Consumption of sound and rotten coarse woody debris from a Northern Idaho mixed conifer forest

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AUTHORIZATION TO SUBMIT THESIS

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Abstract

Coarse woody debris in various states of decay is found in abundance in numerous forested ecosystems, serves a variety of ecosystem functions, and has the potential of affect air quality as it combusts. However, our understanding of the quantities of this debris consumed in forest fires is poor, especially when addressing debris in various states of decomposition; a condition which eventually affects all debris. In this study we examine the effect of decay on consumption and the wood properties of coarse woody debris using three numeric decay classification systems for logs between 7and 23 cm in diameter and moisture contents between 6 and 13%. Results indicate that coarse woody debris in class four, the most advanced decay class, are likely to consume to a greater degree than logs in classes one through three. This supports the current convention of grouping all the classes into two broad categories, sound and rotten, in semi-empirical models such as Consume and the First Order Fire Effects Model. Intermediate classes showed high variation in consumption; this was in part due to surface properties which impact the decay classification and do not reflect the condition of the entire log. For this reason we suggest the use of physical properties to predict consumption of these fuels. In examining debris properties, wood density, lignin content, and volumetric heat content, were the most highly correlated with consumption. This study should be repeated in areas with different decomposition and combustion dynamics, such as that found in the southeastern United States.

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Dedication

This work is dedicated to my family and friends. Thanks to all of you for being there and listening to all my continuous updates on this project. Whether I was praising something that went well, or lamenting something that didn't, you always listened just as intently.

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Chapter 1

The Combustion of Sound and Rotten Coarse Woody Debris: A Review

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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 fewer specifically addressing decomposition; a condition which 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 modeling 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 Mg ha^{-1} 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 modeled, the errors are believed to be high due to our poor understanding of CWD combustion (Brown 2002).

Physical protection of the soil and plants (Graham *et al.*1994) are among the ecosystem functions to which CWD are important. The importance of CWD to ectomychorrizae, nutrient cycling, and soil function is disproportionate 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 upon 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 2001; Cerdà and Robichaud 2009).

The consumption of CWD by fire has management and scientific significance as well. Often CWD are prone to smoldering 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 smoldering 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, smoldering logs may create a hazard by providing the embers to re-ignite fires which 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. While CWD are not the primary drivers of fire behavior 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.

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 impact consumption by fire. To address the concerns outlined above, our goal for this paper is to review research which has evaluated and developed models to predict the combustion of sound and decayed CWD, and to synthesize 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). This 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.* 1993), we will focus only on downed logs and large downed branches.

Combustion and consumption experiments on CWD

Since the early 1970s multiple scientists have documented the ecological role of CWD and the impacts its combustion has on the environment (Tables 1 and 2). These studies have addressed both the consumption, via mass or volume loss, and combustion processes in field and controlled lab 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 focusing 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 upon fine fuel loading (≤ .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 to debris consumption. Fuel moisture was a strong predictor of CWD consumption both in spring and fall 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 northwest. 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 under-predicted 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 focuses less on CWD consumption and more on environmental effects. Researchers investigating the impact of CWD combustion on regeneration and root mortality conducted in the northwestern United States found large (approximately 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 focused on creating a better understanding the smoldering process and its relation to carbon emissions (Carvalho *et al.* 2001; Carvalho *et al.* 2001; Rabelo *et al.* 2004). These studies characterized carbon emission by quantifying the consumption of biomass (Carvalho *et al.* 2001), and have led to advances in our knowledge about the smoldering processes within CWD (Carvalho *et al.* 2002; Rabelo *et al.* 2004).

Researchers studying the smoldering process evaluated fibrous logs burned in the field and laboratory. They found samples to consume almost completely during the smoldering period and concluded this process was controlled by a combination of oxygen supply and heat loss. Field observations showed smoldering was mainly propagated in very porous logs, and the formation of permeable ash facilitated combustion by insulating the smoldering front from heat losses (Carvalho *et al.* 2001; Carvalho *et al.* 2002). Similar conditions facilitating smoldering combustion were observed by Rabelo *et al.* (2004) who recorded several characteristics of logs undergoing smoldering combustion. Researchers found CWD that sustained smoldering had pore sizes which varied between 10 and 2,000 nm in diameter (Rabelo *et al.* 2004). The smoldering 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 smoldering fronts advanced ranged from 0.4 to 7.5 cm per hour (Rabelo *et al.* 2004). The latter speed was observed in debris alternating between smoldering and flaming combustion.

Variations in CWD properties

The foci of this section are the varying properties of CWD that effect 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 age it is altered by weather and fungal decay, undergoing several physical and chemical changes which affect thermal properties. Characterizing these changes in the context of CWD is difficult due to the limited number of studies which 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 smoldering process itself, the authors recommend the recent review on the subject by Rein *et al.* (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 Figure 1. This system provides a reference point for communicating the degree of decay of CWD. Originally developed for Douglas-fir (*Pseudotsuga menziessii*) 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 characterization of debris for wildlife (Maser *et al.* 1979), CWD dynamics through time (Spies *et al.* 1988), and fire effects monitoring (Lutes *et al.* 2006).

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 due 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 which allow one to estimate the conductivity, diffusivity, and specific heat of many species of wood in temperatures ranging from 233° K 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. Characterization of the thermal properties of decomposed wood tends to focus on the heat of combustion associated with specific species. Dobrỳ, Dziurzyński *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 utilize 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 centimeter, often abbreviated by the Greek letter ρ in the literature. Decreasing density with decay has been documented by several studies (Means *et al.* 1985; Sollins 1982; Sollins *et al.* 1987) as displayed in Figure 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 to 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 modeling (Albini *et al.* 1995) and mathematical representations of combustion (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 smolder velocity (Rein 2009), and have been shown to be significant factors for CWD combustion (Carvalho *et al.* 2001; Carvalho *et al.* 2002)

Lignin and cellulose content

The heat of combustion of wood increases as the ratio of lignin to hollocellulse increases (Demirbas and Demirbas 2009). This can be seen in the data recorded by Dobrŷ *et al.* (1986) and Knoll *et al.* (1993). Tillman (1981) describes the combustion process of lignin and hollocellulos, and energy values for various species based on lignin content have been summarized 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.

Percent moisture content

As moisture content increases more energy is required to remove water during the pre-heating and drying phases before volatile gases can be produced (Tillman 1981). For example, it has been estimated that to raise fully dried woody fuel temperatures from 298° K to 673° K it 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 focusing 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 15-24 %, 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 smoldering (Ohlemiller 1986); 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. Cavalho *et al.* (2002) found ignition of sound CWD to occur only in highly porous or fibrous samples and Rabelo *et al.* (2004) characterized pore sizes for their smoldering fuels as ranging from 10 to 1000 nm or larger. In the mathematical model of a smoldering log by 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 sound wood. We looked for but found no studies documenting changes in CWD porosity with advancing decay during periods of time exceeding one 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 smoldering 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. While 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 from. This fracturing may significantly increase the surface-area-to-volume ratio. The affect of log cracks has not been included on empirical or theoretical studies of CWD consumption.

Modeling CWD combustion

The inclusion of CWD is key to modeling total fuel consumption and subsequent emissions. CWD is not addressed in fire behavior 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 behavior. This omission of CWD puts these fire behavior 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 modeling 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 are 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 smoldering combustion of fuels and estimate both the mass loss and rate of smolder. 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 was 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.* (2004) have created models to represent the piloted and spontaneous ignition and subsequent smoldering rate of wood. Bryden and Hagge's (2003) representation of pyrolysis and modeling focused on the influence of structural changes, heat transfers, and the pyrolysis process and rate in wood and Rostami *et al.* (2004) developed a smoldering model stressing the importance of surface heat loss, heat of combustion, airflow rate, porosity on temperature and smoldering velocity. Mardini *et al.* (1996) developed a model to represent the heat and mass transfer in a wildland fire setting. This model was compared to the combustion of wooden dowels and found to be in good agreement with observed data.

More specific to CWD is Costa and Sandberg's one dimensional mathematical model of a smoldering log (2004). This model represents burn rates, temperature profiles, and positions of the drying, pyrolysis, and smoldering fronts. Variations in parameters such as moisture content, diameter, pyrolysis temperature, heat of char oxidation, heat of pyrolysis, porosity, density, char density are considered. This model agreed well with experimental data from Carvalho *et al.* (2002) (Costa and Sandberg 2004). A major conclusion from this latter study was that the models' 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 (Costa and Sandberg 2004). Furthermore, Veras and Alvarado (2006) developed a two dimensional numerical model for prediction of smoldering 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 due 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 which could be 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 into input of variety of 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 analyzed 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 upon fuel moisture, days of curing, and the consumption of 100 hour (2.54-7.62 cm) fuels.

