



Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



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

J.J. Hollis^{a,c,b,*}, S. Matthews^{b,c,h}, R.D. Ottmar^d, S.J. Prichard^d, Slijepcevic^e, N.D. Burrows^f,
B. Ward^f, K.G. Tolhurst^{e,c,g}, W.R. Anderson^a, J.S. Gould^{b,c}

^a University of New South Wales at the Australian Defence Force Academy, Canberra, ACT 2600, Australia

^b CSIRO Sustainable Ecosystems and CSIRO Climate Adaptation Flagship Bushfire Dynamics and Applications, GPO Box 284, Canberra, ACT 2601, Australia

^c Bushfire Cooperative Research Centre, Level 5, 340 Albert Street, East Melbourne, VIC 3002, Australia

^d USDA Forest Service Pacific Northwest Research Station – Pacific Wildland Fire Sciences Laboratory, 400 North 34th Street, Suite 201, Seattle, WA 98103, USA

^e Department of Sustainability and Environment, Level 4, 8 Nicholson Street, East Melbourne, VIC 3002, Australia

^f Department of Environment and Conservation, Locked Bag 104, Bentley Delivery Centre, WA 6983, Australia

^g Department of Forest and Ecosystem Science, University of Melbourne Creswick, VIC 3363, Australia

^h Faculty of Agriculture, Food, and Natural Resources, University of Sydney, 1 Central Ave, Australia Technology Park, Eveleigh, NSW 2015, Australia

ARTICLE

INFO

Article history:

Received 19 March 2010

Received in revised form 3 June 2010

Accepted 5 June 2010

Keywords:

Woody fuel consumption

CONSUME

BURNUP

Model assessment

Eucalypt forest fire

Coarse woody debris

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 Tumbumba 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.

© 2010 Elsevier B.V. All rights reserved.

1. 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,b; 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).

* Corresponding author at: CSIRO Sustainable Ecosystems – Bushfire Dynamics and Applications, GPO Box 284, Canberra, ACT 2601, Australia. Tel.: +61 2 6242 1677; fax: +61 2 6242 1705.

E-mail address: Jennifer.Hollis@csiro.au (J.J. Hollis).

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. dalrympleana* 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. diversicolor*) 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 (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 data sets 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%.

1.1. 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 1990s, 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-h (MEAS-Th), adjusted 1000-h (ADJ-Th), or NFDRS (Cohen and Deeming, 1985) 1000-h (NFDRS-Th) lag time fuel moisture

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 and 5 where 'sound' and 'rotten' distinctions are made for sizes 3, 4 and 5	Sizes ^a 1, 2, 3, 4 and 5 where 'sound' and 'rotten' distinctions are made for sizes 3, 4 and 5	Sizes ^a 1, 2, 3, 4 and 5 where 'sound' and 'rotten' distinctions are made for sizes 3, 4 and 5	Sizes ^a 1, 2, 3, 4 and 5
Woody fuel moisture content	Sizes 1, 3 and all logs >0.6 cm	Size 3	Size 3	Sizes 1, 2, 3, 4 and 5
Area burnt	*			
Wood density				Sizes 1, 2, 3, 4 and 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.

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.

1.1.1. 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 offuels 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 (Hail, 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%.

1.1.2. 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 and 22.5 cm in diameter is by far the most critical variable in determining how much fuel will be consumed (Sandberg and Ottmar, 1983).

1.2. 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 ($1750 \text{ J kg}^{-1} \text{ K}^{-1}$), thermal conductivity ($0.13 \text{ W m}^{-1} \text{ K}^{-1}$), heat content (18676 J kg^{-1}) (Burrows, 1994), ash content (1%), ignition temperature (600 K) (Albini and Reinhardt, 1995), and char temperature (650 K).

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).

2. 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 (Fig. 1 and Appendix Ca, and Cb). 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 (Fig. 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 (Fig. 1 and Appendix Cc). 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 (Fig. 1 and Appendix Cd). 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.

2.1. 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.

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):

$$W = \frac{(f^2/8 \cdot n \cdot QMD^2 \cdot \rho_p)}{L} \quad (1)$$

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:

$$W = \frac{\pi^2 \cdot \rho_p}{8L} \sum d_i^2 \quad (2)$$

in Eqs. (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

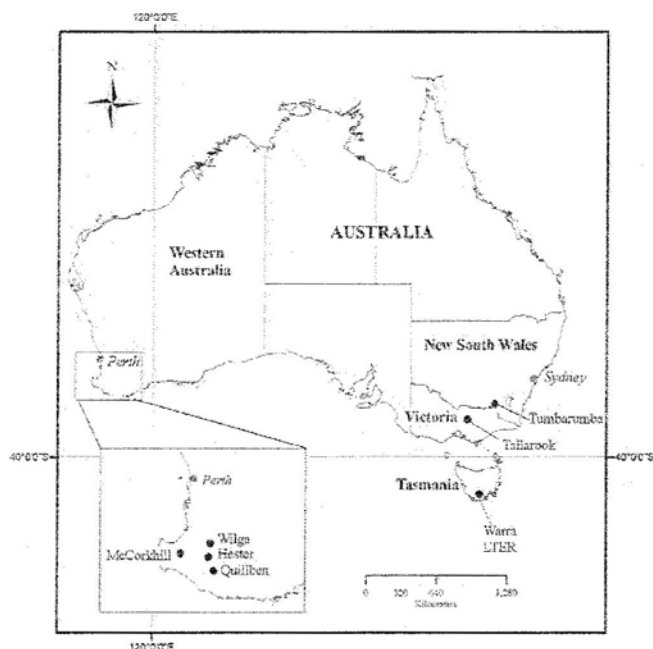


Fig. 1. Location of field sites across southern Australia.

