Forest Ecology and Management 260 (2010) 948–964

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

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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 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.

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).

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doi:10.1016/j.foreco.2010.06.007

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 (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%.

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