots in Figure 4 (a) - (c) show the variation in moisture within and between each of these woody samples. Average fuel moisture content for the samples were (a) 65% (cube range = 18-191%) (b) 47% (cube range = 24-84%) and (c) 74% (cube range 27-129%).

Most woody fuel characteristics were significantly correlated with each other ($p < 0.01$) including; diameter, degree of decay, bark, arrangement, suspension, species and charring (Table 6). The diameter of the woody fuel particle was not correlated with arrangement or species and arrangement was not correlated with the degree of charring. Woody fuel characteristics were also significantly correlated ($p < 0.01$) with FMC and with the surface FMC associated with the 'A' profile (i.e. outer 5 cm) of the fuel (n = 300) with the exceptions of species and the degree of charring.

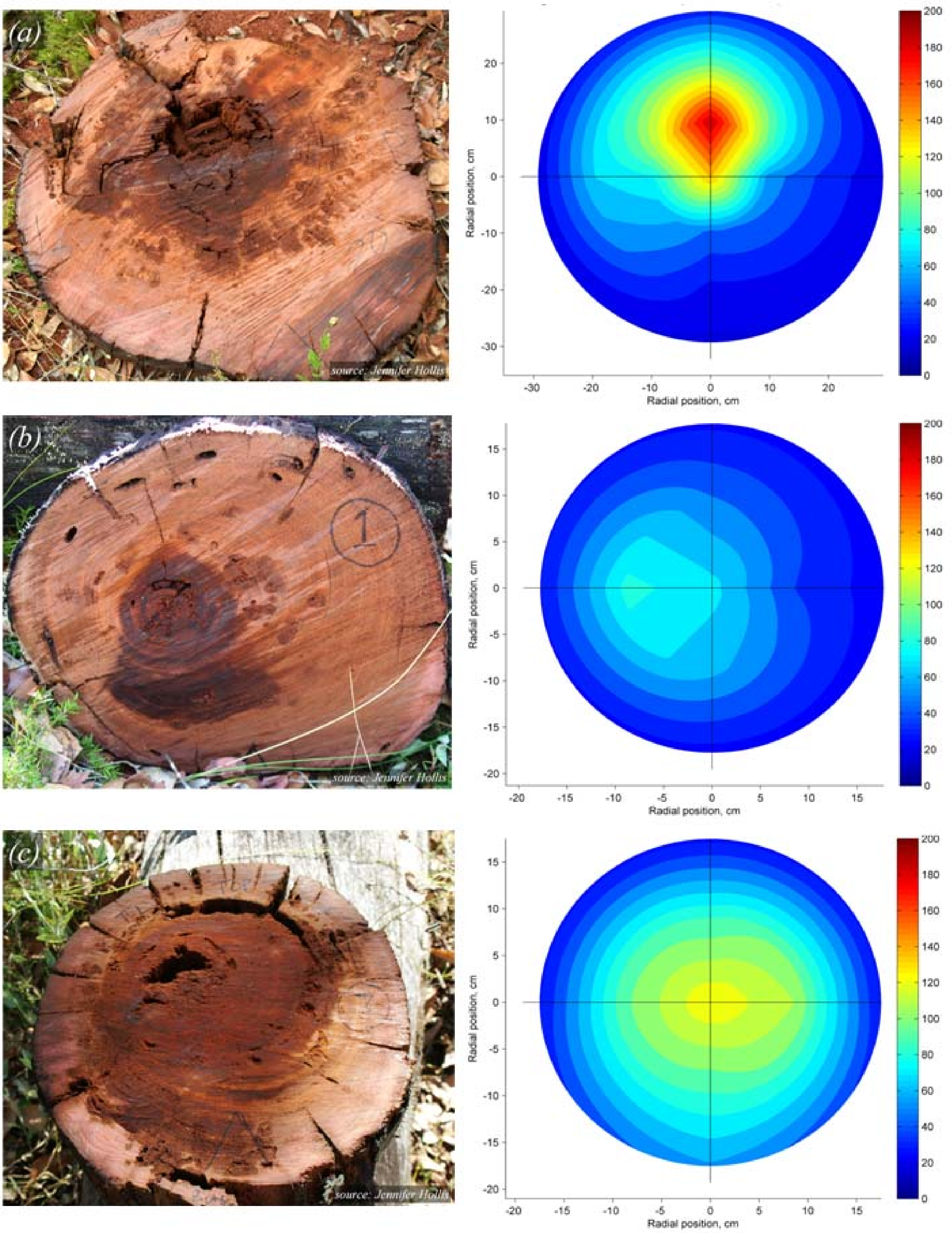

Figure 4. Photographs and matching polar contour plots showing variation in fuel moisture content (%) within and between woody fuels of similar characteristics. Each jarrah sample was taken at the Hester site in Autumn 2008. (a) - (c) have the following characteristics: *d* > 35 cm (size classes 4 and 5); early stages of decay (decay classes 1 and 2); partially suspended above the ground (suspension classes 1 and 2).

Table 6. Correlation coefficient (Pearson *r*) matrix for woody fuel characteristics and the stages of consumption (S1-S4) within the full stage level woody fuel consumption dataset (*n* = 6727).

	Diameter	Decay	Bark	Suspension	Arrangement	Species	Charring	S1	S2	S3a	S3b
Diameter	1	0.366**	-0.044**	-0.100**	-0.018	-0.180	0.232**	0.052**	-0.036**	-0.382**	-0.441**
Decay		1	-0.373**	-0.347**	-0.033**	0.101**	0.073**	-0.022	0.015	-0.168**	-0.275**
Bark			1	0.115**	0.058**	-0.207**	0.245**	0.058**	0.053**	-0.007	-0.059**
Suspension				1	0.249**	-0.093**	-0.091**	0.025*	0.047**	0.073**	0.094**
Arrangement					1	0.092**	0.012	0.026*	0.129**	0.018	-0.024
Species						1	-0.128**	-0.240**	0.030*	0.065**	0.018
Charring							1	0.095**	0.131**	-0.107**	-0.150**

* Correlation is significant at the 0.05 level.
** Correlation is significant at the 0.01 level.

5.5.4. *Plot level woody fuel consumption*

The proportion of woody fuel consumed varied greatly between and within sites (Table 4). Woody fuel consumption varied between 31% at the Quillben prescribed burn to 100% at the Healesville West plot that burned during the Kilmore East wildfire (av. = 57%, st. dev. = 20%). Within the Hester site, woody fuel consumption varied between 42% and 57% across four separate fire plots while at the McCorkhill site, woody fuel consumption varied between 33% and 90% across 18 different plots despite a limited range of weather and fire behaviour characteristics (Hollis *et al.*, 2011). The proportion of woody fuel that was consumed was significantly ($p < 0.01$) positively correlated with FFDI, fireline intensity (I) and 10-m open wind speed (U_{10}) and negatively correlated with fine fuel (profile) moisture content (PMC) (Table 7). By definition, FFDI was also significantly positively correlated with fireline intensity (I) and open 10-m wind speed (U_{10}).