In the event that natural fuels are selected, Consume selects a 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 or boreal forests (Prichard *et al.* 2005). The $\geq$50.8 cm diameter log consumption equation is based upon a small data set 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 southeastern 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). FEPS predicts fuel consumption, percent flaming versus smoldering combustion, emissions of particulate matter, carbon monoxide, 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, percent of CWD which 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 consuming. 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: research and management needs

CWD combustion experiments and properties

Experiments evaluating the combustion of CWD *in situ* will benefit from research focusing on multiple geographic areas. While locations in the western United States and some areas of tropical forest in Brazil often host field burns to evaluate CWD combustion, other systems such as boreal and deciduous forests are underrepresented. Due to variations in multiple field conditions such as moisture, CWD position, and the CWD itself, differing locations may exhibit different results when consumption is evaluated. Capturing and documenting this variability would increase available data which, for empirical and semi-empirical models, could be used to improve or develop new algorithms to represent consumption, or to validate the effectiveness of current algorithms in representing consumption in new locations. New datasets could also be used by modelers to evaluate the agreement between physical and semi-empirical model outputs and the results from burns occurring in various field conditions. Additionally, most experiments have taken place in logging slash, leaving little data available to represent natural fuels. On a landscape scale, in both harvested and natural fuels, further investigation should be performed to investigate the effectiveness of quantifying CWD consumption using remote sensing techniques, especially under varying degrees of severity (Lentile *et al.* 2006). One recent experiment has taken place in an African

Savannah (Smith and Hudak 2005); however there is the need to repeat this study in other regions.

CWD properties

We know more about consumption of sound CWD than we do about decaying CWD, yet more rotten wood burns. Without deeper understanding of why and how decaying wood burns, predictions of biomass consumption, residual carbon, soil effects, and other ecological effects will be less accurate. To understand the combustion process within CWD we must know the various chemical and physical states this fuel occupies. While detailed information about the role of chemical composition, moisture, density, surface area-to-volume ratio, and to some degree porosity have been collected in fine scale laboratory experiments, the relative influence of all these factors combined during the combustion and consumption of wildland fuels is seldom described, and poorly understood. Research which evaluates all of these factors and their relative influence in the combustion of CWD will improve our understanding of this process which and allow researchers the opportunity to improve combustion theory with which physically based models can be driven.

Modeling CWD combustion

There have been several physical based models to represent the combustion of biomass and wood in phases ranging from heating up to self-sustained smolder. Evaluating these models for agreement with CWD data would be a useful step forward in their application for these fuels, as of yet only the model developed by Costa and Sandberg specifically addresses CWD, but there is little reason to believe other models are not just as suitable given accurate inputs. Evaluating models for application to CWD would greatly benefit from published values on the properties of CWD in varying conditions and ecosystems, as detailed descriptions of all the inputs required for these models is either scattered throughout various subjects, incomplete, or not available.

Semi-empirical models such as Consume and FOFEM have been developed to incorporate the consumption of both sound and decayed CWD. However, sound and decayed states are often defined broadly as partially decomposed wood which fragments upon impact, such as the definition used for Consume, or it is not readily defined in the documentation, such as the case with FOFEM. This current accounting of decayed CWD does not stratify beyond 'sound' and 'rotten'. Examination of relevant literature shows little if any published work to indicate either the effectiveness of this current level of stratification, or the potential gains in accuracy that could be achieved by more detailed stratification, especially one which could define the ranges of wood properties likely to affect combustion.

Management implications

Above we have outlined areas of research that would further our understanding of CWD combustion, and our representation of this process in models for scientific and management applications. Better understanding and representation of CWD consumption is likely to facilitate more precise modeling tools to predict CWD consumption and post-fire loading. This allows land managers and fire managers to better predict how their activities impact the systems they are tasked with managing.

Better estimates of CWD consumption also have the potential to improve estimates of air quality impacts from these fuels, especially when we consider that it is often the estimates of fuel consumed that are our biggest sources of error during the development of these estimates. This aspect of management is of particular importance as air quality standards become increasingly stringent, such as the new particulate matter standards promulgated by the United States Environmental Protection Agency in 2007 (Anonymous 2007). Additionally CWD can account for large quantities of carbon (Table 1). Better estimates of the consumption of this material will also allow for more accurate accounting of carbon emissions due to the volatilization of these fuels.

Conclusion

This review has summarized existing research relating to the combustion and consumption of CWD. We recommend research aimed at improving the characterization of these fuels, improving our understanding of the relative influence of wood properties on combustion, and increasing the number of ecosystems in which *in situ* burn data is collected. Specifically, current literature does not characterize 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 to CWD.

More research in these areas would provide modelers 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 for improved emissions production estimates which could be incorporated into dispersion and concentration models.

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Chapter Two

Properties affecting the combustion of rotten coarse woody debris: experimental fires under two ignition conditions

Introduction

Wildland fires are a key aspect of ecological systems, acting as a disturbance agent that rapidly transfers biogeochemical and hydrological stocks stored in terrestrial vegetation to the atmosphere. From 2002 to 2005, PM 2.5 (particulate matter 2.5 µ or less) emissions from forests in the contiguous United States ranged from 90,720 to 181,440 Mg (Zhang, Kondragunta *et al.* 2008).Inventories of PM 2.5 emissions are important given increasing stringent air quality standards. As of 2010, > 2,832,799 ha^{-1} of land administered by the USDA Forest Service exceeded the National Ambient Air Quality Standards (NAAQS) PM 2.5 standards (Anonymous 2010).

Accurately inventorying emissions requires the best possible knowledge of factors which contribute to them, including fuel loading (Peterson 2001). A main component of many forest fuel loadings is coarse woody debris (CWD). This debris is often abundant in various states of decay in forested ecosystems, has implications for fire management (Brown, Reinhardt *et al.* 2003) and air quality (Yokelson, Susott *et al.* 1997). However, our current understanding of the quantity of this debris consumed in forest fires is poor (Hao and Babbit 2007) and is further complicated by its heterogeneous nature as it is found in multiple states of decay. In the United States 92% of the volume of CWD encountered in Forest Inventory and Analysis between 2001 and 2010 was affected by decay (USDA 2010).

To address the consumption of this decaying CWD, we investigated the several intrinsic wood properties and two ignition procedures in relation to the consumption of CWD across a range of decay states as represented by three numerical classification systems. Three research questions were addressed. Namely, (1) Are there statistically significant differences in consumption between CWD in different decay states given logs of similar size and moisture content? (2) What are the properties associated with these decay classes and to what extent do they change throughout the decay process? (3) Are differences apparent in the consumption of rotten CWD ignited with high temperature, low duration conditions and low temperature, high duration methods?

Methods

A four phased project was designed to address the above research questions. As indicated in Figure 3, the initial phase was field classification and sampling of CWD in various states of decay. This was followed by sample characterization (including measures of carbon to nitrogen (C/N) ratio, density, heat content, lignin content, moisture content, and surface area-to-volume ratio). Samples were then ignited in a laboratory setting and allowed to smolder. In the last phase these properties and classifications were compared to the percent mass loss, or consumption, of the CWD.

Study Area and Field Measurements

Samples were collected from the Priest River Experimental Forest (PREF), located in Northern Idaho. The experimental forest is an approximately 2630 ha^{-1} mountainous forest administrated by the United States Department of Agriculture Rocky Mountain Research Station from the Moscow, Idaho, Forestry Sciences Laboratory. It was chosen, as it affords considerable quantities of CWD, in varying degrees of decay. There are several habitat types within PREF with collection sites for this project falling within the *Thuja plicata* habitat series, which includes the major seral tree species *Pseudotsuga menziesii*, *Abies grandis*, *Pinus monticola*, *Picea engelmannii* and *Larix occidentalis* (Cooper, Neiman *et al.* 1991). Presence of *Larix occidentalis* on all collection sites indicated relatively dry habitat types for the *Thuja plicata* series. Soils in this habitat type contain quartzite and alluvial mixtures of metasediments, siltite, ash, and mica schist under an average litter depth of five cm.

Field collection sites (Figure 4) were selected at four locations on the Priest River Experimental Forest, brief descriptions may be found in Table 6. The sites were chosen to capture the potential variability in CWD properties and not to represent variability in abundance or landscape heterogeneity. Additionally, these sites offered accessibility by road to facilitate the harvesting and transportation of samples. At each site, a 50 m long transect line was placed at a random azimuth. All CWD between 7.62 (3 inches) and 22.89 cm (9 inches) in diameter and over one meter in length which intersected the transect were categorized using the classification systems described below and a representative 40 cm sample was harvested using a chainsaw. This harvested section was taken either at the point of intersection with the transect tape, or the nearest section indicative of the overall decay state of the CWD. Logs with more than 50% surface charring or which had a visibly abnormal abundance of pitch were omitted from sampling. While these factors are likely to influence CWD consumption, they were relatively uncommon in the sample area and were deemed outside the scope of this study. Two additional transects were placed 120 degrees apart and the above procedure was repeated. This sampling protocol is similar to the downed woody materials indicator protocol used by the US Forest Service Forest Inventory and Analysis (FIA) program (Woodall and Williams 2005), however, the transect length and number have been increased to raise the likelihood of obtaining samples meeting the size criteria. *Thuja plicata* debris was omitted due to its propensity to dry at different rates than the other species sampled.

Each CWD sample was characterized using three different numeric classification systems based upon Fogel *et al.* (1973) (Table 3), Maser *et al.* (1979) (Table 7), and an extended classification system based on a combination of examples from Fogel *et al.* 1973, Maser *et al.* 1979, Sollins (1982), and Triska and Cromack (1980) (Table 8). Once classified and cut, samples were removed from the field by being carefully wrapped in wire to prevent fragmenting of bark or wood.

