Abstract. Coarse woody debris serves many functions in forest ecosystem processes and has important implications for fire management as it affects air quality, soil heating and carbon budgets when it combusts. There is relatively little research evaluating the physical properties relating to the combustion of this coarse woody debris with even less specifically addressing decomposition, a condition that eventually affects all debris. We review studies evaluating the combustion and consumption of coarse woody debris in the field and under controlled conditions. The thermal properties affected by decomposition are also reviewed, as are current modelling tools to represent their combustion. Management implications and suggestions for future research are then presented.

Introduction

Coarse woody debris (CWD) is dead, woody material in all stages of decay (Graham *et al*. 1994) with a diameter ≥7.62 cm, either resting on the ground surface or partially buried. This material accumulates as trees die through succession, insect- and disease-induced mortality, wind- and weather-induced mortality, and timber-harvesting activities (Graham *et al*. 1994). CWD serves numerous forest ecosystem functions and is abundant in most systems from 1.1 Mg ha^{-1} in some boreal forests (Krankina and Harmon 1995) to 140 Mg ha^{-1} in old-growth mixed-conifer forests (Spears *et al*. 2003). CWD has the potential to sequester several megagrams per hectare of carbon, in some instances up to 50% of a forest carbon budget (Davis *et al*. 2003), though more typically 5–10% (Manies *et al*. 2005; Table 1). If the CWD is fully or partially consumed in a wildland fire, these carbon stores can be released in the form of various carbonaceous species such as carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4). Although the release of these emissions into the atmosphere can be modelled, the errors are believed to be high owing to our poor understanding of CWD combustion (Brown 2002).

Physical protection of the soil and plants (Graham *et al*. 1994) is among the ecosystem functions to which CWD are important. The importance of CWD to ectomychorrizae, nutrient cycling and soil function is disproportionate in relation to CWD abundance (Graham *et al*. 1994). Downed logs are used by many wildlife species for cover, den sites (Maser *et al*. 1979; Bull 2002) and forage (Bull *et al*. 2001), and aquatic species dependent on healthy stream structure and function (Harmon *et al*. 1986). CWD can also influence the success of tree regeneration by creating barriers to browsing or trampling and providing a substrate for plant germination (Ripple and Larsen 2001; Brang *et al*. 2003; Dumais and Prevost 2007). Greatly decayed CWD can hold water important to fungi and plants during dry periods (Harmon *et al*. 1986), and much non-symbiotic nitrogen is fixed in CWD (Larsen *et al*. 1978; Jurgensen *et al*. 1991; Jurgensen *et al*. 1992). Benefits to wildlife and plant regeneration are often reduced when these sources of cover and habitat are consumed by fire. However, partially combusted logs play an important role in the restoration of severely burnt areas by creating physical barriers to prevent soil erosion. Additionally, log decomposition facilitates the recovery of the organic soil matter (Wohlgemuth *et al*. 2001; Cerdà and Robichaud 2009).

The consumption of CWD by fire has management significance as well. Often CWD are prone to smouldering combustion and can continue to slowly combust long after the initial fire has passed (Brown *et al*. 2003; Rabelo *et al*. 2004). During this relatively inefficient smouldering combustion phase, CWD emit large quantities of pollutants such as greenhouse gases and particulate matter (PM) (Bertschi *et al*. 2003), thus affecting regional air quality. Additionally, smouldering logs may create a hazard by providing the embers to re-ignite fires that had previously been extinguished (Brown *et al*. 2003), an event of particular concern if a fire is re-ignited in a critical area, such as within a wildland–urban interface. Although CWD are not the primary drivers of fire behaviour when taking the approach put forth by Rothermel (1972), they often constitute a substantial portion of the forest fuelbed. For this reason, knowledge of the pre- and post-fire quantities of CWD may be important in seeking to quantify fuel heterogeneity, which is likely to be an important factor in the next generation of physics-based fire spread models.