5.5.4.1. *Modelling plot level woody fuel consumption*

Regression analysis using generalised linear models (GLM) fitted to Equation (1) of all possible variables and variable combinations showed the best model for plot level woody fuel consumption for the dataset (including WFCP prescribed fires, Tumbarumba and McCorkhill fires and the Pickering Brook and Kilmore East wildfires; $n = 29$) used McArthur's Forest Fire Danger Index (FFDI: McArthur, 1967) (Table 8, Figure 5) based on the significant p-value ($p = 0.02$) largest reduction in deviance (41%), highest R^2 value (0.58) and minimum error statistics: *MAE* (10.3%) and *RMSE* (0.12). Other variables and variable combinations did not improve the reduction in deviance or decrease errors significantly. For example, the next best model developed included FFDI and fine fuel load, resulting in an $R2$ value of 0.59, *MAE* of 10.2%, *RMSE* of 0.13 and a 40% reduction in deviance. The R^2 value (0.90) and error statistics ($MAE = 5.96$, $RMSE = 0.07$) improved by removing McCorkhill fires however, the FFDI became insignificant ($p = 0.62$) and the reduction in deviance was smaller (15%), (Table 8, Figure 5).

5.5.5. *Stage level woody fuel consumption*

The average proportion of woody fuel consumed at the eight WFCP fire sites used for stage level analysis was 44% and was relatively limited in range between 36% at the Tallarook autumn fire to 57% at the Hester 1 site (st. dev. = 9%).

Each of the woody fuel consumption stages were strongly correlated ($p < 0.01$) with most woody fuel characteristics apart from S1 (preheating and the flaming combustion of fine fuels) and S2 (ignition and flaming combustion) with the degree of fuel decay and S3a (partial consumption) and S3b (full consumption) with the amount of bark, the arrangement of the fuel and the species (Table 6).

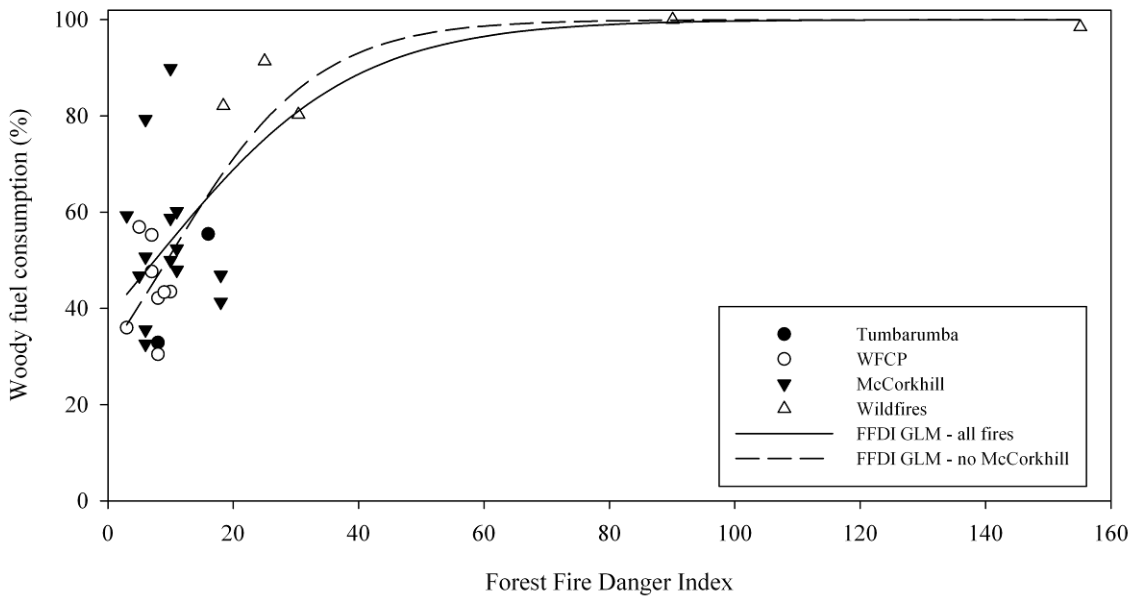

Figure 5. Woody fuel consumption versus Forest Fire Danger Index for all fires, including wildfires.

Of the variables that were specific to each of the eight WFCP fire sites, FFDI, fireline intensity (I) and 10-m open wind speed (U_{10}) were correlated with the proportion of woody fuel consumed (pw_W) while the average plot woody fuel moisture content (FMC_W) was correlated with both the profile fine fuel (litter) moisture content (PMC) and KBDI (Table 9).

Table 7. Correlation coefficient (Pearson *r*) matrix for a selection of the 62 variables tested within the full site consumption dataset.

	Group	pw_W (%)	FMC_W	FFDI	$Load_{ff}$	PMC	$Load_W$	KBDI	SDI	*I*	$Density_W$	U_{10}	HR
$pw_{W\,(\%)}$		1	-0.195	0.639**	0.129	-0.445**	-0.400*	0.037	0.365*	0.672**	-0.134	0.643**	0.213
FMC_W	Woody FMC		1	-0.175	0.262	0.608**	0.019	-0.537**	-0.177	-0.026	-0.657**	0.056	-0.127
FFDI[a]	Environment			1	-0.060	-0.321	-0.387*	-0.191	0.151	0.771**	-0.299	0.898**	-0.186
$Load_{ff}$	Fine fuels				1	-0.176	-0.085	0.230	0.026	0.002	-0.439*	-0.109	0.030
PMC	Fine fuels					1	0.162	-0.151*	-0.059	-0.384*	-0.107	-0.256	-0.150
$Load_W$	Woody fuel load						1	-0.072	-0.258	-0.309	-0.022	-0.307	0.712**
KBDI	Environment							1	0.478**	-0.232	0.315	-0.333	0.107
SDI	Environment								1	0.165	-0.114	0.239	0.055
I	Fire intensity									1	-0.395*	0.834**	-0.003
$Density_W$[b]	Wood density										1	-0.349*	-0.068
U_{10}	Environment											1	-0.089
HR	various												1

pw_W: proportion of woody fuel (*d* > 0.6 cm) consumption (%); FMC_W: plot average woody fuel (*d* > 0.6 cm) moisture content; FFDI: Forest Fire Danger Index (maximum during burn period); $Load_{ff}$: fine fuel (*d* < 0.6 cm) load (kg m^{-2}); PMC: Profile fine fuel (litter) moisture content; $Load_W$: woody fuel (*d* > 0.6 cm) load (kg m^{-2}); KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; *I*: Fireline intensity (kW m^{-1}); $Density_W$: woody fuel (*d* > 0.6 cm) density (kg m^{-3});
U_{10}: 10-m open wind speed (km h^{-1}); HR: Heat release per unit area (kJ m^{-2}).