Properties analysis and sample preparation

As outlined in Figure 3, characteristics were analyzed for each sample and included density, heat content, lignin content, moisture content, surface area-to-volume ratio, and a subset of C/N ratio measurements. These properties were chosen for investigation based upon the review by Hyde *et al.* (In press). Prior to properties and burning analysis, the CWD samples were conditioned to a moisture content of between 6 and 13%. Samples were initially stored in the open air, sheltered from rain, during July and part of August, allowing sufficient drying to prevent further decay that may have influenced the wood properties. Following this curing, all samples were re-located to a closed chamber with $\leq$35% humidity and temperatures ranging between 25 and 37°C. Sample preparation involved cutting each end of the sample with an un-lubricated electric reciprocating saw. This removed any wood contaminated by the oiled chainsaw blade used during field collection. Ten to 15 cm sections were then removed for property analysis. A section of the sample was removed immediately prior to burning to determine moisture content. In the case of very rotten samples, the moisture cross-section often fragmented, at which time the fragments were collected in a paper bag to be dried and weighed. These procedures yielded a 25 cm long section on which to conduct burn trials.

Several analysis methods were used to determine the CWD properties. Carbon to nitrogen (C/N) ratio for a subset of CWD samples was analyzed using a CE Instruments NC 2500 Elemental Analyzer (Wigan, United Kingdom). C/N was calculated as it has been observed to be indicative of the degree of decomposition in vegetation (Swift, Heal *et al.* 1979). Wood samples were ground into a powder capable of passing through a 2 mm mesh and packed in tin capsules. These capsules were then combusted in the analyzer.

Dry wood density was determined using the water displacement method. To obtain dry wood density a thin cross-section of CWD was cut from one end of the CWD and four sub-samples were cut from across it (Figure 5). Each sub-sample was placed in a breathable paper pouch, labeled, and dried at 104°C until its weight equalized. When dried, each sub-sample was removed from the bag and weighed. Following weighing, the sub-sample was waterproofed with melted paraffin wax, and placed in a beaker of water to determine volume. The layer of paraffin on the outside of the sample was assumed to minimally impact the volume of the sample. Density was calculated using the ration of volume of water displaced to the dry weight of each sub-sample. The values for all four sub-samples were averaged to represent the density of the CWD sample.

Heat content was determined both for the mass and volume of material. To prepare the sample for heat content analysis, wood was ground into a powder, capable of passing through a 2 mm sieve. This powder was pressed into a one gram pellet and oven dried at 104°C for 12-24 hours to remove any moisture. The pellet was then placed into a Parr brand oxygen bomb calorimeter (Moline Illinois, USA) and analyzed to obtain the gravimetric heat content in joules per gram contained in the sample. To determine the volumetric heat content, joules per gram was multiplied by the average dry wood density value for each sample. Lignin content was determined using the Klason lignin determination method on powdered wood samples in which extractives had been removed using dichloromethane solvent. To determine lignin content using the Klason method (Milne, Brennan *et al.* 1989) a small sample is submerged in two sulfuric acid bathes and allowed to dry. By weighing the sample before and after submersion in acid, the percent lignin content can be determined.

Moisture content was determined just prior to the burn trials in order to capture the most representative values. A cross-sectional slice of CWD was cut just prior to burning and weighed. This slice was then placed in a drying oven at 104°C for 48 hours (or until weight loss ceased). Following drying the sample was allowed to cool in a dedicator and weighed, this prevented errors due to water absorption. The difference in these two weights yielded the moisture content. Surface area to volume ratio of the CWD was determined by taking the length and diameter measurements for each 25cm burn sample. These numbers were entered into the surface area and volume equations for a frustum shown in Figure 6.

During these laboratory procedures wood porosity was attempted. Other works have cited the use of mercury porosimetry to determine the pore size and volume in wood, however this equipment was not accessible and another method had to be considered. Based upon input from James Reardon at the USDA Missoula Fire Lab (Reardon 2009) and Gabriëls *et al.* (1993) we attempted to measure the percent of pore space in small wood samples in the following manner. First the water displacement method was used to determine the volume of the overall wood sample. To determine the volume of voids samples were placed into porous mesh bags and submerged in water. A vacuum of 2.8 MPa was applied for one hour, after which time the samples were removed and weighed. Samples were then dried completely in an oven at 104°C and dry weights were taken. A comparison of the wet and dry weights allowed for the determination of water weight held by the sample. Since the approximate weight in grams of water to volume in cubic centimeters of water is one to one, we were able to make a determination as to the volume of voids in the sample and compare this to the overall volume. However, this method did not yield reliable measurements and this phase of the property analysis had to be abandoned. However, this did allow us to determine the water holding capacity of samples in various states of decay.

Sample Combustion

Two ignition methods were used to burn CWD samples to simulate a quick high temperature burn and a slow, low temperature, smoldering burn. Prior to burning, each sample was measured to determine its weight and volume. Samples were subject to either high-temperature ignition, or low-temperature smoldering duff ignition, and allowed to smolder on a level fire-proof surface. Each sample smoldered in a separate partition (Figure 7) to prevent the combustion of one sample influencing the combustion of another.

The first ignition method, simulating high-intensity burning, was performed using a Detroit Radiant model PT-32 high intensity infra-red heater (Detroit Michigan, USA) which was attached to a propane tank with an acetylene regulator. The sample was placed upon a bed of sand 18 cm away from the face of the heater with a concrete heat shield placed between the sample and the heater while the heating element reached its full temperature. The shield was then removed and the log was exposed to heat for 120 seconds (Figure 8). Flaming of the log surface typically occurred within 10 to 30 seconds of exposure, with the CWD experiencing surface temperatures of approximately 800°C. The log was then allowed to smolder until it extinguished.

For the second ignition method, CWD were placed on a bed of dried peat moss with two .5 cm diameter, 12 cm long, dowel rods placed just below the surface of the moss. This simulated the approximately 5 cm deep duff layer and fine fuels which was representative of the collection areas. Duff moistures ranged from 6% to 12% and the dowel rod moistures were approximately 3%. This 'duff' layer was ignited using a strip of excelsior lit with a propane torch; the peat moss was then allowed to smolder under the log exposing CWD to temperatures of approximately 500°C for several minutes, with smoldering duff cooling to approximately 300°C (Figure 9). In some instances the peat moss did not carry a smoldering front, and had to be re-ignited using a propane torch. When this occurred every sample on the table was exposed to the torch for the same duration to prevent one sample from receiving more heat than the others. The sample was then allowed to smolder until it extinguished. Consumption of CWD was determined by weighing the remains of the sample after it had extinguished and comparing this to the initial sample weight.

Prescribed Burn Validation

To examine whether the relationships between decay class and consumption were mirrored in the field, prescribed burn data was collected in the Fall of 2009. Coarse woody debris was classified using the Maser decay classification and wired to measure diameter prior to, and after, ignition via prescribed fire. This phase of the experiment took place on the East Hatter Creek Unit of the University of Idaho Experimental Forest. The Ponderosa pine (*Pinus ponderosa*) dominated unit measured 4 ha^{-1} in size. Hand ignition took place between 1226 and 1500, during which time temperatures ranged from 9.5 to 15°C with windspeeds of 1-4 km $hour^{-1}$ and relative humidity between 41% and 73%. Fuel conditions are displayed in Table 9.

Statistical Analysis

The relative material consumed in each decay class was determined using the Kruskal-Wallis Rank Sum Test (Kruskal and Wallis 1952) on the dataset following a natural log transformation. This non-parametric method was chosen after a Shapiro-Wilks (Shapiro and Wilk 1965) test indicated that the dataset did not meet the assumptions of normality, nor did the dataset contain the homogeneity of variance required for an analysis of variance test. Further exploration of wood properties in relation to consumption was conducted using the Spearman method of correlation (Spearman 1904). Total sample size for high temperature low duration ignition was 41, and 35 for low temperature high duration.

Results and Discussion

Consumption by class

Decay class four experienced greater consumption than all other classes in both the high temperature low duration and low temperature high duration ignition trials for all three classification methods (Figure 10). For CWD classified using the Maser method, the median percent mass consumed was 97.6% for class four as opposed to 9.3, 3.25, and 2.5 in classes three through one, respectively. Using the Kruskal-Wallis sum rank test to analyze the Maser method, we found class four to be significantly different than classes one through three, with a $P < 0.001$. Classes one through three were not significantly different from each other.

Using the Fogel classification system, class four experienced a median percent mass consumption of 97.6%, followed by 29.4%, 6.2%, and 2.2% for classes three through one, respectively. The Krukal-Wallis test detected differences among classes; however, class four was not able to be isolated as in the Maser classification system. The Fogel class in this case assigned more examples to class one, and produced greater variability in classes two and three.

In examining the Extended classification method, class four experienced median consumption of 97.85% followed by 68%, 3.8% and 2% for classes three through one, respectively. The Kruskal-Wallis test detected differences among classes, however, class four was not able to be isolated. This is most likely due to the propensity of the extended class to produce high variability within class three.