Table 2
Summary of site characteristics.

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

^a Stern et al. (2000).

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 1 × 1 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 Roussopoulos, 1974):

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

where

$$s = \sqrt{1 + \left(\frac{\text{percent slope}}{100} \right)^2} \quad (4)$$

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 Roussopoulos, 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.

2.2. 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 h. Samples were oven-dried at a nominal temperature of 105°C for 24 h 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):

$$I = H \cdot w \cdot r \quad (5)$$

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 (ms⁻¹). For the Warra silvicultural burns where fuels were ignited using central ignition techniques, the

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 (<i>Lag time</i>)	Size class	Project Aquarius	Warra	Tumbarumba
0.60–2.50 cm (<i>1 h</i>)	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 (<i>10 h</i>)	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 (<i>100 h</i>)	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 (<i>1000 h</i>)	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.

Table 4Summary 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	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 (<i>E. marginata</i>) sites	Decay was not assessed. For CONSUME decay class was based on the average proportion of 'sound' to 'rotten' found at jarrah (<i>E. marginata</i>) 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 (<i>E. marginata</i>) forest. Random sample of at least 20 of each size class by species then submersion method (Technical Association of the Pulp and Paper Industry, 1994)
WFCP-Hester	389 (190–400)			
WFCP-Tallarook	400			
Project Aquarius	584 (60–1620)			
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	
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).

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.

2.3. 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):

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

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

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

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

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

3. Results and discussion

3.1. 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 and 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 diameter) contributing to a total woody fuel load of 175 Mg ha⁻¹, over double the average for other sites (Fig. 2).

Modified fuelbeds at the Warra LTER sites had higher than average fuel loads in each of the size classes (Fig. 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

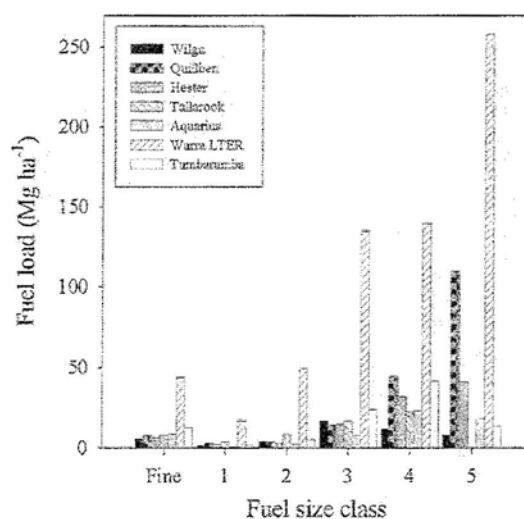


Fig. 2. Pre-fire fuel load distribution by size class across the woody fuel consumption field sites where size classes are fine fuel: <0.6 cm; 1: 0.6–2.5 cm; 2: 2.51–7.5 cm; 3: 7.51–22.5 cm; 4: 22.51–50 cm; 5: >50 cm.

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

Site	Burn and ignition type	Mean rate of spread (ROS)	Residence time	Source of weather data
WFCP–Wilga	Silvicultural slash and 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, 10 m wind, air temperature and relative humidity (RH)
WFCP–Quiliben	Ecological and fuel reduction prescribed burn. Long line >150 m length			Weather station located approximately 500 m away in open field measuring rainfall, 10 m wind, air temperature and RH
WFCP–Hester	Ecological and fuel reduction prescribed burn. Long line >150 m length			Weather station located approximately 1 km away in open field measuring rainfall, 10 m wind, air temperature and RH
WFCP–Tallarook	Ecological and fuel reduction prescribed burn. Long lines and stripping >150 m length			Weather station located approximately 2 km away in open field measuring rainfall, 10 m wind, 2 m wind air temperature and RH
Project Aquarius	Research. Long line and multiple point ignitions	Periodic mapping with infra red line (IR) scanner and visual observation	Modelled (Nelson, 2003)	Weather station in close proximity measuring rainfall, 10 m wind, 2 m wind air temperature and RH
Warra LTER	Silvicultural slash/prescribed burn. Central ignition and long line stripping	Not collected. For BURNUP residence time: ROS modelled using <i>BehavePlus</i> (Andrews et al., 2008) for heavy slash fuels (fuel model 13; Anderson, 1982)	Modelled (Nelson, 2003)	Localised hand sampling and Geeveston AWS located approximately 22 km 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, 10 m open wind, 2 m in-forest wind air temperature and RH

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 Jess 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.

3.2. 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 10m 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 (FMC) 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 88-5 to 1053 MJ m⁻² at Warra 8B-3. While fireline intensity was not 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

Table 6Summary 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 hr ⁻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; U₁₀: 10 m open wind speed; KBDI: Keetch Byram Drought Index; SDI: Soil Dryness Index; ROS: rate of spread.

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.