[a] NB. FFDI correlation co-efficients are slightly different to those published by Hollis *et al.* (2011) due to the division of Hester fires into four separate fires, rather than grouping as one fire.

[b] Site average.

* Correlation is significant at the 0.05 level; ** correlation is significant at the 0.01level.

Table 8. Parameter estimates for generalised linear models for the proportion of woody fuel consumed based on the Forest Fire Danger Index (Figure 5).

Coefficient	Estimate	Standard error	P (> |t|)	R^2
		FFDI GLM (Plot level dataset)		
β_0	-0.4732	0.3067	0.135	0.58
β_1	0.0633	0.0257	0.021	
		FFDI GLM (Plot level dataset excluding McCorkhill fires)		
β_0	-0.8048	2.1483	0.714	0.90
β_1	0.0852	0.1693	0.623	

5.5.5.1. Modelling each woody fuel consumption stage

Principal components analysis on the set of 62 independent variables allowed 99.99% of variance to be captured in 11 or 12 components (Table 10). This level of variable reduction was possible because many of the variables were correlated, either systematically (e.g. SDI and KBDI) or coincidentally (e.g. wind speed and litter depth). For the ignition model, all models performed poorly, and had a reduction in deviance less than 15%. For the S3a and S3b models, performance was slightly better with classes 1, 4, and 5 having a reduction in deviance greater than 20%. Size class 1 fuels were largely consumed in most plots (av. = 78%, st. dev. = 26) and so the higher reduction in deviance (44%) is a property of the data set rather than an indication of greater model skill. Given the poor performance of the ignition models (S2), an attempt to construct a predictive model based on measured variables was not pursued. Although the reduction in deviance was higher for some of the consumption models, these cannot be applied without an ignition model and so predictive models for consumption of individual size classes was not attempted.

Table 9. Correlation coefficient (Pearson *r*) matrix for a selection of the 62 variables tested within the 8 WFCP prescribed fire sites.

	Group	pw_W (%)	FMC_W	FFDI	$Load_{ff}$	PMC	$Load_W$	KBDI	SDI	*I*	$Density_W$	U_{10}	HR
$pw_{W\,(\%)}$		1	-0.486	0.746*	-0.484	-0.497	-0.343	0.508	0.238	0.717*	0.315	0.816*	0.286
FMC_W	Woody FMC		1	-0.593	0.086	0.904**	-0.264	-0.742*	-0.101	-0.483	-0.398	-0.464	-0.566
FFDI[a]	Environment			1	-0.251	-0.638	-0.545	0.223	-0.128	0.526	0.424	0.407	-0.115
$Load_{ff}$	Fine fuels				1	0.398	0.038	-0.233	0.199	-0.226	-0.740*	-0.336	0.225
PMC	Fine fuels					1	-0.227	-0.572	0.238	-0.416	-0.752*	-0.356	-0.481
$Load_W$	Woody fuel load						1	0.319	-0.037	0.065	0.113	-0.097	0.789*
KBDI	Environment							1	0.627	0.334	0.114	0.772*	0.709*
SDI	Environment								1	0.092	-0.641	0.612	0.258
I	Fire intensity									1	0.140	0.474	0.532
$Density_W$[b]	Wood density										1	0.069	0.194
U_{10}	Environment											1	0.472
HR	various												1

pw_W: proportion of woody fuel (d > 0.6 cm) consumption (%); FMC_W: plot average woody fuel (d > 0.6 cm) moisture content; FFDI: Forest Fire Danger Index (maximum during fire period); $Load_{ff}$: fine fuel (d < 0.6 cm) load (kg m^{-2}); PMC: Profile fine fuel (litter) moisture content; $Load_W$: woody fuel (d > 0.6 cm) load (kg m^{-2}); KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; *I*: Fireline intensity (kW m^{-1}); $Density_W$: woody fuel (d > 0.6 cm) density (kg m^{-3}); U_{10}: 10-m open wind speed (km h^{-1}); HR: Heat release.

[a] Site average.

* Correlation is significant at the 0.05 level.

** Correlation is significant at the 0.01 level.

Table 10. Generalised linear mixed model characteristics based on principal components for the P2 (ignition) phase and the P3b (full consumption) phase.

	P2 (ignition) phase			P3b (full consumption) phase		
Size Class	*n*	Principal components retained	Reduction in variance (%)	*n*	Principal components retained	Reduction in variance (%)
1	3991	12	3	2805	12	44
2	678	12	7	497	12	8
3	545	12	7	387	12	16
4	328	12	14	217	12	24
5	129	11	12	82	11	21

n: Number of sample woody fuels.

5.6. Discussion

Our plot level analysis of the proportion of woody fuel consumed identified McArthur's FFDI (McArthur, 1967) as the best predictor of woody fuel consumption. FFDI is an index of fire behaviour potential that incorporates the effect of air temperature, relative humidity, wind speed, and a drought factor. Although FFDI is most sensitive to wind speed and relative humidity (McArthur, 1967; Matthews, 2009), a GLM approach based on these variables used individually yield poor goodness-of-fit statistics. The McCorkhill subset showed large variability in the fuel consumption outcomes which was attributed to unquantified variation in field plots and data collection techniques (Hollis *et al.*, 2011a). A GLM based on FFDI but excluding McCorkhill data yield higher precision (lower mean absolute error) but poorer reduction in deviance than with the full dataset.

Model evaluation statistics showed highest accuracy for the GLM based on FFDI with mean absolute errors of 10% (full dataset) and 6% (excluding McCorkhill). These are comparable to the errors obtained by Hollis *et al.* (2011) using fireline intensity as the explanatory variable (*MAE* of 11% (full dataset) and 7% (excluding McCorkhill) or relying on the Australian National Carbon Accounting System (ANCAS: Gould and Cheney, 2007) model of 50% woody fuel consumption in any fire (*MAE* = 11%) (Hollis *et al.,* 2010). These error levels are lower than found by Hollis *et al.* (2010) in evaluating the CONSUME (*MAE* between 12 and 18%) and BUNRNUP (*MAE* between 19% and 45%) models when applied to fire in Australian southern eucalypt forests.