Table 1. Coarse woody debris carbon estimates for a variety of ecosystems

Environment description	Carbon load (Mg ha^{-1})	Percentage of carbon pool	References
Upland old-growth tropical rain forest (Costa Rica)	22.3	30	Clark *et al*. (2002)
10-year seedling stands of *Nothofagus* forest (New Zealand)	87.4	58	Davis *et al*. (2003)
25-year sapling stands of *Nothofagus* forest (New Zealand)	51.4	45	Davis *et al*. (2003)
120-year pole stands of *Nothofagus* forest (New Zealand)	13.0	6	Davis *et al*. (2003)
>150-year mature stands of *Nothofagus* forest (New Zealand)	11.3	6	Davis *et al*. (2003)
Mixed oak–pine forest, pre-burn (United States)	7.6	8	Hubbard *et al*. (2004)
Mixed oak–pine forest, post-burn (United States)	0.9	8	Hubbard *et al*. (2004)

Despite the effects of CWD combustion on ecology, regional air quality, and the representation of fuel beds, there are relatively few studies that evaluate the combustion of these fuels (Hao and Babbit 2007), or address the physical properties of CWD that may influence combustion (Tillman 1981; Kanury 1994; Veras and Alvarado 2006). The need to understand these physical properties, and their relative significance in the combustion process, is essential for decomposing CWD as these have undergone several physical and chemical changes that potentially affect consumption by fire. To address the concerns outlined above, our goal for this paper is to review research that has evaluated and developed models to predict the combustion of sound and decayed CWD, and to synthesise studies that have investigated the relationships between wood properties and combustion. Field inventory and estimation of CWD, being topics unto themselves, are outside the scope of this review, and have been addressed in several recent studies (Bate *et al*. 2004; Sikkink and Keane 2008; Pesonen *et al*. 2009). The present review will conclude by describing areas of further research. Though the term coarse woody debris has been used broadly in the past to refer to downed logs, snags and large branches (Harmon *et al*. 1986), we will focus only on downed logs and large downed branches.

Combustion and consumption experiments on CWD

Since the early 1970s, many scientists have documented the ecological role of CWD and the effects its combustion has on the environment (Tables 1, 2). These studies have addressed both the consumption, via mass or volume loss, and combustion processes in field and controlled laboratory settings. Most of the combustion studies in the field incorporate sound and decayed (rotten) CWD in harvested forests of the western United States or Mato Grosso, Brazil. Field studies focussing on CWD consumption have also been conducted in Australia (Tolhurst *et al*. 2006). The most common result of these studies has been the development of regression equations incorporating a variety of explanatory variables to predict consumption (Norum 1976; Sandberg and Ottmar 1983; Brown *et al*. 1991; Carvalho *et al*. 2002).

Experiments in temperate ecosystems

In the western United States, regression equations for CWD consumption have incorporated several explanatory variables. In the interior West, Norum (1976) predicted large fuel loads consumed based on fine fuel loading (≤0.63-cm diameter), large rotten fuel loading (≥7.62 cm diameter) and lower duff moisture content. In the Pacific Northwest Sandberg and Ottmar (1983) initially sought to correlate consumption with tree species, bark presence, contact with the ground and fuel moisture before determining this latter variable to be the most influential in debris consumption. Fuel moisture was a strong predictor of CWD consumption both in spring and fall (autumn) burning conditions (Ottmar *et al*. 1990). The relationship of increasing moisture content with decreased consumption was supported by Brown *et al*. (1991), who evaluated spring and fall burns of mixed-conifer logging slash in the inland north-west. This relationship between fuel moisture and consumption is reasonable given the increased energy required to drive water from wood during the heat-up and drying phases of combustion (Tillman 1981).

Differences in the combustion of sound and decayed CWD have also been observed. For example, Brown *et al*. (1985) evaluated a regression equation for consumption of sound CWD, developed in fall burns (Sandberg and Ottmar 1983). When applied to data from fall burns incorporating sound and rotten CWD (Ryan 1982) and spring and fall (Norum 1976) burns, the algorithm underpredicted consumption of decayed CWD by 35%. Similarly, relative increases in consumption of decayed CWD have been observed in interior logging slash burned in the fall, and undisturbed Australian forests in fall and summer (Tolhurst *et al*. 2006).

Recent work focusses less on CWD consumption and more on environmental effects. Researchers investigating the effect of CWD combustion on regeneration and root mortality conducted in the north-western United States found large (~40-cm diameter) decayed logs produced higher soil surface temperatures than did large sound logs (Monsanto and Agee 2008). This, and the above studies, indicate differences in the combustion and effects of sound and decayed CWD; however, little research is available specifically comparing their physical and chemical properties, which would be likely to affect combustion and consumption.

Experiments in tropical ecosystems

Research in CWD combustion in tropical ecosystems has focussed on creating a better understanding of the smouldering process and its relation to carbon emissions (Carvalho *et al*. 2001; Carvalho *et al*. 2002; Rabelo *et al*. 2004). These studies characterised carbon emission by quantifying the consumption of biomass (Carvalho *et al*. 2001), and have led to advances in our knowledge about the smouldering processes within CWD (Carvalho *et al*. 2002; Rabelo *et al*. 2004).