3.3. 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 and 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% to 56.9% with highest woody fuel consumption (56.9%) occurring at Hester 1 which had the highest fireline intensity (678 kWm⁻¹) and the lowest woody fuel consumption 42.2% at Hester 3 (284 kWm⁻¹) and 43.5% at Hester 4 (52.9 kWm⁻¹). This supports the find-

ings of Tolhurst et al. (2006) where woody fuel consumption increases with fireline intensity, at least at the lower range of intensities.

3.4. 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 Fig. 3a–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 Fig. 3a–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

Table 7Summary 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)

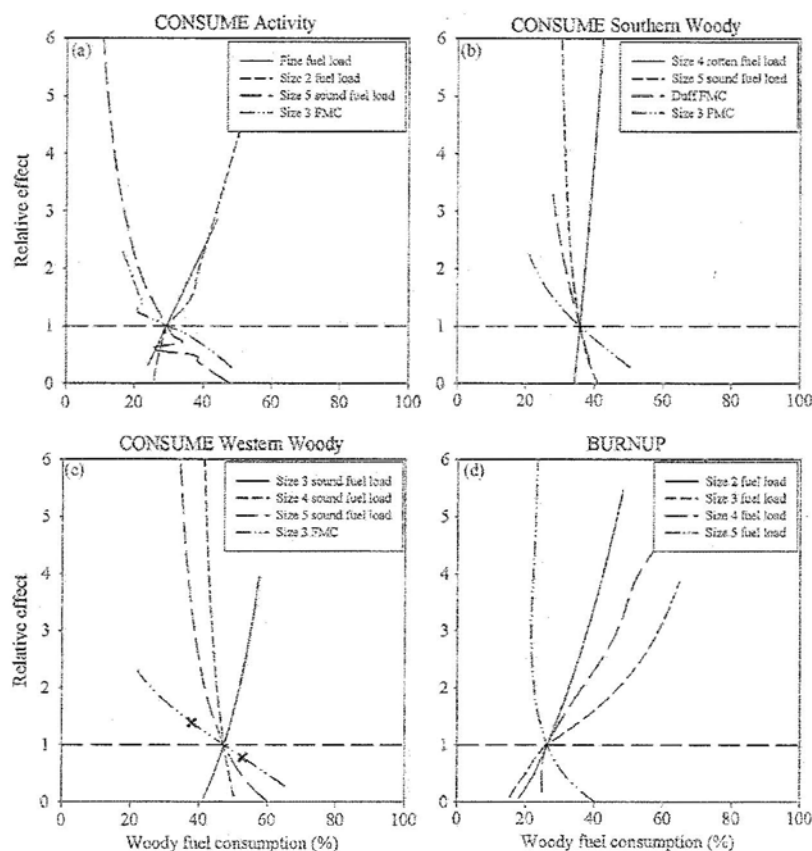


Fig. 3. Relative sensitivity of the (a) CONSUME Activity, (b) CONSUME Southern Woody, (c) CONSUME Western Woody, and (d) BURNUP models to the four most influential variables for each model. Variable effects are bounded by the limits of the field dataset; except for size 3 fuel moisture content (%) where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

beyond these extremities when more than one variable is varied per simulation.

Observed fuel consumption data was plotted against an primary model variables for our dataset (Fig. 4a–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 (Fig. 4a–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 ($R^2 = 0.097$) (Fig. 4k). This result suggests that model performance based on our dataset and using these as key variables is likely to be poor.

3.5. Prediction of woody fuel consumption

Fig. 5a–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% and 89.9%. The CONSUME Western Woody model had very little bias (–1.9%) and a larger range of predicted woody fuel consumption, 38.2–76.2%. For each of the CONSUME models a good proportion of predictions were within $\pm 10\%$ 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 eval-

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 and WFCP Data)	45.16	45.16	47.96	86.99
BURNUP (Warra Data)	19.03	–16.28	25.63	77.49
ANCAS woody fuel consumption equals 0% 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.