Consumption by class and ignition method

When each classification described above was separated by ignition method and re-analyzed the same results were observed, with the exception of the extended classification. While class four could not be isolated when analyzing the entire dataset, it could be isolated when only the low temperature high duration samples were evaluated. In that case class four was different than and all other classes with a $P < 0.02$, and no detectable differences between classes one through three was found. In all classification systems the low temperature high duration ignition method produced greater variability in consumption classes. Consumption values may be seen in Table 10.

Consumption by properties

The Spearman correlation method was used to examine the relationship between the CWD properties and consumption. When all the data was analyzed lignin content was most highly correlated to consumption, followed by density, volumetric heat content, and gravimetric heat content, respectively. Median values for these properties for each class may be seen in Table 11. For samples ignited using the high temperature low duration method C/N ratio had the strongest correlation with consumption; this was followed by lignin content, density, volumetric heat content, respectively. For the low temperature high duration method, consumption was the most strongly correlated to density, followed by lignin, volumetric heat content, and gravimetric heat content respectively. Correlation coefficients for each of the above may be seen in Table 12.

Prescribed burn validation

Volume loss by Maser class resembled laboratory results for mass loss in that class four experienced greater consumption on average than classes three through one. Percent consumption was 75% for class four, and 24%, 58% and 15% for classes three through one respectively. However, with the largest sample size being 6 for class four, and the smallest being one for class two, this was not enough data to draw any meaningful conclusions.

Consumption and Properties

To examine the consumption of CWD in a repeatable and non-subjective manner, the physical and chemical properties must be evaluated. The range of property values recorded in this study may be seen in Figure 11 (lines on each portion of the figure convey the overall trend, and are not for predictive purposes). Samples which experienced the highest levels of consumption had very low C/N ratios, indicating advanced decay. By examining the properties, these fuels are best described as a low density body of high heat content material. Though the objective of this study was to characterize properties, not state causation, we propose that one potential reason for the increased consumption could be the combination of low density (equating to lower heat conductivity), and material containing relatively more J g^{-1}. Infrared photography comparing very decayed CWD with more sound samples shows decayed CWD will maintain higher temperatures for longer durations give exposure to similar temperature inputs (Figure 12).

Another potential cause of increased consumption could be oxygen availability, a key factor in smoldering consumption of CWD (Carvalho, Veras *et al.* 2002). While density and porosity are not the same measurement, it should be noted that during the density lab analysis, there were visibly larger air spaces in the more rotten CWD samples. These air spaces could provide gaps though which oxygen could be made available to the combustion front (Alvarado 2009).

These results and properties of decaying CWD are likely dependent upon the specific decay organisms associated with CWD in the western portion of the United States. Logs in this study were predominantly affected by brown rot fungi. These organisms utilize cellulose much more readily than lignin (Schmidt 2006). This results in wood with a much higher percent content of lignin than it would originally have. Increased lignin content accounts for higher heat content (Demirbas 2001), which in large part explains the highest gravimetric heat content in highly decayed ,class four, samples. The lower volumetric heat content is due to the decline in density with decay. If this study were repeated in an ecosystem dominated by white rot fungi, the lignin concentrations and heat content is likely to be different. Surface area-to-volume ratio and percent moisture were held relatively constant during this study, so our inferences on these factors are somewhat limited. We found that neither changes in surface area-to-volume ratio for CWD between 7 and 23 cm in diameter, nor moisture contents within our range of 6-13 % had any affect on the consumption of CWD in this study.

Data was bimodal in nature for both consumption and CWD properties, with approximately 75% of the samples grouped together in the low consumption region of the graph, and the last 25%, the most decayed samples, grouped in the highest consumption region (Figure 11). This split in high and low consumption and wood properties can be seen clearly in Table 13. This may indicate a threshold beyond which the properties of the CWD are conducive to consumption. It may also be an artifact of management practices on Priest River Experimental Forest. This portion of the data indicates an area in which further research would be beneficial to further investigate the existence of a threshold in wood properties and consumption.

Classification Systems

In both the Fogel and Maser decay classification systems high variability in classes two and three are apparent, however in the Fogel system we see that the variability in class one is less. The extended classification system shows reduced variability, with the exception of class two. In all systems class four experienced distinctly higher consumption values than all other classes. The variance in these may be due, in part, to their subjective nature, and past research has found that class three, tends to capture CWD with a higher variety of attributes (Pyle and Brown 1999).

A greater potential issue is one of encountering CWD with surface characteristics that do not represent the physical properties of the log as a whole. Notice in Figure 10 the high consumption values in class 2. Two samples which consistently classed as two with all methods were samples numbered 51, and 126 (Figure 13). A look at the sample cross-sections reveals a predominantly sound log with channels of decay running through it. While these small channels of decay were only weakly represented in the overall wood properties for each of these sample they provided a sufficient environment for a sustained smolder which ultimately ignited the sound wood and led to consumption values closer to those for a class four log than a class two. These account for some of the variation visible in the classification bar charts.

All these classifications consistently sort very low consumption samples into class one, and very high consumption samples into class four regardless of ignition method. This clearly mirrors the bimodal trends in consumption results sorted by property (Figure 11), and suggests that the current stratification in Consume and FOFEM, a binary split into either sound or rotten categories, is appropriate. The issue arises in sorting logs in the intermediate classes two and three. While these still generally experience less consumption than class four logs, they are quite varied. Even in the Fogel classification system, which takes into account specific gravity, there is still high variation, and in cases such as samples 51 and 126, none of the characterization systems would have been able to predict the high consumption. A similar situation is seen in 29, in which the outer layer of the CWD appears sound, but the inner layer, in this case the majority of the material, is decayed (Figure 14). Cases such as the latter, which would cause variability in a classification system based upon surface characteristics, could more easily be identified when intrinsic properties are taken into account. We feel the variability in classes two and three could be reduced by relying on physical properties, rather than classifications which are dependent upon surface characteristics.

Management Implications

The USDA Forest Inventory and Analysis program reports 24% of CWD surveyed in the United States fell into decay class four (USDA 2010). Based upon the results of this study, under low moisture conditions, this debris is prone to extremely high consumption. The remaining 76%, in classes three through one, are more difficult to draw conclusions upon. One possibility to better characterize these fuels for input into predictive models, may be a table such as Table 13, which outlines characteristics of logs in varying states of decay, the shaded areas indicate properties which correlate to 50% consumption or greater. To bring a table such as this into use in the management community, validation of data through field burns, and a method of quickly making inferences about these properties in the field, is recommended. This could mean the development of a photo-series style guide to match logs in the field to regions of this table, or the use of one metric, such as density, and the development of a tool to quickly measure it in the field, such as a pressure gauge styled device. Either method may hold potential for taking a detailed table like this and making it applicable to a quickly conducted field protocol. Once CWD is allocated to a region of the table, it could then be better characterized for modeling purposes.

Lumping of CWD into sound and rotten classes in Consume and FOFEM appears to be capturing the bimodal nature of consumption in this study; a logical next step is evaluating the algorithms of each. It is recommended that both of these tools be evaluated in relation to how well they match consumption of decayed CWD in field conditions and assess the potential need for incorporating data from studies such as this. In the case of Consume, where CWD consumption algorithms incorporate duff moisture, and fuel loading, incorporation of this data would require the addition of physical parameters such as density, or lignin content. In the case of FOFEM, which incorporates density into algorithms, it would require evaluating whether or not there is a need to add parameters such as heat content or lignin content. Before any this undertaken of course, extensive field validation would be necessary, as this is are preliminary study, and is limited by a relatively small sample size and lack of supporting field data.

Other considerations

An important note on the surface area-to-volume in this study is the fact that this was estimated using the area and volume equations for a frustum. This method is quick to derive, though it provides a course view of the actual surface area due to its inability to capture surface texture. Specifically, sound CWD samples, often without bark, had a relatively smooth surface when compared to rotten class four material, in which brown cubicle rot had created a checkerboard pattern of cracking, protrusions, and high points formed as the wood decayed and fragmented. A method which more accurately captures these differences in surface textures may indicate a stronger relationship between surface area to volume ratio and consumption than that reported in this study. For solid wood particles the method by Fernandes and Rego (1998) may be a better indicator, however its application to highly decayed samples, such as those found in decay class four, presents difficulty due to the frailty of the material and its propensity to absorb water when dry.

Logs in more advanced states of decay may be more conducive to holding moisture. This was demonstrated in a failed attempt to measure wood porosity for this project. When samples of CWD in the lab were submerged in water under 2.8 Mpa^{-1} of pressure and weighed, samples in class four had twice the water-holding capacity on average than samples in classes one through three. As such, there may be a threshold beyond which the propensity of this fuel to burn is overshadowed by high moisture contents which require a prohibitively large amount of energy to drive moisture from the wood.

Conclusion

The study demonstrates that in general once a log achieves a certain degree of decay, such as represented by the median wood property values for class four in Table 10, near complete consumption is likely. Given 24% of CWD surveyed under the USDA Forest Service FIA program falls into this category or higher, decayed CWD is likely to create substantial amounts of emissions due to its increased consumption. All classification systems surveyed in this study tended to accumulate variation in middle classes. For this reason physical properties are recommended as a more consistent and reliable measure of potential consumption. Specifically, density, lignin content, and C/N ratio which are all highly correlated with consumption and change with increasing decay in a relatively predictable manner show potential.