Table 2. Coarse woody debris (CWD) combustion experiments by region, variables investigated, focus of study, fuel type, and log condition

NEON, National Ecological Observatory Network

Ecoregion (NEON region if applicable)	Variables investigated	Focus of study	Fuel type	Log condition	Reference
North central Rockies (12)	Fuel loads $\leq$7.62 cm, fuel moisture content, duff moisture content, shrub loading, grass and forb loading, fuel depth, slope, wind speed, duff depth, average small tree diameter, fire intensity	Consumption	Natural, mature *Pseudotsuga menziesii*	Unspecified	Norum (1976)[A]
North central Rockies (12)	Season, position of logs, type of activity, diameter, moisture content	Consumption	Post-harvest conifer forest	Sound and decayed	Brown *et al*. (1991)
Pacific Northwest (16)	Measured and estimated fuel moisture, species, bark presence and contact with the ground	Consumption	Post-harvest *Pseudotsuga menziesii* and *Tsuga heterophylla*	Sound	Sandberg and Ottmar (1983)
Pacific Northwest (16)	Measured and estimated fuel moisture for 10-, 100- and $\geq$1000-h fuels	Consumption	Post-harvest *Pseudotsuga menziesii* and *Tsuga heterophylla*	Sound	Ottmar *et al*. (1990)
Tropics	C/H/N ratio, density, diameter, moisture content, porosity	Smouldering speed	Post-harvest tropical forest	Sound	Rabelo *et al*. (2004)
Tropics	Border width and curing time	Consumption, carbon emissions, soil heating, seasonal variations in consumption	Post-harvest tropical forest	Sound	Carvalho *et al*. (2001)[A]
Pacific Northwest (16)	Combustion temperature, potential root damage	Soil heating	Logs removed from field	Sound and decayed	Monsanto and Agee (2008)
Tropics	Combustion temperature, moisture content, size, species	Factors initiating and sustaining smoulder	Post-harvest tropical forest	Sound and decayed	Carvalho *et al*. (2002)
Intermountain, Pacific Northwest, and interior Alaska (12, 16)	Forest floor fuel loading, moisture content, weather	Consumption	Natural and harvested *Pinus ponderosa*, *Picea mariana*, *Abies* spp., and mixed hardwood	Sound	Ottmar *et al*. (2006)
South-west Australia	Physical dimensions, density, decay state	Consumption	Natural eucalypt	Sound and decayed	Tolhurst *et al*. (2006)

[A]Indicates CWD was included in the study, but not the primary topic of interest.

Table 3. Decay classification originally presented in Fogel *et al.* (1973)

Feature	Log decay class 1	2	3	4	5
Bark	Intact	Intact	Trace	Absent	Absent
Twigs <0.003 m	Present	Absent	Absent	Absent	Absent
Specific gravity (dimensionless)	0.474	–	0.420	0.222	0.046
Texture	Intact	Intact, partly soft	Hard, large pieces	Soft, small, blocky pieces	Soft, powdery
Wood colour	Original, colour	Original colour	Reddish brown or original colour	Reddish or light brown	Red-brown to dark brown
Epiphytes	None	None	Conifer seedlings	*Vaccinium*, moss, *Tsuga heterophylla* seedlings	*Vaccinium*, moss, *T. heterophylla* seedlings
Invading roots	None	None	Conifer seedlings	*Vaccinium*, moss, TSHE seedlings	*Vaccinium*, moss, TSHE seedlings
Fungi fruiting	Similar to Class 4	*Cyathus*, *Tremella*, *Mycena*, *Collybia*, *Polyporus*, *Fomes*, *Pseudohydnum*	*Polyporus*, *Polyporellus*, *Pseudohydnum*, *Fomes*	*Cortinarius*, *Mycena*, *Marasmius*	*Cortinarius*, *Collybia*, *Cantharellus*

Researchers studying the smouldering process evaluated fibrous logs burned in the field and laboratory. They found samples that were consumed almost completely during the smouldering period and concluded this process was controlled by a combination of oxygen supply and heat loss. Field observations showed smouldering was mainly propagated in very porous logs, and the formation of permeable ash facilitated combustion by insulating the smouldering front from heat losses (Carvalho *et al.* 2001; Carvalho *et al.* 2002). Similar conditions facilitating smouldering combustion were observed by Rabelo *et al.* (2004), who recorded several characteristics of logs undergoing smouldering combustion. Researchers found CWD that sustained smouldering had pore sizes that varied between 10 and 2000 nm in diameter (Rabelo *et al.* 2004). The smouldering fronts in these porous logs advanced depending on day and night temperatures, chemical and physical properties, location on the site, and position in relation to the ground. The rate at which smouldering fronts advanced ranged from 0.4 to 7.5 cm per h (Rabelo *et al.* 2004). The latter speed was observed in debris alternating between smouldering and flaming combustion.