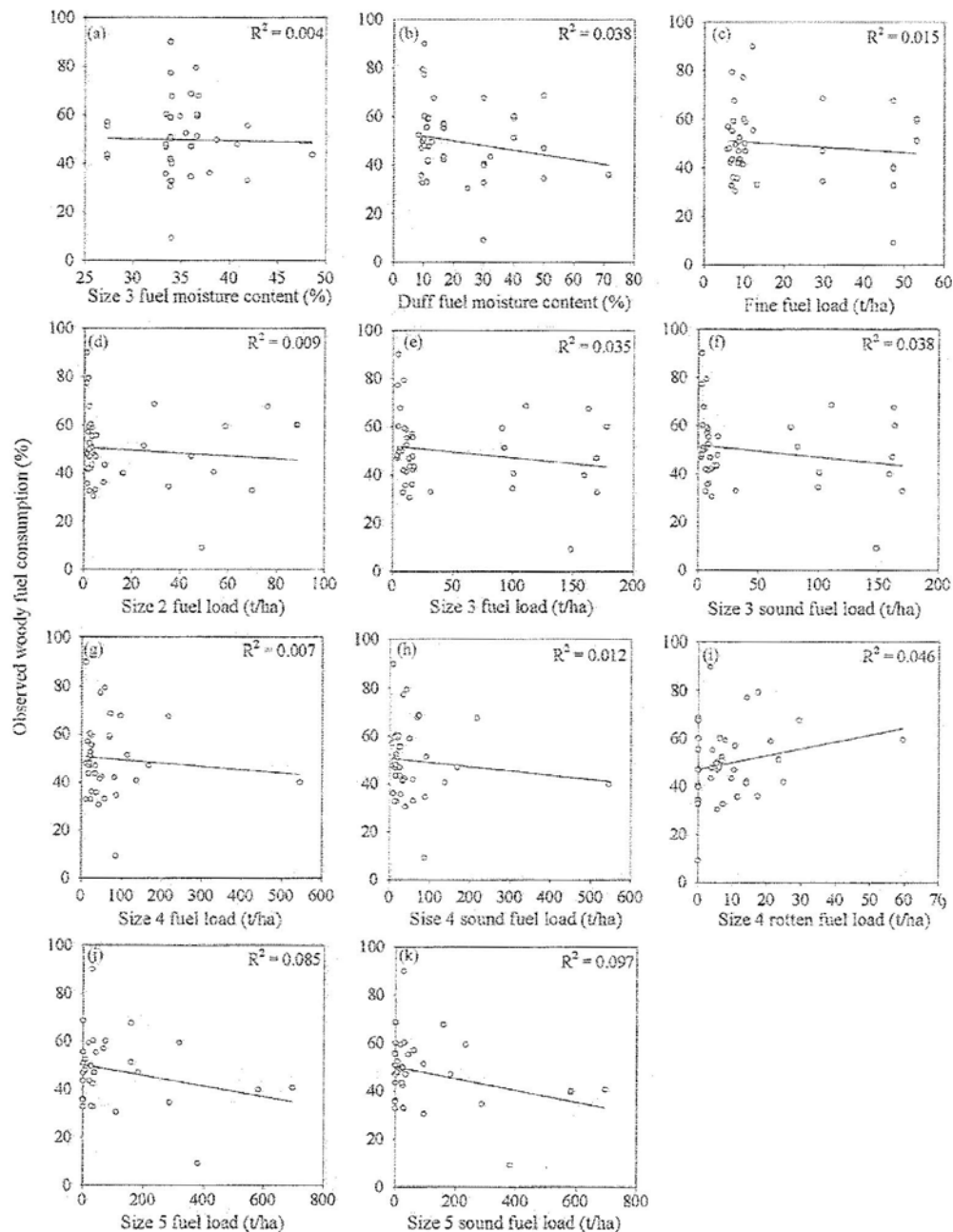


Fig. 4. Regression relationships of the woody fuel consumption dataset and primary influencing variables for CONSUME and BURNUP models for (a) size 3 fuel moisture content (%), (b) duff fuel moisture content (%), (c) fine fuel load (Mg ha^{-1}) and the woody fuel loads for (d) size 2, (e) size 3, (f) 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.

uation 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 MAE 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 equa-

tion which gave the largest MAE (37.5%) for the Southern model as well.

It was evident from Fig. 5d 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 under-predicted 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 (Fig. 6a) with the other sites such as Hester (Fig. 6b). At the Hester site, the small fuels <7.5 cm in diameter (size classes 1 and 2)