A small proportion (15%) of the plot level dataset was collected under high intensity wildfire conditions. Like the shape of the fireline intensity GLM (Hollis *et al.*, 2011), the FFDI GLM is highly influenced by the wildfire data points and will require ground-truthing and validation.

We were not able to find a significant relationship between woody fuel moisture content and woody fuel consumption. This relationship has been found to be significant in determining woody fuel consumption in studies in North America (Table 1) and raises an important question as why such an evident relationship between woody fuel moisture and consumption was not apparent in our dataset. Woody fuel moisture at our study sites was highly variable, both at a plot level and within woody fuels particles. This agrees with McCaw *et al.* (1997) and the findings of Tolhurst *et al.* (2006) who also reported large variation in woody fuel moisture content and were unable to find a clear relationship with the proportion of woody fuel consumed. While the apparent trend between woody fuel diameter and moisture was evident, with average moisture increasing with size class, it may be that the large variability in fuel moisture within individual woody fuel particles found in natural eucalypt forests makes the observation of a clear relationship between woody fuel moisture and consumption not possible, at least with the current data available. Furthermore, woody fuel particle characteristics that are known (Table 1) to influence their ignition and combustion rate, such as decay, position, suspension and arrangement, were found to be significantly correlated with fuel moisture. This highlights the potential difficulty associated with attempting to establish a relationship between woody fuel moisture, physical characteristics and consumption. For the plot level modelling approach, a wider range of burning conditions and larger sample sizes are necessary to adequately represent the effect of variable woody fuel moisture on woody fuel consumption. Further research is needed to determine what adequate sample size would be required to adequately capture the variability in woody fuel moisture.

The principal components analysis (PCA) was used with generalised linear mixed effect models to model woody fuel ignition and consumption on a size class basis. This approach relied on the stage level dataset, a subset of data with more detail relating to fuel and consumption characteristics. PCA showed the best reduction in deviance possible for models of woody fuel consumption.

The reduction in deviance for each of the stage level woody fuel ignition and consumption models was not large enough to make any of the models useful for operational application. This limited explanatory power might arise from the limited variation in burning conditions found in the dataset rather than the modelling concept. The fire weather and fire behaviour conditions represented within the stage level dataset were restricted to the spectrum of fire weather and behaviour typically observed in prescribed burning operations. The average fireline intensity was 297 kW m^{-1} and the FFDI ranged from 3 to 10, of a possible > 100 range. It may be that variables affecting fire behaviour (and FFDI) have a greater impact on woody fuel consumption than do woody fuel characteristics (e.g. decay). It could also be that there is no good linear model for the stages of woody fuel consumption and that it may be necessary to create a non-linear model; however this is beyond the scope of this paper.

Expanding the dataset to include additional medium and high intensity fires would benefit analysis of both plot level and stage level woody fuel consumption, particularly for validating the FFDI GLM and improving understanding of the combustion stages and how woody fuel characteristics may affect the proportion of woody fuel consumed. Woody fuel consumption data is difficult to collect making opportunistic observations of wildfires and high intensity fire experiments both costly and difficult to implement. Nonetheless, opportunistic data collection at locations burnt by high intensity wildfires paired with sampling of unburned sites with matching characteristics will be necessary to improve our understanding of woody fuel consumption outcomes under high fire potential.

5.7. Management implications

Knowledge of the amount of woody fuel (d > 0.6 cm) consumed under distinct burning conditions is necessary to support important decisions on a range of fire management applications. Our study, based on a number of experimental/prescribed fires and high intensity wildfires covered a wide range of woody fuel consumption outcomes and found the Forest Fire Danger Index, FFDI, to be the best predictor of woody fuel consumed in Australian southern eucalypt forests. Based on this dataset a model describing the proportion of woody fuel consumed was developed using generalised linear model (GLM) regression analysis.

The FFDI model to predict woody fuel consumption provides forest and fire managers with a tool to manage woody fuel consumption objectives. From a priori estimates of woody fuel load, the model allows fire managers to forecast the total energy output and amount of heat release from forest fires. Outputs from the FFDI model can also be linked to a range of other models that allow estimates of fire characteristics, for example, estimates of the potential for convection plume development through simple (Latham, 1994) or more refined (Clark *et al.*, 1996) formulations of buoyant plume development. Linkages between the FFDI model outputs and models of woody fuel consumption rates (Albini and Reinhardt, 1995) will also assist fire managers with forecasting the potential for re-ignition, suppression/mop-up difficulty and the thermal and smoke environment to which firefighters are exposed (Sullivan *et al.*, 2002). The model may also and assist the development of fire prescriptions that target particular first and second order fire effects associated with combustion of woody fuels, for example the degree of soil heating and tree mortality associated with the heating of tree boles and superficial roots.

The FFDI model may also assist forest and fire managers to better meet land management goals and to comply with air quality and emission targets. Given the difference observed between low FFDI fires (characteristic of prescribed fires and low intensity fires) and high FFDI fires (characteristics of wildfires), the FFDI model may improve current national carbon accounting systems which are based on a simple model which assumes 50% of the woody fuel load is burnt during forest fires under a broad range of conditions (Gould and Cheney, 2007). Our analyses demonstrate that the FFDI model will decrease the degree of error, particularly associated with capturing extremes in woody fuel consumption.

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5.10. Appendix A. Woody decay assessment. *Adapted from*: Tolhurst *et al.* (2006), Maser *et al.* (1988) and Whitford and Williams (2001).

Characteristics	Decay class 0	Decay class 1	Decay class 2	Decay class 3	Decay class 4
Relationship with log ignition, combustion, moisture exchange and decay rate	Nutrient in bark, bark wick to fire and moisture, still partly "green". Predominantly resistant to moisture exchange and fire. Detaching bark may provide potential habitat.	Cracks provide habitat and path for more rapid wetting and drying. Cracks may assist internal surface heating.	Rapid moisture exchange, easier ignition, good potential habitat. Rotting sapwood provides wick for wetting and drying, easier ignition. Cracks may assist deeper heat penetration during fire.	Will burn slowly and hot, little or no flaming. Deep cracks and furrows hold water and promote accelerated rate of decay. Deep cracks may assist internal heat penetration to the core during fire.	Usually moist, mixed with litter, will smoulder and produce significant smoke and heat if ignited.
Description	Solid, cross-section maintaining original shape Bark intact and mostly attached Minor branches, twigs or stems may be present and intact Original colour Sapwood hard, brown Fissures and cracks absent Heartwood hard	Solid with cracks present, slight fissuring (1-2 cm deep, 8-10 cm apart) due to age Bark usually absent Possible branch stubs, no twigs or stems Sapwood can be scuffed by boot, grey Original colour fading Heartwood predominantly hard	Surface decaying with cracks and fissuring (3-4 cm deep) due to age Bark absent Sapwood is predominantly decayed and crumbly, easily broken away by hand Brach stubs absent Heartwood can be broken away Partial collapse is present Maintaining size integrity	Surface decaying with cracks and fissuring (5-7 cm deep) due to age Furrows may be present. Bark absent Sapwood is decayed and missing on parts of the log Loss of shape and collapse is present, possibly some solid wood present Original colour faded	Log has decayed and collapsed due to age Bark and Sapwood are completely absent Less than 25% of original shape remains Heartwood is rotten, can be easily kicked away. Log is predominantly blocky, punky, brown decayed wood Live vegetation may be growing out of decayed wood