Variations in CWD properties

The foci of this section are the varying properties of CWD that affect combustion. These include both physical properties such as density and porosity, and surface area-to-volume ratio, as well as other properties likely to vary within CWD such as moisture content, lignin and cellulose content, and thermal properties, which dictate how heat moves through these materials. As CWD ages, it is altered by weather and fungal decay, undergoing several physical and chemical changes that affect thermal properties. Characterising these changes in the context of CWD is difficult owing to the limited number of studies that specifically describe CWD properties with regards to combustion (Tillman 1981). However, literature on physical and chemical properties influencing the combustion of small wood samples in a laboratory setting is more easily located. In this section, we will review these properties, their changes with decay, and how they affect CWD combustion. For a review of the smouldering process itself, the authors recommend the recent review on the subject by Rein (2009).

CWD decay classification

Often when physical properties of CWD are described, they are related to degree of decay. One of the most common methods of quantifying degree of decomposition of CWD in the United States is the use of a simple five-category decay classification system such as the one used by Fogel *et al.* (1973). The majority of the categories (Table 3) rely predominately on easily observable physical features, typical examples of which may be seen in Fig. 1. This system provides a reference point for communicating the degree of decay of CWD. Originally developed for Douglas-fir (*Pseudotsuga menziesii*) in the Cascade ecoregion of the United States, the system has been used to assess decay in numerous species and ecosystems for a variety purposes including the characterisation of debris for wildlife (Maser *et al.* 1979), CWD dynamics through time (Spies *et al.* 1988), and fire effects monitoring (Lutes *et al.* 2006).

Fig. 1. Typical examples of mixed conifer coarse woody debris (CWD) in the decay classification system based on Maser *et al*. (1979).

In some cases, judging decay by the outward appearance of the logs may be a poor indicator of their overall condition. For example, logs occupying very dry exposed sites in southern Norway have appeared sound on the outside only to be decayed within (Næsset 1999). In this instance, referred to as case-hardening, decay is slowed on the surface of the log owing to inhospitable environmental conditions. Location of decay may also present some difficulty in applying this classification; several tree species are prone to heart rots, in which the core becomes rotten but the outer layers of wood remain sound.

Thermal properties of CWD by decomposition

Steinhagen (1977) published a collection of data from various sources that allow one to estimate the conductivity, diffusivity and specific heat of many species of wood in temperatures ranging from 233 to 373 K and moisture contents of up to 130%. In this case, diffusivity refers to the ability of the wood to absorb heat from its surroundings, more precisely defined by Simpson and TenWolde (1999) as the ratio of conductivity and the product of the wood density and heat capacity. TenWolde *et al*. (1988) discuss heat transfer across the wood grain, and Ragland *et al*. (1991) provide a broad summary of values describing thermal, physical and chemical properties of wood.

Data for conductivity and diffusivity for CWD in various stages of decay do not appear to be present in published literature. Characterisation of the thermal properties of decomposed wood tends to focus on the heat of combustion associated with specific species. Dobrỳ *et al*. (1986) examined the heat of combustion via semi-micro calorimeter for spruce (*Picea* spp.) affected by brown rots (*Fomitopsis pinicola* and *Serpula lacrymans*) and compared these with beech (*Fagus* spp.) wood affected by white rots (*Pleurotus ostreatus* and *Lentinus tigrinus*), and sound samples of spruce and beech. The brown rot-affected spruce produced more joules per gram than either white rot-affected beech or sound samples after they had lost 30% of their solid mass. Higher heats of combustion per gram in relation to sound wood were also observed in white-rotted (*Fomes igniarius*) aspen (*Populus tremuloides*) using a differential scanning calorimeter (Knoll *et al*. 1993). This makes sense considering the positive correlation between lignin and heat of combustion (White 1987), and the preference of some decay fungi, such as brown rot fungi, to utilise cellulose and leave behind higher concentrations of lignin.

Density

The five-category decay classification system is easy to apply, but fairly subjective. Assigning a class to a log can occasionally be challenging as downed logs can frequently exhibit characteristics from multiple decay classes (Pyle and Brown 1999). Another potential method of assessing decay is by measuring the dry wood density in grams per cubic centimetre, often abbreviated by the Greek letter ρ in the literature. Decreasing density with decay has been documented by several studies (Sollins 1982; Means *et al*. 1985; Sollins *et al*. 1987; Busse 1994), as displayed in Fig. 2 along with the reported relationships to the decay classification system. The overall decline in density with decomposition holds true in all species displayed.