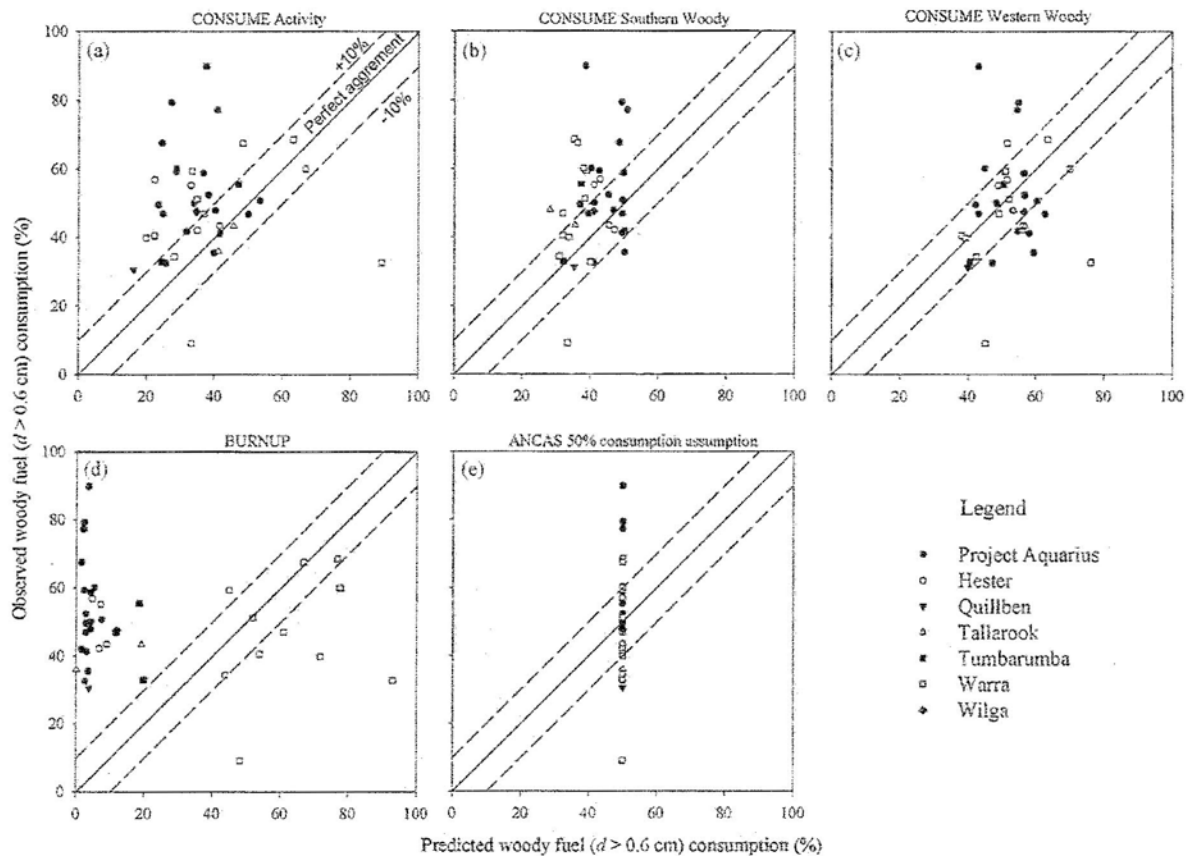


Fig. 5. Predicted versus observed woody fuel consumption for (a) CONSUME Activity, (b) CONSUME Southern Woody, (c) CONSUME Western Woody, (d) BURNUP and (e) ANCAS assumption of 50% for site woody fuel consumption.

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 >22.5 cm in diameter (size classes 4 or 5) 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

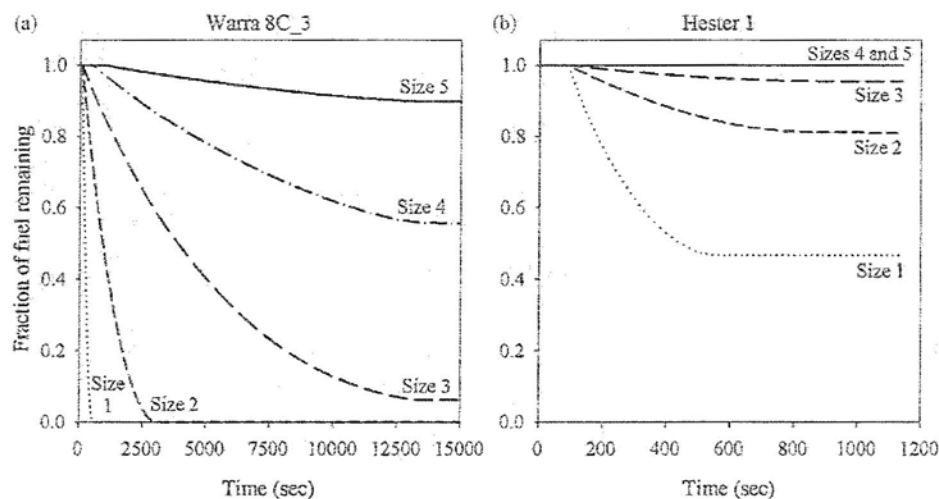


Fig. 6. Time series plots of fuel consumption by size class in the BURNUP model at (a) Warra 8C-3 and (b) Hester 1 burns.

Warra LTER data and 44.2% for all other sites, an improvement of 1.5 and 0.9% respectively.

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 $\pm 10\%$ 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 (Fig. 4a–k).

3.6. 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.

4. 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 $\pm 10\%$ 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.

Acknowledgements

Many thanks to the Bushfire Cooperative Research Centre, the Department of Environment and Conservation, Western Australia

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

(DEC), the Department of Sustainability and Environment, Victoria (DSE) and the CSIRO Sustainable Ecosystems Bushfire Dynamics and Applications team who have supported and financially contributed to the Woody Fuel Consumption Project. Without the help of researchers, technical staff and fire crews, this work would not have been possible. Many thanks also to Phil Cheney and the staff

at DEC for their support, contributions and data collected during Project Aquarius and to Jon Marsden-Smedley, the Tasmanian Fire Research Fund and Forestry Tasmania for sharing data from the Warra LTER site. We also thank Mark Finney for his support and assistance with the Burnup model code and Miguel Cruz for his comments on drafts of this paper.

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
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

Burn ID	RH (%)	T (°C)	U ₁₀ (km h ⁻¹)	KBDI	SDI	ROS (m h ⁻¹)	Residence time (s)	Heat release (kJ m ⁻²)
Warra 1A-1	90.0	17.0	2.5	–	41	–	266.0	551,538
Warra 1A-2	90.0	17.0	2.5	–	52.4	–	266.0	332,767
Warra 1A-3	90.0	17.0	2.5	–	52.4	–	266.0	379,947
Warra 8B-1	52.0	19.0	2.5	–	52.4	–	388.6	868,428
Warra 8B-2	52.0	19.0	2.5	–	52.4	–	388.6	831,813
Warra 8B-3	52.0	19.0	2.5	–	52.4	–	388.6	1,053,203
Warra 8B-4	52.0	19.0	2.5	–	52.4	–	388.5	233,956
Warra 8B-5	52.0	19.0	2.5	–	52.4	–	388.6	184,719
Warra 8C-1	70.4	17.8	2.5	–	31	–	459.7	703,382
Warra 8C-2	70.4	17.8	2.5	–	31	–	459.7	511,239
Warra 8C-3	70.4	17.8	2.5	–	31	–	459.8	474,887

RH: relative humidity; T: temperature; U₁₀: 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
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, Tumberumba.