The bimodal nature of consumption data appears to be in agreement with the current convention of lumping CWD into two broad categories of "sound" and "rotten" in systems such as Consume and FOFEM. Once that distinction is made however, the algorithms of each should be evaluated. This study indicates rotten CWD are likely to consume to a high degree, and sound CWD are likely to experience less consumption overall, but experience higher variability. Examining consumption data from the field and comparing it to this would help determine if this is a consistently occurring pattern. If so, consumption predictions may possibly be improved upon by incorporating CWD properties which change with decay and are correlated with consumption such as C/N ratio, lignin content, and density.

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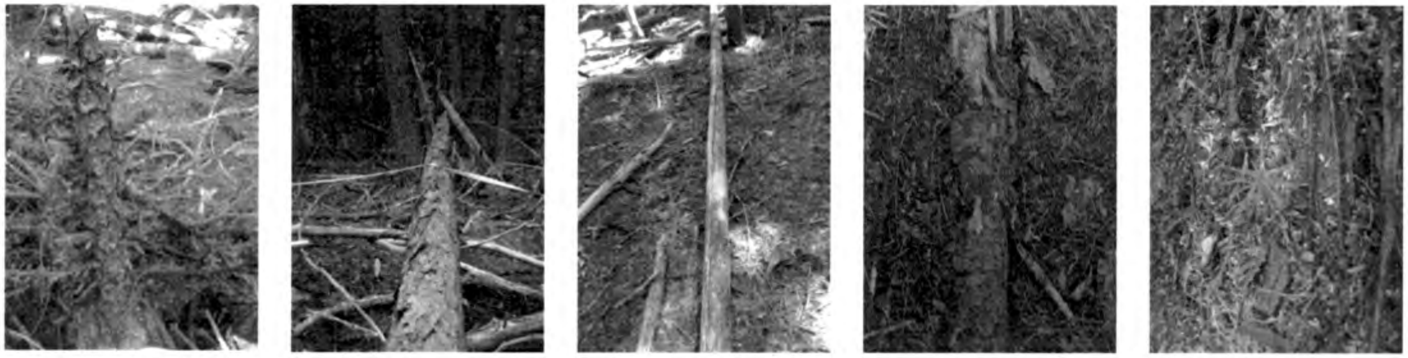


Class 1 Class 2 Class 3 Class 4 Class 5

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

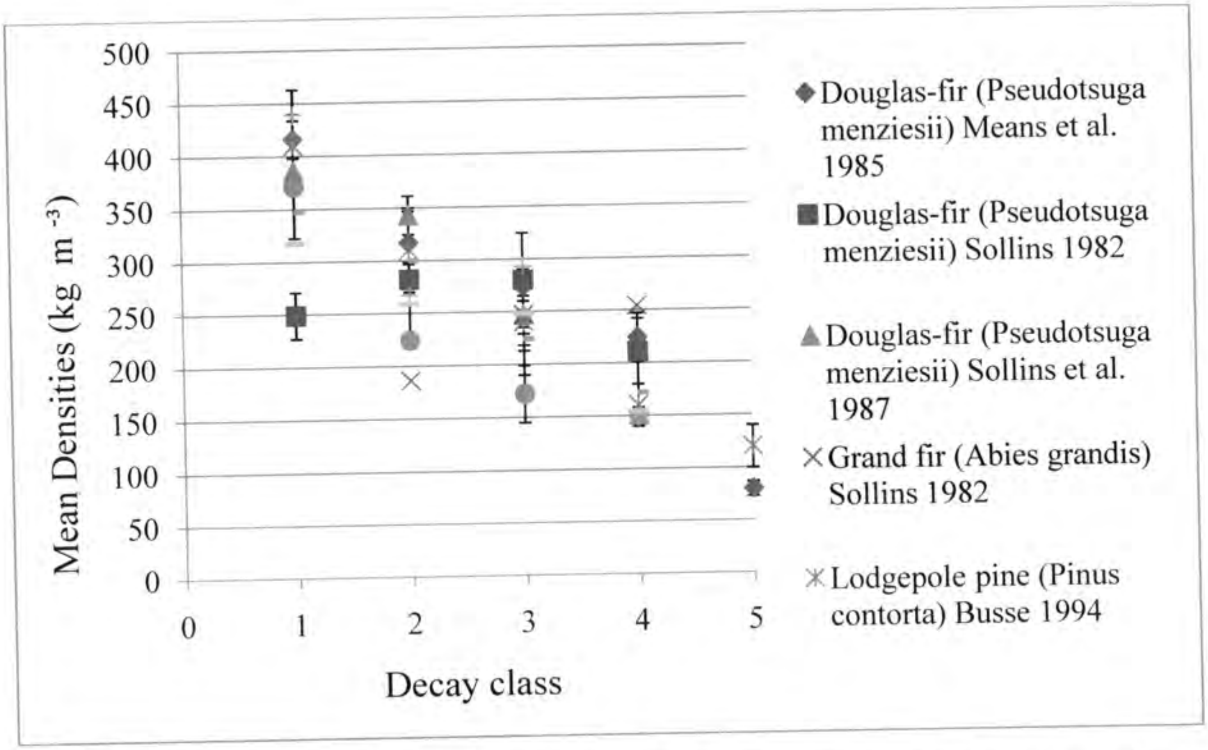


Figure 2. Wood density changes with advancing decay in North American Coniferous Tree Species. Standard error bars omitted where no standard error was provided.

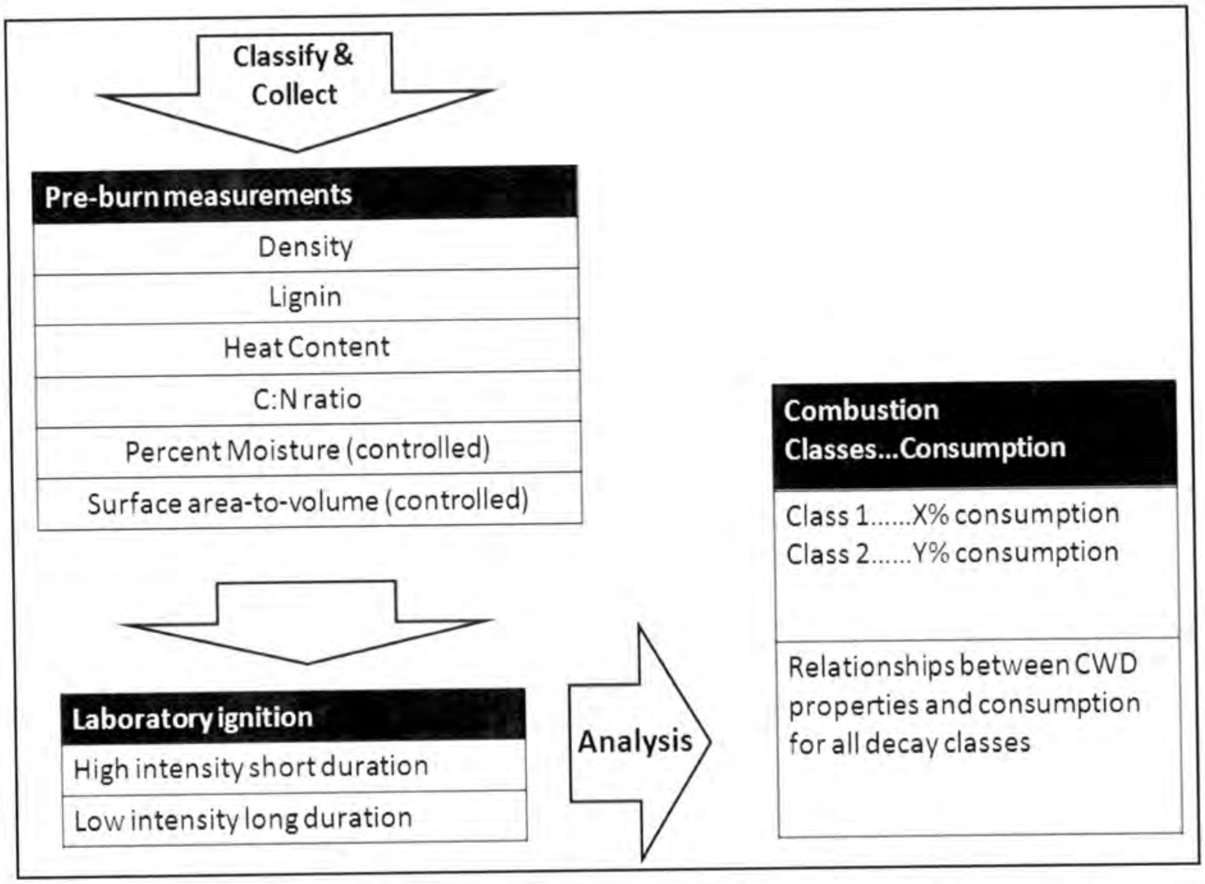


Figure 3. This project was designed in four phases. (1) Sample classification and collection (2) Sample characterization evaluating C/N ratio, density, heat content, and lignin content (3) Laboratory ignition using high and low intensity ignition methods, and (4) Analyzing the consumption of each sample and linking this information back to sample properties.