Densities, and moisture, influence the thermal conductivity and diffusivity of wood (Simpson and TenWolde 1999). Generally, logs of lower density have reduced thermal conductivity compared with more dense or sound material. However, as experiments have demonstrated, less consumption of decayed wood relative to sound wood is not usually found. Density is incorporated in consumption modelling (Albini *et al*. 1995) and mathematical representations of combustion (de Souza Costa and Sandberg 2004); however, its influence in the combustion and consumption of CWD may be overshadowed by other variables such as heat losses to the environment, which have a greater influence on smoulder velocity (Rein 2009), and have been shown to be significant factors for CWD combustion (Carvalho *et al*. 2001, 2002).

Lignin and cellulose content

The heat of combustion of wood increases as the ratio of lignin to holocellulse increases (Demirbas and Demirbas 2009). This can be seen in the data recorded by Dobrỳ *et al*. (1986) and Knoll *et al*. (1993). Tillman (1981) describes the combustion process of lignin and holocellulose, and energy values for various species based on lignin content have been summarised by White (1987). Advancing decay influences this ratio (Schmidt 2006) and examples of various heat contents with various decayed samples can be seen in the 'thermal properties' subsection above.

Percentage moisture content

As moisture content increases, more energy is required to remove water during the preheating and drying phases before

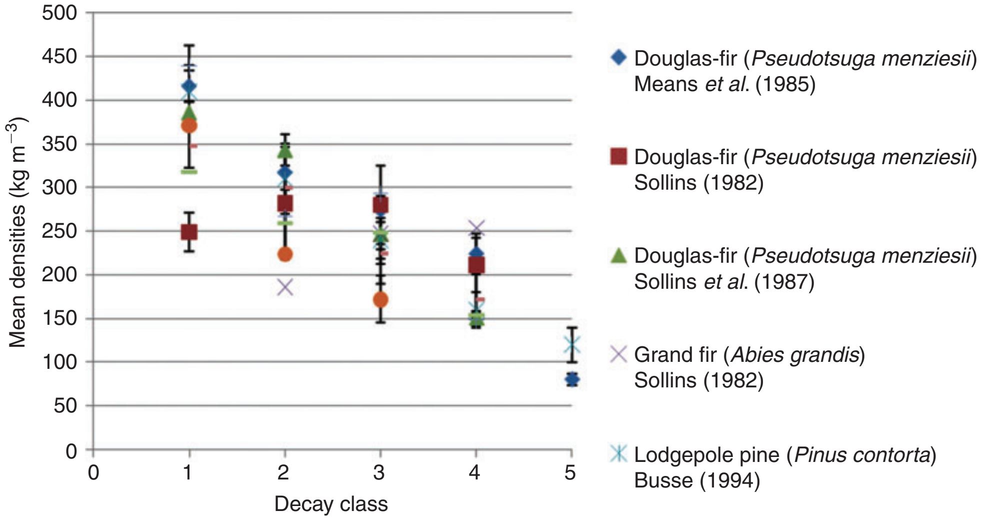

Fig. 2. Wood density changes with advancing decay in North American coniferous tree species. Standard error bars omitted where no standard error was provided.

volatile gases can be produced (Tillman 1981). For example, it has been estimated that to raise fully dried woody fuel temperatures from 298 to 673 K requires 0.42 J kg^{-1}; however, 1.46 J kg^{-1} are needed for the same temperature increase in wood with 100% moisture content (Shafizadeh and DeGroot 1977). Prescribed fire research focussing on consumption of sound woody debris has yielded strong relationships between moisture content and consumption (Sandberg and Ottmar 1983; Ottmar *et al*. 1990). Similar findings have been observed in a laboratory setting. Stockstad (1979) found increasing moisture content, from 15 to 24%, required more time to ignite decayed ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*) and subalpine fir (*Abies lasiocarpa*). Even after ignition occurs, moisture content will affect combustion by influencing the flame temperature (Babrauskas 2006), rate of combustion (Dadkhah-Nikoo and Bushnell 1994) and the volume of products resulting from combustion (Dadkhah-Nikoo and Bushnell 1994). With regard to CWD, logs in a more advanced state of decay may have a higher water-holding capacity than their sound counterparts.