References

- Abbott, I., Burrows, N.D., 2004. Monitoring biodiversity in jarrah forest in south-west Western Australia: the FORESTCHECK initiative. In: Lunney, D. (Ed.), Conservation of Australia's Forest Fauna, second edition. Royal Zoological Society of New South Wales, Mosman, NSW, pp. 947–958.
- Albini, F.A., 1976a. Computer-based Models of Wildland Fire Behavior: A Users' Manual. USDA Forest Service, Intermountain and Range Experiment Station, Ogden, UT.
- Albini, F.A., 1976b. Estimating Wildfire Behavior and Effects. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
- Albini, F.A., Brown, J.K., Reinhardt, E.O., Ottmar, R.D., 1995. Calibration of a large fuel burnout model. *International Journal of Wildland Fire* 5 (3), 173–192.
- Albini, F.A., Reinhardt, E.D., 1995. Modeling ignition and burning rate of large woody natural fuels. *International Journal of Wildland Fire* 5 (2), 81–91.
- Albini, F.A., Reinhardt, E.D., 1997. Improved calibration of a large fuel burnout model. *International Journal of Wildland Fire* 7 (1), 21–28.
- Alexander, M.E., Cruz, M.G., 2006. Evaluating a model for predicting active crown fire rate of spread using wildfire observations. *Canadian Journal of Forest Research* 36 (11), 3015–3028.
- Anderson, H.E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. General Technical Report INT-122. USDA Forest Service, Intermountain Research Station, Ogden, UT.
- Anderson, H.E., 1990. Relationship of Fuel Size and Spacing to Combustion Characteristics of Laboratory Fuel Cribbs. Research Paper INT-424. USDA Forest Service, Intermountain Research Station, Ogden, UT.
- Andrews, P.L., Bevins, C.R., Seli, R.C., 2008. BehavePlus Fire Modeling System, Version 4.0: User's Guide. General Technical Report RMRS-GTR-106WWW Revised. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.
- Bertschi, I., Yokelson, R.J., Ward, D.E., Babbitt, R.E., Susott, R.A., Goode, J.G., Hao, W.M., 2003. Trace gas and particle emissions from fires in large diameter and belowground biomass fuels. *Journal of Geophysical Research* 108 (013), 8-1-8-12.
- Brown, J.K., 1974. Handbook for Inventorying Downed Woody Material. General Technical Report INT-16. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
- Brown, J.K., Reinhardt, E.D., Fisher, W.C., 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. *Forest Science* 36 (7), 1550–1566.
- Brown, J.K., Roussopoulos, P.J., 1974. Eliminating biases in the planar intersect method for estimating volumes of small fuels. *Forest Science* 20, 250–256.