5.11. Appendix B. Variable Listing.

Groups identified during the literature review and the variables within each group used to develop the models for woody fuel consumption in this manuscript. Variable listed in italics are specific to woody fuel particles.

Woody fuel moisture content	**Fire intensity**	**Environment**
Plot average woody FMC	Fireline intensity	10-m open wind speed
Size 1 FMC	Average rate of spread	Relative humidity
Size 2 FMC	Flame height	Temperature
Size 3 FMC	Maximum rate of spread	Drought factor
Size 4 FMC	Minimum rate of spread	FFDI
Size 5 FMC	Flame depth	SDI
	Residence time	KBDI
	Heat release	2-m in-forest wind speed
Wood density	**Decay**	**Bark**
Species	*Decay class*	*Bark class*
Green woody density	*CONSUME model decay class*	
Plot average wood density		
Fine fuels	**Diameter**	**Woody fuel load**
Profile FMC	*Pre-fire diameter*	Woody fuel load
Litter depth	*Pre-fire size class*	Total fuel load
Overstorey cover score	Site average basal area	Heat release
Overstorey hazard score		S1 fuel load
Understorey cover score		S2 fuel load
Understory hazard score		S3 fuel load
Elevated fuel cover score		S4 fuel load
Elevated fuel hazard score		S5 fuel load
Near-surface cover score		S3 CONSUME rotten fuel load
Near-surface hazard score		S3 CONSUME sound fuel load
Surface cover score		S4 CONSUME rotten fuel load
Surface hazard score		S4 CONSUME sound fuel load
Elevated top height		S5 CONSUME rotten fuel load
Near-surface top height		S5 CONSUME sound fuel load
Fine fuel load		
Arrangement	**Char**	
Arrangement class	*Char class*	
Suspension class		

Note: Fire size was not analysed due to the relatively limited size of WFCP fires being mostly below 2-3 ha. Disturbance variables were not analysed.

Chapter 6.

General conclusions and management implications

6.1. General conclusions

The proportion of woody fuel consumed during fires in southern Australian eucalypt forests varied greatly between and within sites. In our dataset, woody fuel consumption ranged from 9% at a silvicultural fire at the Warra Long Term Ecological Research site in Tasmania, to 100% at the Healesville West site which burnt during the Black Saturday fires in Victoria in 2009.

At the plot level, the proportion of woody fuel consumed was significantly ($p < 0.01$) positively correlated with McArthur's Forest Fire Danger Index (FFDI: McArthur, 1967), fireline intensity (I) and 10-m open wind speed (U_{10}) and negatively correlated with fine fuel (profile) moisture content (PMC). These correlations, together with correlations between these variables (i.e. FFDI was also significantly positively correlated with fireline intensity (I) and open 10-m wind speed (U_{10})) made identifying the unique effect of individual variables and multi-variable modelling a difficult task. Fireline intensity was identified as having a statistically significant, positive relationship with the proportion of woody fuel consumed, thereby showing a clear difference between woody fuel consumption at high intensity wildfires compared to low intensity prescribed burns.

The performance of five existing models that predict woody fuel consumption at a site (or plot) level, against field observations in Australian eucalypt forests was variable. Model evaluation statistics showed that the CONSUME Activity and CONSUME Southern Woody models under-predicted observations while the CONSUME Western Woody model had very little bias and a better proportion of predictions (59%) within ±10% of the observed woody fuel consumption. The BURNUP model showed the greatest overall level of error when used with natural fuels; however its performance improved when applied to heavy, modified fuel loads resulting from timber harvesting operations. The minimum level of error using existing models was achieved by applying the Australian National Carbon Accounting System model (Gould and Cheney, 2007) which simply assumes 50% of the woody fuel load at a site is likely to be consumed under the majority of fuel and fire scenarios. However this model failed to capture extremes where woody fuel consumption was particularly high or low.

Of all the variables and possible models tested, FFDI was found to be the best predictor of the proportion of woody fuel consumed at the plot level. The FFDI model of fire behaviour potential, incorporating the effects of air temperature, relative humidity, wind speed, and a drought factor yielded better goodness-of-fit statistics than models based on these variables alone. The FFDI model also yielded less error than any of the existing models when applied to the combined dataset from fires in southern Australian eucalypt forests. Fireline intensity was also a significant variable in determining the proportion of woody fuel consumed by fire; however the use of a model based on fireline intensity has some drawbacks. Its use requires the estimation of fine fuel consumption and rate of spread. Estimating these quantities can introduce further error and uncertainty in the prediction of woody fuel consumption so the FFDI model will be more accurate and better meet the needs of land and fire managers.

The proportion of individual particles consumed (stage level) was also highly variable, which together with limited variation in burning conditions, prevented the development of a model that accurately predicted individual woody fuel ignition and consumption. While it was disappointing that no useful model was able to be developed, the results showed that variation in fire behaviour has a potentially greater impact on woody fuel consumption than does variation in fuel characteristics (e.g. state of decay, fuel suspension and interactions with other fuel particles).

Surprisingly, a significant relationship between woody fuel moisture and the proportion of woody fuel consumed was not identified; possibly due to correlations with other variables that influence woody fuel ignition and combustion rate (e.g. decay, position, suspension and arrangement). It may also be that the large variability in fuel moisture within individual woody fuel particles in eucalypt forests makes obscures the relationship between woody fuel moisture content and consumption.

6.2. Implications for fire and land managers

Understanding the variables that affect woody fuel (d > 0.6 cm) consumption and being able to accurately predict consumption is essential in achieving land, forest and fire management objectives.