Porosity

Porosity, in addition to sufficient surface area-to-volume ratio and gas permeability, is among the properties necessary for a material to undergo sustained smouldering (Ohlemiller 1985; Drysdale 1998) and is often abbreviated as φ in literature. Porosity has been noted as having an effect on fuel combustion and consumption during field studies. Carvalho *et al*. (2002) found ignition of sound CWD to occur only in highly porous or fibrous samples, and Rabelo *et al*. (2004) characterised pore sizes for their smouldering fuels as ranging from 10 to 1000 nm or larger. In the mathematical model of a smouldering log by de Souza Costa and Sandberg (2004), higher moistures are expected with fuels with less pore space.

In a controlled setting, Flournoy *et al*. (1991) evaluated the affect of decay on wood porosity and found that the pore size of sweetgum (*Liquidambar styraciflua*) inoculated with brown rot fungi (*Postia placenta*) increased to a range of 1.2–3.8 nm. These diameters are obviously much smaller than those noted by Rabelo *et al*. (2004), but give reason to expect more pore space in decayed wood than in sound wood. We looked for but found no studies documenting changes in CWD porosity with advancing decay during periods of time exceeding 1 month.

Surface area-to-volume ratio

The surface area-to-volume ratio has been demonstrated to be a critical factor in the sustained combustion of CWD (Carvalho *et al*. 2002). Rein (2009) indicates higher ratios provide more area for the smouldering front to access oxygen. In work with Douglas-fir logs in the Cascade ecoregion, Means *et al*. (1985) found the surface area-to-volume ratio of CWD to increase as decay became more advanced, though they reported some degree of this observation to be an attribute of the tree circumference during the time of mortality. Furthermore, changes in surface area-to-volume ratio might also be expected given the type of fragmentation produced by brown cubicle rot. Grier (1978) observed a decrease in CWD volume with time since death; however, the ratio of surface area to this value was not noted. Although this change in surface area-to-volume ratio is plainly visible, few studies document this characteristic over extended periods of time.

Another aspect often ignored in the literature is the fact that logs often tend to crack longitudinally, especially near the combustion zone (Veras and Alvarado 2006) where smoke and heat have been observed to emerge. This fracturing may significantly increase the surface-area-to-volume ratio. The effect of log cracks has not been included in empirical or theoretical studies of CWD consumption.

Modelling CWD combustion

The inclusion of CWD is key to modelling total fuel consumption and subsequent emissions.

CWD is not addressed in fire behaviour and spread models that are based on Rothermel's (1972) fire spread equation, as these systems operate under the premise of fine-fuel-driven spread and behaviour. This omission of CWD puts these fire behaviour and spread models outside the scope of this section. It is worth noting, however, that the US National Fire Danger Rating System (NFDRS) does include CWD (≥7.6-cm diameter) as a way of tracking seasonality of fire hazard (Burgan 1988). CWD does play a substantial role in modelling fuel consumption, heat flux and subsequent emissions, and it is these 'fire effect' and 'emission' models that will be the focus of this section. The role of CWD in physical and semi-empirical models is described below.

Physical models

There are several physical models that take into account mass transfer, thermal properties and detailed fuel inputs to represent the drying, pyrolysis and smouldering combustion of fuels and estimate both the mass loss and rate of smoulder. The term 'fuels' is used instead of 'CWD' in this instance because many models have been developed and validated with wood samples combusted on a small scale, whereas specific CWD combustion models are rare. However, given the physics-based nature of these models, they should apply equally well to CWD given adequate input information. For example, Mardini *et al*. (1996) and Peters and Bruch (2003) report thermal properties derived from laboratory experiments of wood combustion. These authors concluded that experimental and predicted results for heat-up, drying and pyrolysis were in good agreement under different fuel particle sizes and boundary conditions and that their data were applicable to large particle sizes.

Recent works representing combustion of wood have varied in their foci. Broad-application works such as those by Bilbao *et al*. (2001) have created models to represent the piloted and spontaneous ignition and subsequent smouldering rate of wood. Bryden and Hagge's (2003) representation of pyrolysis and modelling focussed on the influence of structural changes, heat transfers, and the pyrolysis process and rate in wood, and Rostami *et al*. (2004) developed a smouldering model stressing the importance of surface heat loss, heat of combustion, airflow rate and porosity on temperature and smouldering velocity. Mardini *et al*. (1996) developed a model to represent the heat and mass transfer in a wildland fire setting. This model was compared with the combustion of wooden dowels and found to be in good agreement with observed data.