- Burrows, N.D., 1987a. Fire Caused Bole Damage to Jarrah (*Eucalyptus marginata*) and Marri (*Eucalyptus calophylla*). Research Paper Number 3. Department of Conservation and Land Management, WA.
- Burrows, N.D., 1987b. The SoU Dryness Index for use in fire control in the south-west of Western Australia. Technical Report No. 17.
- Burrows, N.D., 1994. Experimental development of a fire management model for jarrah (*Eucalyptus marginata* donn ex sm.) forest. PhD Thesis. Department of Forestry, Australian National University.
- Byram, G.M., 1959. Combustion of forest fuels. In: Davis, K.P. (Ed.), *Forest Fire: Control and Use*. McGraw-Hill, New York, pp. 61–89.
- Call, P.T., Albini, F.A., 1997. Aerial and surface fuel consumption in crown fires. *international journal of Wildland Fire* 7 (3), 259–264.
- Catchpole, W.R., Wheeler, C.J., 1992. Estimating plant biomass: a review of techniques. *Australian Journal of Ecology* 17, 121–131.
- Chatto, K., Tolhurst, K.G., 1997. The Development and Testing of the Wiltronics t-h Fine Fuel Moisture Meter, Fire Management Research Report No. 46. Department of Natural Resources and Environment, Victoria.
- Cheney, N.P., 1981. Fire behaviour. In: Gill, A.M., Groves, R.H., Noble, I.R. (Eds.), *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 151–175.
- Cohen, J.D., Deeming, J.E., 1985. The National Fire-Danger Rating System: Basic Equations. General Technical Report PSW-82. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.
- Eron, Z., 1991. Using Fuel Moisture Sticks for High-Intensity Planned Burns. Forestry Commission, Hobart, Tasmania.
- Finney, M.A., 1998. FARSITE: Fire Area Simulator-Model Development and Evaluation. Research Paper RMRS-RP-4. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Finney, M.A., Seli, R.C., Andrews, P.L., 2003. Modeling Post-frontal Combustion in the FARSITE Fire Area Simulator. In: *Proceedings of the 2nd International Wildland Fire Ecology and Fire Management Congress*, Orlando, FL.
- Fosberg, M.A., 1970. Drying rates of heartwood below fibre saturation. *Forest Science* 16 (1), 57–63.
- Garden, J.G., McAlpine, C.A., Possingham, H.P., Jones, D.N., 2007. Habitat structure is more important than vegetation composition for local-level management of native terrestrial reptile and small mammal species living in urban remnants: a case study from Brisbane, Australia. *Austral Ecology* 32 (6), 669–685.
- Gould, J., 2003. Fire behaviour: integrating science and management. In: Cary, G.J., Lindenmayer, D., Devers, S. (Eds.), *Australia Burning: Fire Ecology, Policy and Management Issues*. CSIRO Publishing, Collingwood Australia, pp. 55–64.
- Gould, J., Cheney, N.P., 2007. Fire management in Australian forests. In: Raison, R.J., Squire, R.O. (Eds.), *Forest Management in Australia: Implications for Carbon Budgets*. Australian Greenhouse Office.
- Gould, J.S., Cheney, N.P., Hutchings, P.T., Cheney, S., 1996. Final Report on Prediction of Bushfire Spread for Australian Co-Ordination Committee International Decade of Natural Disaster Reduction (IDNDR). Project: 4/95. CSIRO Forestry and Forest Products Bushfire Behaviour and Management Group.
- Hail, J.N., 1991. Comparison of fuel consumption between high intensity and moderate intensity fires in logging slash. *Northwest Science* 65 (4), 158–165.
- Hirsch, K.C., Martell, D.L., 1996. A review of initial attack fire crew productivity and effectiveness. *International journal of Wildland Fire* 6 (4), 199–215.
- Jones, P., 1978. **Fuel Removal, Fuel Conditions and Seedbed Preparations in Karri Slash Disposal Burns**. Research Paper No. 42. Forests Department of Western Australia.
- Keetch, J.J., Byram, G.M., 1968. A Drought Index for Forest Fire Control. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
- Knapp, E.E., Keely, J.E., Ballenger, E.A., Brennan, T.J., 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* 208, 383–397.
- Loane, I.L., Gould, J.S., 1986. Aerial Suppression of Bushfires: Cost-benefit Study for Victoria. National Bushfire Research Unit, CSIRO Division of Forest Research, Canberra, ACT.
- Mackensen, J., Bauhus, J., 1999. The Decay of Coarse Woody Debris. National Carbon Accounting System Technical Report No. 6. Australian Greenhouse Office.
- Makridakis, S., Wheelwright, S.C., Hyndman, R.J., 1998. *Forecasting: Methods and Applications*, third edition. John Wiley and Sons.
- Marsden-Smedley, J.B., Slijepcevic, A., 2001. Fuel characteristics and low intensity burning in *Eucalyptus obliqua* wet forest at the Warra LTER site. *Tasforests* 13 (2), 261–280.
- Maser, C., Tarrant, R.F., Trappe, J.M., Franklin, J.F., 1988. From the Forest to the Sea: A Story of Fallen Trees. General Technical Report PNW-GTR-229. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
- McArthur, A.G., 1967. Fire Behaviour in Eucalypt Forests. Leaflet No. 107. Forest Research Institute, Forestry and Timber Bureau.
- McArthur, A.G., 1973. Forest Fire Danger Meter MkV.
- McCaw, W.L., Smith, R.H., Neal, J.E., 1997. Prescribed burning of thinning slash in regrowth stands of karri (*Eucalyptus diversicolor*). I. Fire characteristics, fuel consumption and tree damage. *International Journal of Wildland Fire* 7 (1), 29–40.
- McRae, D.J., 1980. Preliminary Fuel Consumption Guidelines for Prescribed Burning in Ontario Slash Fuel Complexes. Report O-X-315. Canadian Forest Service, Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario.
- Miehs, A., York, A., Tolhurst, K., Di Stefano, J., Bell, T., 2009. Sampling downed coarse woody debris in fire-prone eucalypt woodlands. *Forest Ecology and Management* 259 (3), 440–445.
- Mount, A.B., 1972. The Derivation and Testing of a Soil Dryness Index using Run-off Data. Bulletin NO.4. Tasmanian Forestry Commission.
- Nelson, J.R.M., 2003. Reaction times and burning rates for wind tunnel headfires. *International journal of Wildland Fire* 12 (2), 195–211.
- O'Loughlin, E.M., Cheney, N.P., Burns, J., 1982. The bushrangers experiment: Hydrological response of a eucalypt catchment to fire. In: *Proceedings of the First National Symposium on Forest Hydrology*. The Institution of Engineers, Australia.