With the knowledge that variation in fireline intensity and FFDI will result in different woody fuel consumption outcomes, fire managers have a predictive tool to support decision making on a range of fire management applications. The FFDI model for woody fuel consumption will assist fire managers to forecast post-frontal fire behaviour. From a priori estimates of woody fuel load, the model allows fire managers to forecast the total energy output and amount of heat release from forest fires. Outputs from the FFDI model can also be linked to a range of other models that allow estimates of fire characteristics, for example, estimates of the potential for convection plume development through simple (Latham, 1994) or more refined (Clark *et al.*, 1996) formulations of buoyant plume development. Linkages between the FFDI model outputs and models of woody fuel consumption rates (Albini and Reinhardt, 1995) will also assist fire managers with forecasting the potential for re-ignition, suppression/mop-up difficulty and the thermal and smoke environment to which firefighters are exposed (Sullivan *et al.*, 2002).

It will also assist the development of fire prescriptions that target particular first- and second-order fire effects associated with combustion of woody fuels. For example, prolonged heating due to consumption of woody fuels that may damage stems, tree boles and superficial roots (Burrows, 1987a; Cheney *et al.*, 1990a) can be reduced by burning under low FFDI conditions and targeting lower fireline intensities (e.g. backing and flank fires).

A large proportion of the woody fuel load at sites studied was comprised of material greater than 22.5 cm in diameter, highlighting the importance of larger size classes (4 and 5) in determining the proportion of woody fuels consumed. Given this, both the FFDI model and fireline intensity models provide a tool to assist management of forest structural complexity, biological diversity and ecosystem processes. Forest managers will now be able to use the FFDI and fireline intensity models to minimise combustion of woody fuel, particularly for large woody fuels that many plants and animals rely on for habitat. For example, low and moderate intensity fire regimes could be used to treat fuels in areas where management objectives include fine fuel hazard reduction and ensuring that large woody fuel habitat is not compromised (e.g. as habitat for rare and threatened insects such as the blind velvet worm or hollow-nesting mammals such as the chuditch).

The FFDI and fireline intensity models for woody fuel consumption also provide a basis for examining potential impacts of climate change on woody fuels in Australian southern eucalypt forests. Analyses based on our dataset suggest that any changes to fire regimes which include modifications to fireline intensity and FFDI conditions under which forest fires occur will have direct implications for woody fuel consumption and subsequently carbon storage and emissions of greenhouse gases and smoke. For example, increased occurrence of summer bushfires will result in an increase in the proportion of woody fuel consumed and a subsequent reduction in the woody fuel load at that location. The FFDI model may also assist forest and fire managers to better meet land management goals and to comply with air quality and greenhouse gas emission obligations under the Kyoto protocol. Given the difference observed between low FFDI fires (characteristic of prescribed fires and low intensity fires) and high FFDI fires (characteristic of wildfires), the FFDI model will improve woody fuel consumption estimates within national carbon accounting systems which are currently based on a simple model which assumes 50% of the woody fuel load is burnt during forest fires under a broad range of conditions.

6.3. Limitations

The combined datasets used for both model evaluation and model development are limited by quantity of data and breadth of conditions under which experiments were conducted. Woody fuel consumption was highly variable (ranging between 9 and 100%) and many of the variables that have been found in previous studies to affect woody fuel consumption, were correlated.

Evaluation results for existing models are based on a dataset where woody fuel consumption is limited to relatively low to moderate intensity and mostly under prescribed burning conditions. The CONSUME and BURNUP models were developed for North-American conifer forests, and fundamental differences in fuel particle characteristics (e.g. decay, density) and fuelbed structure exist between conifer forests and the eucalypt forests used in this study.

Only a small proportion (15%) of the dataset used to develop FFDI and fireline intensity models was collected under high intensity wildfire conditions (FFDI > 18). The shape of both generalised linear models are highly influenced by the wildfire data points and both should be interpreted and applied with care.

Correlated variables together with limited variation in burning conditions within the dataset used to explore the ignition and consumption of individual wood fuel particles hindered potential model development. Fire weather and fire behaviour conditions were restricted to the spectrum of fire weather and behaviour typically observed in prescribed burning operations. Expanding the dataset to include additional medium and high intensity fires would benefit analysis and improve understanding of combustion stages and how woody fuel characteristics affect the proportion of woody fuel consumed.

6.4. Key recommendations and further research

6.4.1. Testing and validation of woody fuel consumption models

Both FFDI and fireline intensity models which predict woody fuel consumption require evaluation and validation. To do this, additional woody fuel consumption data is required, particularly representing fires burnt under high fire potential and intensity. Accurate field observations of woody fuel consumption are difficult to collect with opportunistic observations of wildfires and high intensity fire experiments both costly and difficult to implement. Nonetheless, opportunistic data collection at long term CWD monitoring sites (e.g. *Forestcheck* sites in Western Australia (Abbott and Burrows, 2004)) and at locations burnt by high intensity wildfires (possibly including paired burnt and unburned sites with matching characteristics) present valuable options.

6.4.2. Improved understanding of processes and variables determining woody fuel consumption

To improve understanding of the determinant variables and physical processes influencing woody fuel consumption, a broader dataset with a wide range of burning conditions and large sample size is necessary. Any additional data should provide accurate consumption outcomes at both the plot level (to allow testing and validation of FFDI and/or fireline intensity models) and individual particle level (to improve understanding of combustion stages). This additional data will enable further modelling of woody fuel ignition and consumption on a size class basis without limitations of burning conditions.

6.4.3. Improved understanding of woody fuel dynamics, carbon storage and potential impacts of climate change

Application of both FFDI and fireline intensity woody fuel consumption models requires prior knowledge relating to the load and dynamics of woody fuels within forest systems over time. While some data exists within each Australian state quantifying woody fuel load, most of this data is unpublished and relates to limited forest and fuel types at a particular point in time (Woldendorp *et al.*, 2002a). Together with the uncertainties that exist regarding the methodology used to collect woody load data and the scarcity of information regarding the impact of decay on wood density, volume and cycles, makes current calculations of woody fuel load volumes limited and unreliable (Grierson *et al.*, 1992; Mackensen *et al.*, 2003).

Further research and more robust figures are required to accurately account for temporal changes in woody fuel biomass and carbon stocks within eucalypt forests in southern Australia, particularly if woody fuel consumption models are to be used for broad-scale application (e.g. carbon accounting, integrating within geographic and spatial information systems). This information is also crucial for assessing the potential impacts of climate change across the Australian landscape where eucalypt woody fuels make an important contribution to the biosphere carbon pool and have important role in potential strategies for increasing terrestrial carbon stocks (Bauer *et al.*, 2006). Data collected and reported by state agencies also require a more consistent approach in order to draw accurate conclusions about the trends in wildfire numbers and area burnt (Gould and Cheney, 2007).