More specific to CWD is de Souza Costa and Sandberg's one-dimensional mathematical model of a smouldering log (de Souza Costa and Sandberg 2004). This model represents burn rates, temperature profiles, and positions of the drying, pyrolysis and smouldering fronts. Variations in parameters such as moisture content, diameter, pyrolysis temperature, heat of char oxidation, heat of pyrolysis, porosity, density and char density are considered. This model agreed well with experimental data from Carvalho *et al*. (2002) (de Souza Costa and Sandberg 2004). A major conclusion from the latter study was that the model's performance could potentially be improved by incorporating data on finite rate kinetics for the drying and pyrolysis processes, diffusion of oxygen into porous char with volumetric char oxidation, axisymmetric burning, tar formation and deposition, and reactions inside char pores (de Souza Costa and Sandberg 2004). Furthermore, Veras and Alvarado (2006) developed a two-dimensional numerical model for prediction of smouldering front propagation and gas emissions of cylindrical logs. The numerical results of the simulations were found to be in good agreement with validation data from Carvalho *et al*. (2002).

Other authors have studied the combustion process on small-diameter fuel particles. For instance, Mardini *et al*. (1996) conducted an experimental and analytical study of heat and mass transfer in wooden dowels. Their model fails to predict mass during the drying phase because of the rapid water migration in small-diameter fuels. Peters and Bruch (2003) were able to predict mass loss of fir and spruce wood particles by including an evaporation temperature model. The results of the two previous works stress the importance of fuel moisture as a predictor variable for consumption.

Semi-empirical models

Physical models of combustion allow the incorporation of numerous inputs to represent the combustion of materials largely regardless of their spatial position. In representing combustion in a forest setting, the presence of other fuels, varying moisture contents and factors such as slope can alter the combustion CWD; variations in these factors are difficult to account for in fine-scale detail owing to the heterogeneity of forest fuels. It is in this area that semi-empirical models can be useful tools to represent combustion and consumption of fuels. The semi-empirical consumption models that were located for this review include Consume 3.0, Fire Emissions Production Simulator 1.1.0 (FEPS) and First Order Fire Effects Model 5.7 (FOFEM). These models enable users to input different variables to describe the surrounding fuels (Table 4) and subsequently report predicted fuels consumption and emissions information (Table 5).

Consume

Consume predicts fuel consumption, energy released during fire, and emissions of particulate matter, carbon monoxide, carbon dioxide, methane, and non-methane hydrocarbons (Prichard *et al*. 2005). Empirically derived consumption equations based on physical combustion properties were developed from data compiled and analysed for forested, woodland, shrubland and grassland ecosystems throughout the United States. The software requires fuel characteristics, lighting patterns, fuel conditions and meteorological attributes to populate the equations that drive the energy and emissions outputs. To use Consume, the operator must specify whether the fuel bed of interest is the result of an activity, such as harvesting, or natural accumulation. If activity is selected, it is assumed that the CWD is relatively sound and equations developed for sound wood are used for all large woody fuels. This is because the quantity of rotten wood in an activity plot is assumed to be fairly small. From this point on, the model selects the appropriate equation based on fuel moisture, days of curing, and the consumption of 100-h (2.54–7.62-cm) fuels.

In the event that natural fuels are selected, Consume selects consumption equations determined by the size class of fuel and the decay class. These equations originated from the work by Ottmar *et al*. (1990) and other studies occurring in the western

Table 4. Inputs required by semi-empirical models

An 'x' indicates that there are specific fields for these data within the user interface of the model. Asterisks indicate there are specific fields for these variables that are not labelled; however, there are unassigned stratified fields for these data to be included. FEPS, Fire Emissions Production Simulator; FOFEM, First Order Fire Effects Model; CWD, coarse woody debris

Inputs model	Consume	FEPS	FOFEM
Fuel inputs			
1-h fuel loading	x	*	x
10-h fuel loading	x	*	x
100-h fuel loading	x	*	x
1000-h fuel loading	x	*	x
>1000-h fuel loading	x	*	x
≥1000-h sound and rotten	x		x
Percentage			
Branch loading			x
Canopy loading	x	x	x
Duff depth	x		x
Duff loading	x	x	x
Herbaceous or foliage loading	x		x
Litter depth	x		
Litter loading		x	x
Litter percentage cover	x		
Shrub loading	x	x	x
Slash (broadcast) loading		x	
Slash (pile) loading	x	x	
Snag loading	x		
Moisture content inputs			
1-h fuel		x	
10-h fuel	x	x	
100-h fuel		x	x
1000-h fuel	x	x	
≥1000-h fuel			x
Duff	x	x	x
Live fuel		x	
Other inputs			
Activity or natural fuelbed	x		x
Burn area	x		
Cover type	x	x	x
Distribution of CWD			x
Fire shape		x	
Ecoregion	x	x	x
Ignition pattern	x		
Pasquill stability		x	
Percentage canopy consumed	x	x	x
Season			x
Slope	x		
Wind speed (midflame)	x		
Tree dimension measurements			x

or boreal forests (Prichard *et al*. 2005). The ≥50.8-cm diameter log consumption equation is based on a small dataset in which many of the logs sampled were rotten. The large woody fuel equations only exist for western and boreal forests and these equations are used to represent south-eastern US forests (Prichard *et al*. 2005).