Figure 4. Collection sites one through four from left to right, respectively.

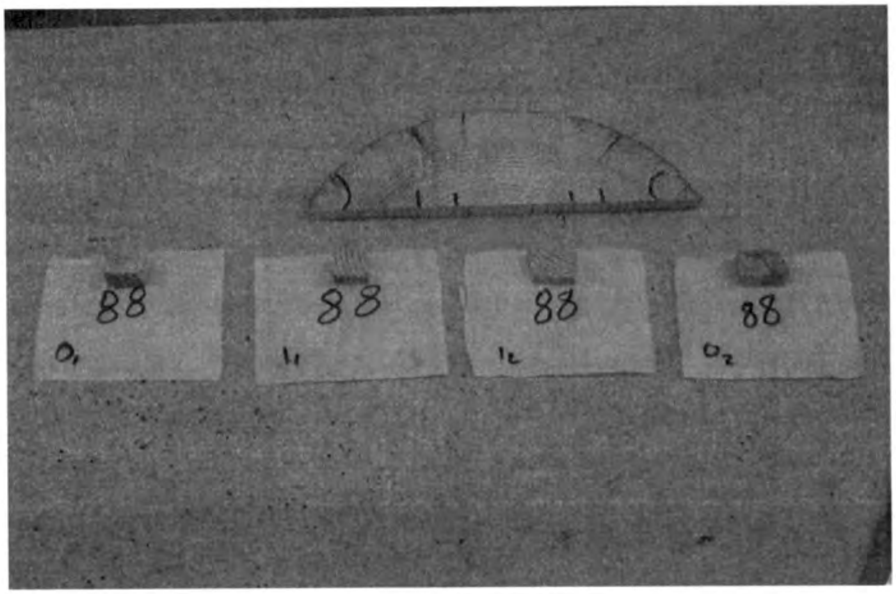
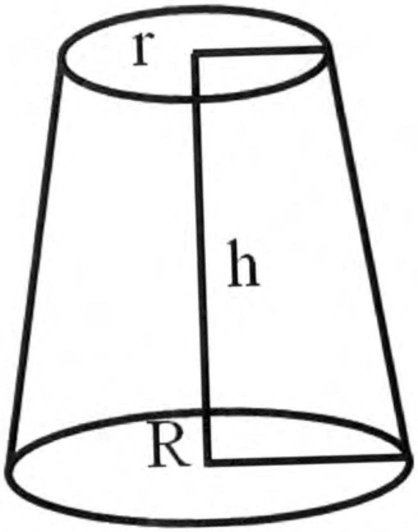


Figure 5. A cross sectional piece of CWD with four density sub-samples removed and waiting to be placed into labeled bags prior to drying.



$$\text{Area} = \boldsymbol{\pi}(R + r)\sqrt{(R - r)^2 + h^2}$$

$$\text{Volume} = \frac{\pi}{3} h\,(R^2 + r^2 + R * r)$$

Figure 6. Frustum with area and volume equations.

Figure 7. Partitioned table on which CWD samples were allowed to smolder. Brick cells sheltered the samples from wind and heat from adjacent samples.

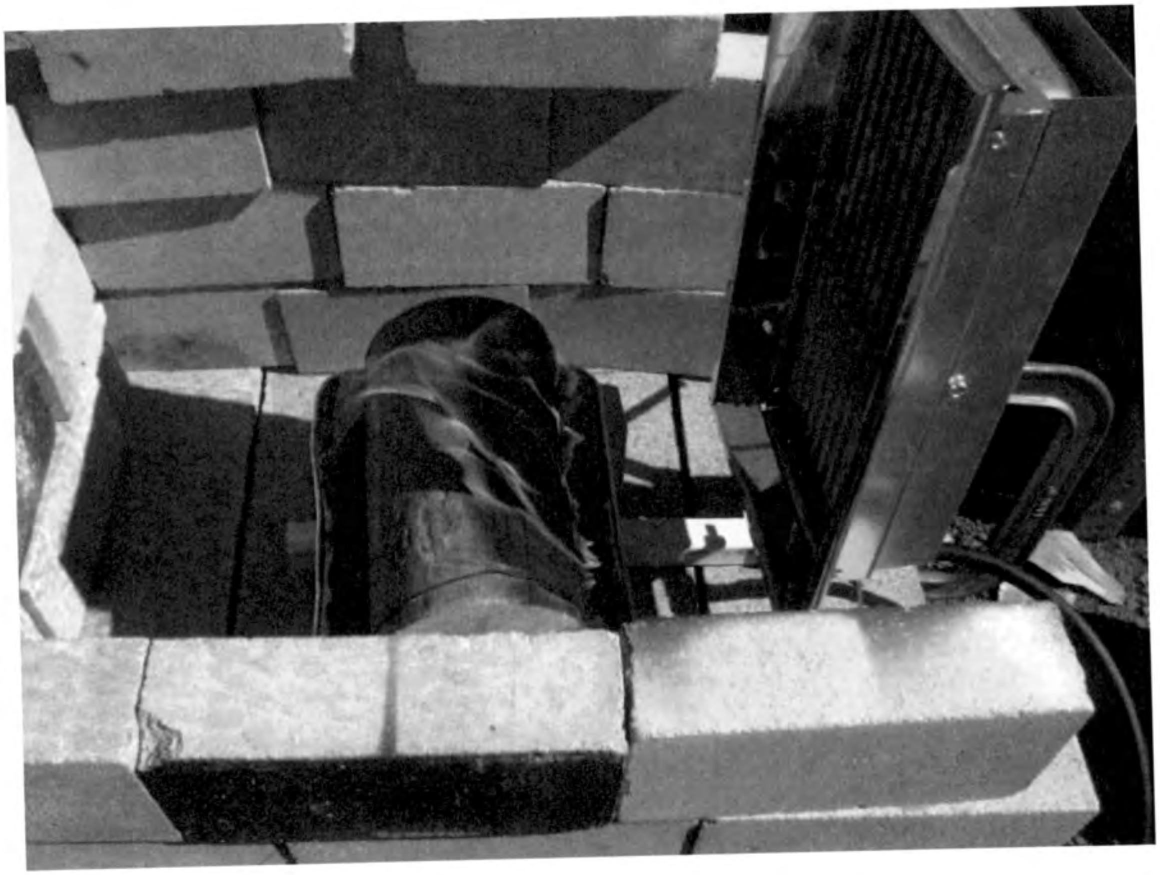


Figure 8. A sample achieving flaming ignition and a surface temperature of 800°C. Ignition was achieved using a Detroit Radiant PT 32 high intensity heater attached to an acetylene regulator.

Figure 9. A sample achieving ignition and a surface temperature of 300°C. This ignition was conducted by allowing dried peat moss to smolder under the log.