6.4.4. Improved understanding of woody fuel moisture variability and effect on woody fuel consumption

Data collected in this study showed that woody fuel moisture was significantly correlated ($p < 0.01$) with woody fuel characteristics including diameter, degree of decay, bark, arrangement and suspension. All of these woody fuel characteristics were also significantly correlated with each other making it difficult to understand the relative effect of each independent variable and how interactions between variables influence woody fuel moisture characteristics.

Additional research providing woody fuel moisture data from southern Australian eucalypt forests that adequately captures moisture variability and isolates the effect of correlated variables is needed in order to determine why such an evident relationship between woody fuel moisture and consumption was not apparent in the dataset. Further research is also needed to confirm whether a moisture threshold for ignition and combustion exists in Australian eucalypt forest woody fuels and if it does, at what moisture content extinction occurs.

Appendix 1.

Down but not out: Discovering the significance of dead wood.

Hollis, J.J., Whitford, K., Robinson, R., Danti, S., 2008. Down but not out: Discovering the significance of dead wood. Landscope 24, 10-16.

by Jennifer Hollis, Kim Whitford, Richard Robinson and Stephen Danti

Down but not out:

discovering the significance of dead wood

Dead wood may not have the visual appeal of live trees but it plays a highly important role in forest ecosystems.

There is perhaps nothing in the forest more majestic or enchanting than a huge, ancient and gnarly tree. These stately beauties create an atmosphere of awe and wonder, but when they die and fall over, little thought is given to what happens to the dead wood that falls to the forest floor. Dead wood was once thought of as forest waste, of no use but to be gathered up and burnt, but we now realise that dead wood is far from dead—it is teeming with life. The end of the life of a forest veteran marks the beginning of life for a myriad of other organisms—and the initiation of a recycling process that is important for the future health and vitality of forest ecosystems. The shell of these old giants that once provided valuable habitat and structural features within the forest canopy now continues the same roles and more on the forest floor.

Ecologists call these newly fallen and decaying logs and branch wood 'coarse woody debris', and it is an important component of forest ecosystems. It provides habitat on the forest floor, a source for nutrient and carbon cycling, fuel for forest fires, and a substrate for many organisms that depend on dead wood for their survival. The process of decay adds nutrients to soils and the lives of many organisms involved in the decay process, or that simply live within hollows of logs, are intertwined.

Recycling in action

Once on the ground, a fallen log begins to dry, bark is shed and the wood cracks allowing water to enter. Bacteria, invertebrates and wood decay fungi begin to colonise the fallen logs. Decay progresses as cycles of wetting and drying enlarge cracks which funnel water into the heart of the log, furthering the decay process. A moist environment is created encouraging complex interactions between the decay process and the succession of organisms. In this way, dead wood becomes habitat for a wide range of organisms including bacteria, fungi, protozoa, nematodes, lichens, invertebrates and other plants and animals which use or remove the remaining tissue. The process of decay is not swift and for large jarrah logs it may take as long as 100 years or more. Termites can influence this progression at any time as they invade after fungi colonise dead wood and begin to break down the woody tissue.

Disturbances such as fire and timber harvesting can substantially change the volume of coarse woody debris, its pattern of distribution and its decay state, all of which can impact significantly on communities of organisms that use dead wood as habitat.

Vital habitat

Coarse woody debris provides important habitat for many species. Logs and branches of various sizes scattered over the forest floor break up the terrain and moderate the extremes of weather by providing shelter from the sun, wind and rain, as well as valuable protection from radiant heat during fires.

In wet regions of the south-west, large moss-covered logs provide suitable habitat for ferns like the forked spleenwort (*Asplenium aethiopicum*) and seedlings of other plants establish themselves on dead wood or stumps in the final stages of decomposition. Ground-dwelling invertebrates, like cockroaches, beetles and worms, live and breed on, in, under and about the coarse woody debris. They form a major component of the food web and the diet of many forest mammals and birds.

Previous page
Main Forked spleenwort fern on moss-covered log.
Photo – Richard Robinson/DEC
Inset Fungi growing from a decaying gum nut.
Photo – Wanda Finkle/Sallyanne Cousans Photography

Below Napolean skink (*Egernia napoleonis*).
Photo – Jennifer Hollis

Below right Rosenberg's monitor (*Varanus rosenbergi*).
Photo – Duncan Sutherland

Above Juvenile numbats playing at the entrance to their home log.
Photo – Jiri Lochman

Right Onycophoran velvet worms are rare survivors of the ancient super-continent Pangea and rely on well-rotted logs for habitat.
Photo – Janet Farr

Animal life

Logs that sit above the surrounding vegetation provide a sunning platform for larger reptiles such as Rosenberg's monitors (*Varanus rosenbergi*), which emerge from their burrows in winter to bask and revitalise themselves during breaks from their hibernation. Napoleon skinks (*Egernia napoleonis*) hide deep in cracks and crevices that form as dead wood dries with age. Marbled geckos (*Christinus marmoratus*) shelter under the bark and in cracks and various small skinks bask and hunt on the surface of dead wood. Dugites (*Pseudonaja affinis*) sometimes nest in hollow logs and, for large goannas, the hollows provide a den for refuge.

Mammals such as the chuditch (*Dasyurus geoffroii*), numbat (*Myrmecobius fasciatus*), mardo (*Antechinus flavipes*), and western pygmy-possum (*Cercatetus concinnus*) also live and breed in the hollows of decaying logs. Hollows suited to larger mammal fauna are uncommon and occur only in the largest logs. The relative scarcity of these large hollows makes them particularly valuable biological resources.

Invertebrates also make good use of dead wood. There are more species of insects in the world than any other group of organisms. In fact, beetles alone account for 25 per cent of the global species count. Yet, many invertebrate species are still undescribed and very little is known about their life history patterns. What invertebrates lack in size they definitely make up in effort. They are vital in aiding the breakdown of organic matter which returns carbon and other nutrients to the soil. They also assist with the pollination of flowers and are themselves a food source for many birds and mammals. Coarse woody debris is particularly important for many invertebrate species, being used as habitat for many groups including slaters and millipedes, centipedes and spiders. For wood-boring beetles it is also an important food source and for parasitic wasps, a habitat for reproduction. In the southern jarrah forests, Onycophorans, or velvet worms, rely on large well-rotted logs for their survival. Onycophorans are little changed from their ancient ancestors. There are marine Onycophorans fossils more than 540 million years old.