Fire Emissions Production Simulator (FEPS)

Fire Emissions Production Simulator (FEPS) is the modified Emissions Production Model (EPM) (Anderson *et al*. 2004).

Table 5. Outputs generated by semi-empirical models

An 'x' indicates that there are specific fields for these data within the user interface of the model. Asterisks indicate these outputs are all grouped into one number. PM, particulate matter; NMHC, non-methane hydrocarbons

Outputs model	Consume	FEPS	FOFEM
Consumption			
Crown	x	*	x
Duff	x	*	x
Herbaceous	x		x
Litter	x	*	x
Percentage woody fuel	x	*	x
Shrub	x	*	x
Emissions			
PM_{10}	x		x
$PM_{2.5}$	x	x	x
CH_4	x	x	x
CO	x	x	x
CO_2	x		x
NMHC	x		
Oxides of nitrogen			x
SO_2			x
Displays heat release	x		x
Displays results by hour		x	
Displays results by combustion phase		x	x
Plum rise		x	
Buoyancy		x	
Heat release			
Crown	x		
Herbaceous	x		
Litter consumed	x		
Overall intensity	x		
Percentage woody fuel consumed	x		
Shrub	x		
Soil temperature			x
Mortality			
Tree			x

FEPS predicts fuel consumption, percentage flaming versus smouldering combustion, emissions of particulate matter, carbon monoxide and methane, and plume height based on inputs of fuel loading, moisture content and a variety of constants developed from the literature and expert opinion. There is no stratification by large fuel size or sound and rotten.

First Order Fire Effects Model (FOFEM) and BURNUP

The First Order Fire Effects Model (FOFEM) predicts fuel consumption, emissions of 2.5- and 10-μm particulate matter ($PM_{2.5}$ and PM_{10}), methane, carbon dioxide, carbon monoxide, oxides of nitrogen and sulfur dioxide, as well as tree mortality and soil heating (Reinhardt *et al*. 1997). Inputs required for FOFEM include fuel loading by size class, fuel moisture, duff depth and percentage of CWD that is rotten, as well as information on the abundance of ground fuels. Tree species are required for the mortality section. FOFEM uses the BURNUP model to predict the consumption of woody debris such as CWD (Reinhardt 2005).

The BURNUP model uses a mix of heat transfer theory and empirical observations that replaced earlier work by Albini

(Albini 1976; Albini and Reinhardt 1995). It bases consumption on the calculated time to ignition and heat transfer of woody fuels subjected to a fire environment. Once the fuel loading by size class has been input, a given heat source is applied to the fuels. Depending on the time required for ignition and heat transfer, the model determines whether woody fuels have ignited and are being consumed. Calculations were derived by observing forest fuels, sound and rotten, immersed in flame (Albini and Reinhardt 1995). Empirical data from crib and field burns were used to calibrate the equations (Albini *et al*. 1995).

Discussion

Conclusion

This review has summarised existing research relating to the combustion and consumption of CWD. We recommend research aimed at improving the characterisation of these fuels, improving our understanding of the relative influence of wood properties on combustion, and increasing the number of eco-systems in which *in situ* burn data are collected. Specifically, current literature does not characterise multiple variables affecting combustion of CWD with regards to their relative importance during the combustion process. More information on this subject would improve our basic understanding of combustion in these fuels. Current models in use would benefit from on-site burns in multiple ecosystems, which could be used for validation, and to potentially improve existing algorithms. The effectiveness of these models could also be enhanced by investigating the need for stratification to address decayed fuel, and to what degree stratification is necessary. This would allow us to better address the heterogeneity inherent in CWD.

More research in these areas would provide modellers with information to further develop their products in such a way as to more accurately represent the complexity of surface fuels commonly consumed by fire in a variety of ecosystems. Increasing the accuracy of consumption estimates gives managers and researchers more accurate information on how much material will exist in the post-fire environment for wildlife use, tree regeneration and carbon storage. This would also allow improved emissions production estimates, which could be incorporated into dispersion and concentration models.

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