- Ottmar, R.D., Burns, M.F., Hall, J.N., Hanson, A.D., 1993. Consume Version 1.0. General Technical Report PNW GTR 304. USDA Forest Service, Pacific Northwest Research Station.
- Ottmar, R.D., Hall, J.N., Vihnanek, R.E., 1990. Improved Prediction of Fuel Consumption during Spring-like Prescribed Burns. Final Report. USDA Forest Service, Pacific Northwest Research Station, Fire and Air Resource Management Project.
- Ottmar, R.D., Miranda, A.I., Sandberg, D.V., 2009. Characterizing sources of emissions from wildland fires. In: Bytnerowicz, A., Arbaugh, M., Riebau, A., Andersen, C. (Eds.), *Wildland Fires and Air Pollution*. Elsevier, Amsterdam.
- Ottmar, R.D., Prichard, S.J., Vihnanek, R.E., Sandberg, D.V., Bluhm, A., 2006. Modification and Validation of Fuel Consumption Models for Shrub and Forested Lands in Southwest, Pacific northwest, Rockies, Midwest, Southeast and Alaska. Final Report JFSP Project 98-1-9-06. USDA Forest Service, Fire and Environmental Applications Team, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, Seattle, WA.
- Ottmar, R.D., Sandberg, D.V., 1983. Estimating 1000-hour fuel moistures in the Douglas-fir subregion. In: *Proceedings of 7th Conference on Fire and Forest Meteorology*, Ft. Collins, CO.
- Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J., 2007. An overview of the fuel characteristic classification system-quantifying, classifying, and creating fuelbeds for resource planning. *Canadian Journal of Forest Research* 37 (12), 2383.
- Potter, R.E., 2005. The role of released moisture in the atmospheric dynamics associated with wildland fires. *international Journal of Wildland Fire* 14 (1), 77–84.
- Potter, R.E., Charney, J.J., Heilman, W.E., Bian, X., 2004. Advances in fire convection dynamics. In: *Advancing the Fundamental Sciences: Forest Service National Earth Sciences Conference*, San Diego, CA, pp. 60–66.
- Prichard, S.J., Ottmar, R.D., Anderson, G.K., 2005. *Consume 3.0 User's Guide*. United States Department of Agriculture Forest Service, Pacific Northwest Research Station, Seattle, WA.
- Prichard, S.J., Wright, C.S., Vihnanek, R.E., Ottmar, R.D., 2006. **Predicting forest floor and woody fuel consumption from prescribed burns in ponderosa pine forests**. In: *Proceedings of the Third International Fire Ecology and Management Conference: Fire as a Global Process*, San Diego, CA.
- Pyne, S.J., Andrews, P.L., Laven, R.D., 1996. *Introduction to Wildland Fire*, second edition. John Wiley and Sons Inc., New York.
- Raison, K.J., Squire, R.O., 2007. *Forest Management in Australia: Implications for Carbon Budgets*. Technical Report 32. Australian Greenhouse Office.
- Reinhardt, E.D., Keane, R.E., Brown, J.K., 1997. *First Order Fire Effects Model: FOFEM 4.0, User's Guide*. General Technical Report INT-GTR-344. USDA Forest Service, Intermountain Research Station, Ogden, UT.
- Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Research Paper INT-115. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
- Rothermel, R.C. 1993. Some Fire Behaviour Modeling Concepts for Fire Management Systems**. In: *Proceedings of the 12th Conference on Fire and Forest Meteorology*, Jekyll island, GA.
- Sandberg, D.V., Ottmar, R.D., 1983. Slash burning and fuel consumption in the Douglas-fir subregion. In: *Proceedings of the Seventh Conference on Fire and Forest Meteorology Symposium Proceedings*. American Meteorological Society, Fort Collins, CO, pp. 90–93.
- Slijepcevic, A., 2001. Loss of carbon during controlled regeneration burns in *Eucalyptus obliqua* forest. *Tasforests* 13 (2), 281–290.
- Slijepcevic, A., Marsden-Smedley, J.B., 2002. In: Viegas, D.X. (Ed.), *Fuel Characteristics, Low Intensity Burning and Loss of Carbon during Regeneration Burning in Eucalyptus obliqua Wet Forest at the Warra LTER site*. Forest Fire Research and Wildland Fire Safety, Portugal.
- Stern, H., de Hoedt, G., Ernst, J., 2000. Objective classification of Australian climates. *Australian Meteorological Magazine* 49, 87–96.
- Sullivan, A.L., Knight, I.K., Cheney, N.P., 2002. Predicting the radiant heat flux from burning logs in a forest following a fire. *Australian Forestry* 55 (4), 59–67.
- Technica: Association of the Pulp and Paper Industry, 1994. *Basic Density and Moisture Content of Pulpwood*. Test Method T268 om-94. Technical Association of the Pulp and Paper Industry, Atlanta, GA.
- Tolhurst, K.G., 2009. Report on the Physical Nature of the Victorian Fires occurring on 7th February 2009. Department of Forest and Ecosystem Science, University of Melbourne.
- Tolhurst, K.G., Anderson, W.R., Gould, J., 2005. Woody fuel consumption experiments in an undisturbed forest. In: Viegas, D.X. (Ed.), *Conference Proceedings of the V International Conference on Forest Fire Research*.
- Van Wagner, C.E., 1968. The line intersect method in forest fuel sampling. *Forest Science* 14 (1), 20–26.
- Van Wagner, C.E., 1982. Notes: graphical estimation of quadratic mean diameters in the line intersect method. *Forest Science* 28, 852–855.
- Van Wagner, C.E., 1987. Development and Structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35. Canadian Forestry Service.
- Whitford, K.R., Williams, M.R., 2001. Survival of jarrah (*Eucalyptus marginata* sm.) and marri (*Corymbia calophylla* Lindl.) habitat trees retained after logging. *Forest Ecology and Management* 146, 181–197.

- Woldendorp, G., Keenan, R.J., Ryan, M.F., 2002a. Coarse Woody Debris in Australian Forest Ecosystems. A Report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Management). Bureau of Rural Sciences, Australia.
- Woldendorp, G., Spencer, R.D., Keenan, R.J., Barry, S., 2002b. An Analysis of Sampling Methods for Coarse Woody Debris in Australian Forest Ecosystems. A report for the national greenhouse strategy, module 6.6 (criteria and indicators of sustainable forest management). A Report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Management). Bureau of Rural Sciences, Australia.