Wood-inhabiting fungi

Like invertebrates, fungi are extremely diverse and numerous and the majority are undescribed. They are important forest organisms (see 'Forest fungi: lifestyles of the little known', *LANDSCOPE*, Spring 2002). Wood and litter-inhabiting fungi are the forest recyclers, decomposing logs and other dead wood that accumulates during the life of a forest. Decomposition of dead wood by fungi releases large amounts of nutrients back into the soil, which is important for maintaining soil fertility and forest health. A single log may support many species of fungi. Some rot the bark, others rot the

sapwood or specialise in rotting heart wood and there are different species of fungi associated with different stages of decay. A number of species, including *Podoscypha petaloides*, are only associated with large logs or wood in an advanced state of decay, so it is important to maintain and conserve old dead wood. Wood-rotting fungi are very diverse in shape and colour. They vary from the common mushroom shape, to being woody or tough brackets, having a jelly-like texture, leathery fan-like structures or simply thin flat or wrinkled sheets on the surface of the wood. Fungi invade and rot wood via thread-like filaments called mycelium and their spore-bearing fruit bodies are generally only seen in the autumn and winter. It is the thread-like filaments that actively release enzymes and other compounds that degrade wood and release compounds for their own nutrition, while also creating suitable environments for invertebrates.

Lichens and mosses

Dead wood also provides an important habitat for lichens and mosses. Lichens represent a symbiotic relationship between algae and fungi. They colonise the surface of logs and other woody debris. There are many species of lichens in the south-west forests. Lichens don't have roots—some attach to the wood by short root-like structures called rhizoids or holdfasts and others sit passively on the surface. They gain nutrition through photosynthesis by the algal partner as well as from their substrate either by releasing weak acids that gradually erode the surface or by absorbing nutrients that become dissolved in water that flows over the surface. Many species are susceptible to pollutants, which makes them important indicators of healthy ecosystems.

Top left Thread-like mycelium can be seen in well-rotted banksia wood if the bark is removed.

Centre left Fan-shaped *Trametes versicolor* are common on stumps and small logs in the early stages of decay.

Left The fairy castle lichen (*Cladonia cervicornis* var. *verticillata*) grows in well-decayed crevices of rotting logs.
Photos – Richard Robinson/DEC

Right A camera (shown in photo opposite) captures a time sequence of images of a decayed marri log consumed by a prescribed fire in the jarrah forest near Hester as part of collaborative research between DEC, Bushfire CRC and CSIRO Sustainable Ecosystems.
Photos – Jennifer Hollis

Lichens are well known 'primary colonisers' so most species are found on dead wood where the surface is still more or less intact. Species more commonly found on the ground may be present on the surface of decaying logs or on decomposed heaps of organic matter produced by large logs in the final stages of decay. The structure of lichens found on wood varies from being branched and plant-like to coral-like, flat and foliose or crust-like structures. Their fruit bodies are generally cup or disc-shaped or line-like structures on their upper surface.

Mosses cover old logs in wet or shaded situations. Like lichens, many mosses are pioneer colonisers on bare surfaces. They act like sponges to absorb nutrients and store water that would otherwise be lost through run-off. This stored moisture benefits other organisms in dry periods. A good cover of moss on large logs also reduces evaporation and maintains humidity within the wood, which is vital for the continuance of decomposition. Many invertebrates use mosses and lichens for shelter and protection and some likely use them as a food source. However, a thick covering of leaves and small twigs will retard the development of lichens and mosses because they need sufficient light to flourish.

Carbon cycling

On 3 December 2007, the Australian Government agreed to ratify the Kyoto Protocol, which came into effect in March 2008. Since then, Australian media has headlined talks of emission cuts, global warming and carbon taxes, offsets and trading. While everyday Australians grapple with reducing their own carbon footprint, the Australian Government is undertaking an ongoing accounting of all relevant ecosystem components that contribute to greenhouse gas sources and sinks in order to achieve its Kyoto obligations. But how does this relate to our forests and the coarse woody debris that lay within them? The coarse woody debris within our forests is a significant source of carbon which can remain in the ecosystem for many years before being released to the atmosphere—either slowly through decay or rapidly through combustion when burnt in a forest fire. Coarse woody debris is an important part of a continuous cycle where carbon stocks move between the living biomass, dead organic matter and the soil and are significantly affected by disturbances such as wildfires, storms and timber harvesting. This makes accounting for its contribution to the carbon stocks of a whole ecosystem a tricky process. For example, in the jarrah forest the coarse woody debris on the ground can contribute up to 32 per cent of the above-ground forest biomass and carbon stock and, when a wildfire sweeps through, coarse woody debris volume can be significantly reduced resulting in changes to carbon stocks and increased greenhouse emissions.

At a regional scale, forest fires have an impact on the dead woody material and the forests' carbon budget for many years. This will vary from forest to forest and due to differences in the fire behaviour and weather conditions

under which they are burnt. The relative emissions from each fire will vary as well, including variations in the amount and type of emissions such as carbon dioxide, carbon monoxide and methane. For example, a prescribed burn with its characteristic low intensity and mosaic of burned and unburned areas will consume less of the dead woody material on the forest floor and produce less in the way of greenhouse gas emissions compared to an intense wildfire.

On a local scale, variations exist between species for each piece of dead wood lying on the forest floor in terms of the length of the decay process and how moist they are. For example, jarrah logs tend to burn hot and relatively quickly compared to marri, which can burn and smoulder for weeks and even months after a fire. These local variations have a significant effect on the heat radiating from the fire ground as well as the fire behaviour characteristics that influence smoke and convection column development, the potential for re-ignition and the strategies that fire managers implement for fire suppression.

Top Ancient mossy stumps, Porongurup National Park.
Photo – Rob Olver

Right Small funnel-shaped *Podoscypha petaloides* fungus on a moss-covered log.
Photo – Richard Robinson/DEC

The projected impacts of climate change will affect Western Australian fire regimes and the biodiversity for which the southern forests are so well known. Climate models suggest that the south-west is expected to become increasingly warmer and drier which will consequently affect wildfire seasons and the period suitable for prescribed burning. For fire and land managers, such as the Department of Environment and Conservation (DEC), understanding the effects that altered fire regimes could have on the amount and quality of coarse woody debris and the resulting implications for carbon stocks and cycles within a forest ecosystem is becoming increasingly important.

Where to from here?

Monitoring of forest biodiversity through DEC's FORESTCHECK monitoring program has greatly increased knowledge of the rich array of forest species that use and depend on coarse woody debris (see 'Keeping our forests in check', *LANDSCOPE*, Autumn 2004). In addition, understanding how fire affects coarse woody debris and the carbon stored within it is growing, as scientists across the world focus their attention on the details of forest carbon cycling. This evolving knowledge has motivated DEC researchers and collaborators to focus their attention on the role of course woody debris in the south-west forest ecosystems.

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