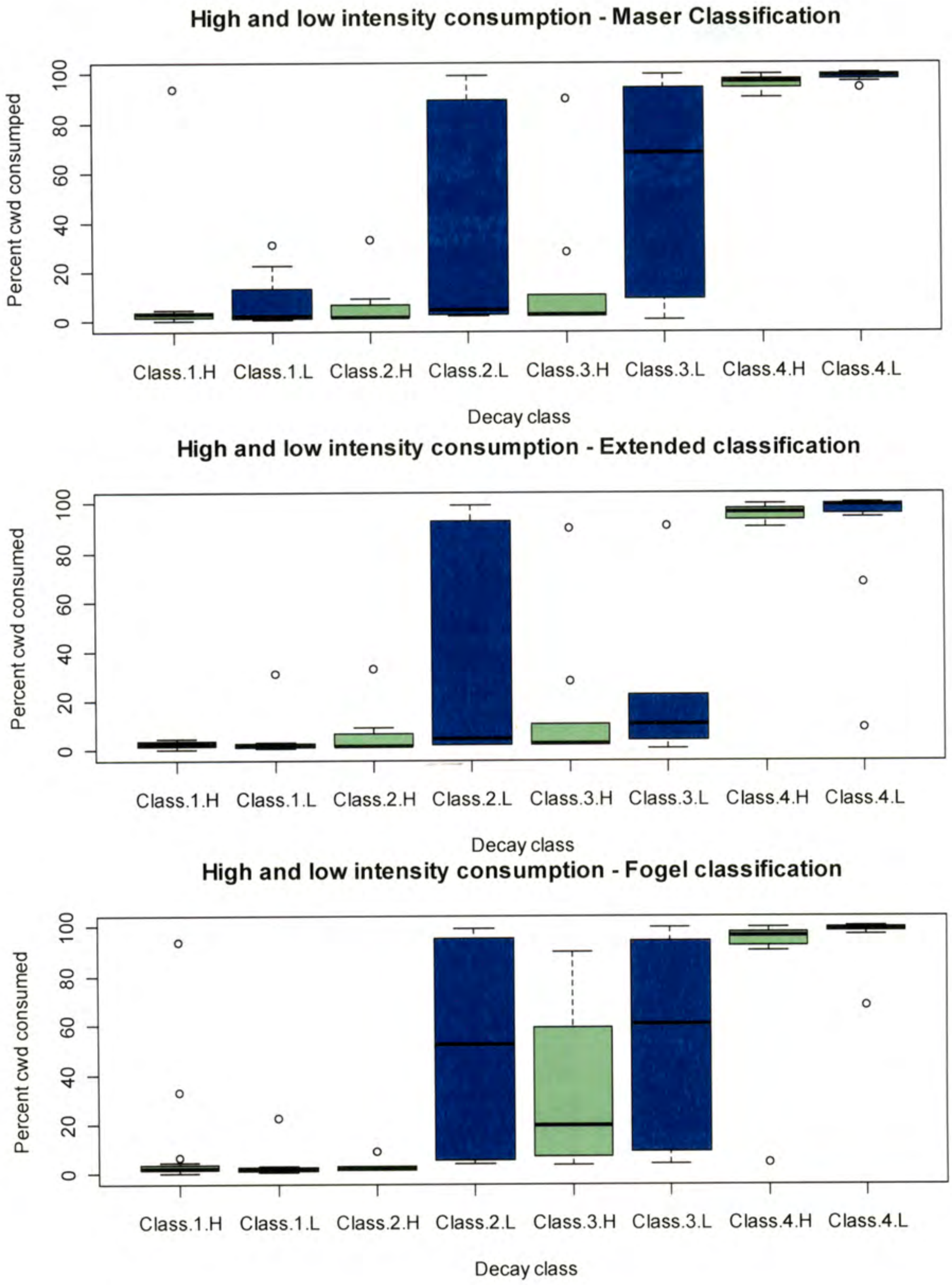


Figure 10. Bar charts of raw consumption data for each classification system and ignition pattern. 'H' indicates high temperature ignition, 'L' indicates low temperature ignition.

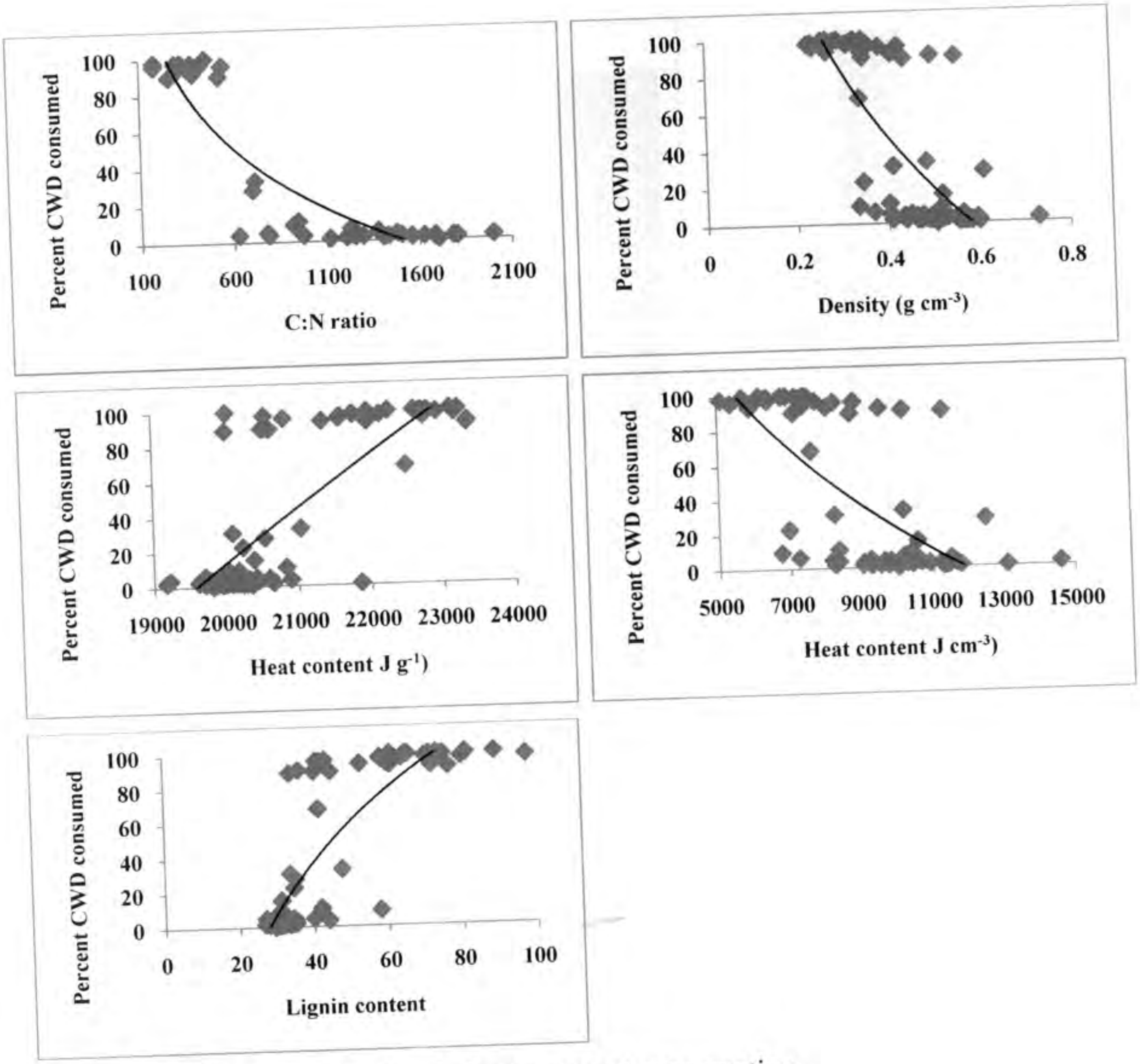


Figure 11. CWD properties in relation to percent consumption

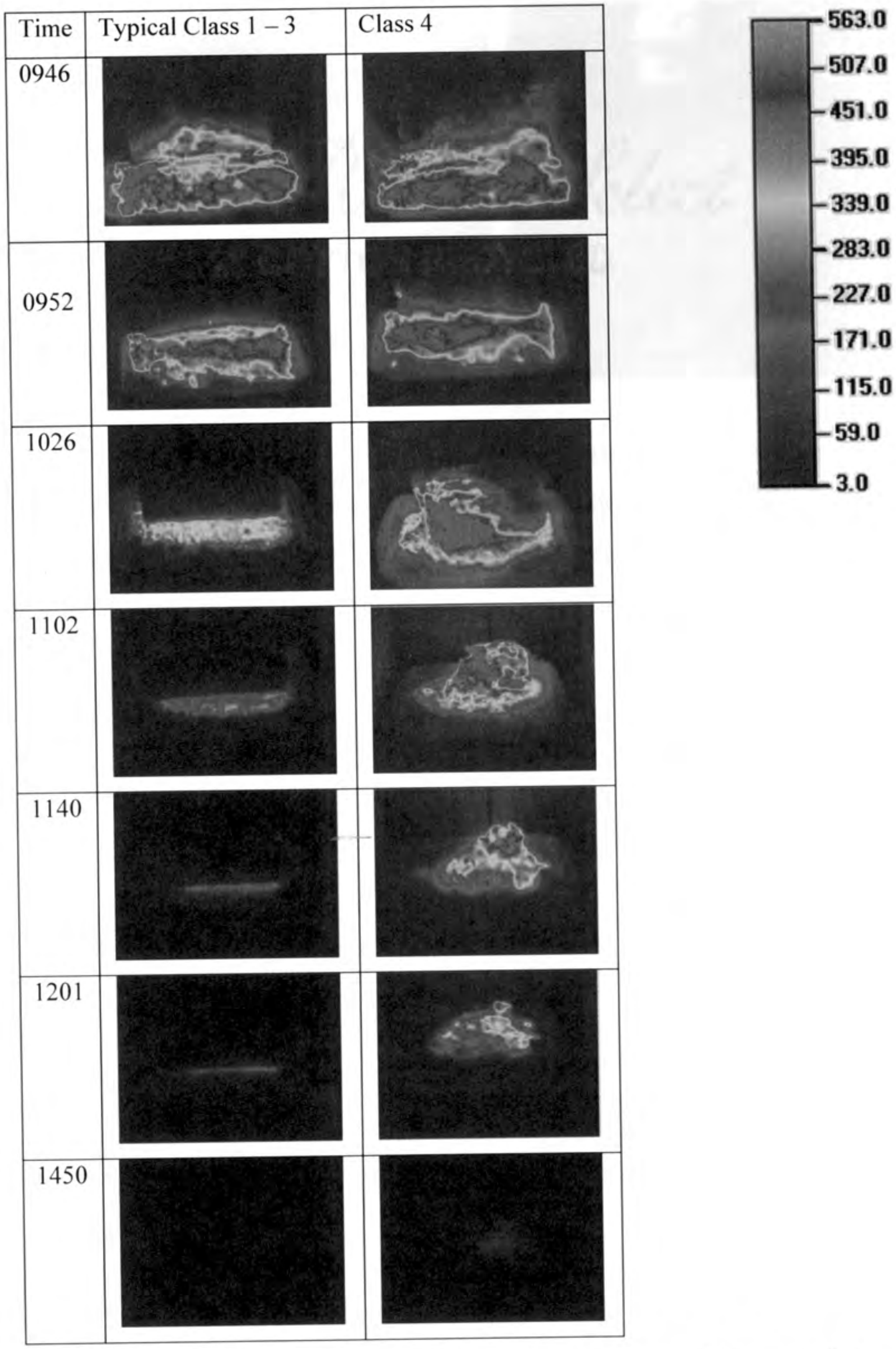


Figure 12. Infrared photographs of CWD combustion over a 5.5 hour period

Figure 13. Samples numbered 51 (left) and 126 (right). Here we see these are predominantly sound wood with the exception of some channels of interior decay. In both cases this interior decay became an ignition point from which smoldering in the sound sections was initiated. The pictured ruler is 15cm for scale.

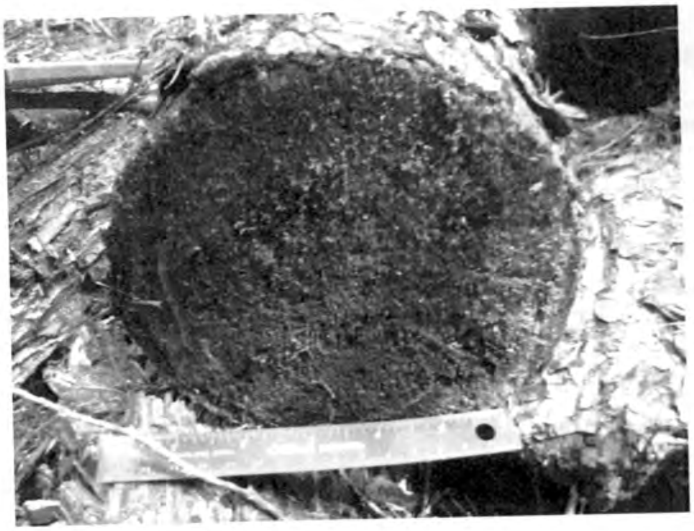


Figure 14. Sample number 29, with a relatively sound outer portion and completely decayed inner portion.

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

Environment description	**Carbon Load ($Mg\ ha^{-1}$)**	**Percent 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)

Table 2. CWD Combustion Experiments by region, variables investigated, focus of study, fuel type, and log condition.

Ecoregion	Variables Investigated	Focus of Study	Fuel Type	Log condition	Reference
North Central Rockies	Fuel loads ≤ 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	Season, position of logs, type of activity, diameter, moisture content	Consumption	Post harvest conifer forest	Sound and decayed	(Brown *et al.* 1991)
Pacific Northwest	Measured and estimated fuel moisture, species, bark presence and contact with the ground	Consumption	Post harvest *Pseudotsuga menziessi* and *Tsuga heterophylla*	Sound	(Sandberg and Ottmar 1983)
Pacific Northwest	Measured and estimated fuel moisture for 10, 100, and ≥1000 hour fuels.	Consumption	Post harvest *Pseudotsuga menziessi* and *Tsuga heterophylla*	Sound	(Ottmar *et al.* 1990)
Tropics	C/H/N ratio, density, diameter, moisture content, porosity	Smoldering 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	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 smolder	Post harvest tropical forest	Sound and decayed	(Carvalho *et al.* 2002)
Intermountain, Pacific Northwest, and Interior Alaska	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)
Southwest Australia	Physical dimensions, density, decay state	Consumption	Natural Eucalypt	Sound & decayed	(Tolhurst *et al.* 2006)

Table 3. Decay classification based on Fogel *et al.* 1973

Feature	**Log Decay Class**				
	1	**2**	**3**	**4**	**5**
Bark	Intact	Intact	Trace	Absent	Absent
Twigs <.003 m	Present	Absent	Absent	Absent	Absent
Specific Gravity	.474	----	.420	.222	.046
Texture	Intact	Intact, partly soft	Hard, large pieces	Soft, small, blocky pieces	Soft, powdery
Wood Color	Original Color	Original color	Reddish brown or original color	Reddish or light brown	Red-brown to dark brown
Epiphytes	None	None	Conifer seedlings	*Vaccinium*, moss, TSHE seedlings	*Vaccinium*, moss, TSHE 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

Table 4. Inputs required by semi-empirical models

Inputs	Model		
	Consume	**FEPS**	**FOFEM**
Fuel inputs			
1 hour fuel loading	X	*	X
10 hour fuel loading	X	*	X
100 hour fuel loading	X	*	X
1000 hour fuel loading	X	*	X
>1000 hour fuel loading	X	*	X
≥1000 sound and rotten percentage	X		X
Branch loading			X
Canopy loading	X	X	X
Duff depth	X		X
Duff loading	X	X	X
Herbaceous/Foliage loading	X		X
Litter depth	X		
Litter loading		X	X
Litter percent cover	X		
Shrub loading	X	X	X
Slash (broadcast) loading		X	
Slash (pile) loading	X	X	
Snag loading	X		
Moisture Content Inputs			
1 hour fuel		X	
10 hour fuel	X	X	
100 hour fuel		X	X
1000 hour fuel	X	X	
≥ 1000 hour 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	
Percent canopy consumed	X	X	X
Season			X
Slope	X		
Windspeed (midflame)	X		
Tree dimension measurements			X

*** Indicates there are specific fields for these variables are not labeled, however there are unassigned stratified fields for this data to be included.**

Table 5. Outputs generated by semi-empirical models

Outputs	Model		
	Consume	**FEPS**	**FOFEM**
Consumption			
Crown	X	*	X
Duff	X	*	X
Herbaceous	X		X
Litter	X	*	X
Percent 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		
Percent woody fuel consumed	X		
Shrub	X		
Soil temperature			X
Mortality			
Tree			X

*** Indicates these outputs are all grouped into one number.**

Table 6. Collection site descriptions.

Site	Aspect	Description
1	Southwest	*Larix occidentalis*, *Thuja plicata* overstory with *Pseudotsuga menziesii* and some *Abies grandis* in the understory.
2	South	*Thuja plicata, Pinus spp*. Some *Larix occidentalis*.
3	South	*Thuja plicata, Pinus spp*. Some *Larix occidentalis*.
4	North	*Thuja plicata, Pinus spp*. Some *Larix occidentalis* and *Pseudotsuga menziesii.*

Table 7. Coarse woody debris decay classes one through 5 based on Maser et al. 1979.

Feature	Log decay class				
	Class 1	Class 2	Class 3	Class 4	Class 5
Bark	Intact	Intact	Trace	Absent	Absent
Twigs ≤ 3 cm	Present	Absent	Absent	Absent	Absent
Texture	Intact	Intact to partly soft	Hard, large pieces	Small, soft, blocky pieces	Soft and powdery
Shape	Round	Round	Round	Round to oval	Oval
Color of wood	Original color	Original color	Original to faded color	Light to dark brown or faded brown, grey, or yellow	Light to dark brown or faded grey or yellow
Portion of log on ground	Log elevated on branches	Log elevated on branches but slightly sagging	Log is sagging near ground or touch ground	Log is touching ground or partially buried	Log is nearly completely buried

Table 8. Expanded classification system based upon Fogel et al. 1973, Maser et al. 1979, Sollins 1982, and Triska and Cromack 1980.

Feature	**Log Decay Class**				
	1	**2**	**3**	**4**	**5**
Bark	Intact	Intact	Sloughing	Absent	Absent
Twigs <3 cm	Present	Absent, some large, branch system entire	Absent, some large	Absent, large stubs	Absent
Texture/structure	Intact	Intact, some parts of sapwood soft	Heartwood sound, supports own weight, large areas of sapwood soft	Heartwood rotten, does not support own weight, branch stubs pull out, soft small blocky pieces	Soft, powdery pieces, no structural integrity
Wood Color	Original Color	Original color	Original, Faded, or reddish brown	Light to reddish brown or faded yellowish	Faded light yellow or grey or Red-brown
Roots	None	None	Sapwood only,	Throughout	Throughout
Epiphytes	None	None	Seedlings or moss	Smaller plants or trees and moss	Larger plants or trees and moss
Contact with ground	Above ground or elevated	Above ground or elevated	Above ground, some parts buried	Many parts buried	Mostly underground
Shape	Round	Round	Round	Round to Oval	Oval to Flat

Table 9. Fuel loading for East Hatter Creek.

Fuel Loading in Tons per acre								
Fuel Size	1 hr	10 hr	100 hr	1-100 hr	1000 hr solid	1000 hr rotten	duff	litter
Pre-Fire	0.08	0.54	0.49	1.62	0.09	1.03	3.88	1.28
Post-Fire	0.05	0.92	0.40	1.38	0.10	0.93	3.33	2.15

Table 10. Table showing the mean consumption for all classification and ignition methods. Standard deviations are shown in parenthesis.

Average consumption by class and ignition method						
	High temperature low duration		Low temperature high duration			
	Fogel		Maser		Extended	
Class	Hi temp.	Low. Temp	Hi temp.	Low temp.	Hi temp.	Low temp.
1	8.6 (21.2)	3.7 (6.4)	10.9 (27.4)	8.0 (11.9)	9.2 (25.3)	5.9 (8.3)
2	3.6 (3.1)	51.1 (46.7)	6.5 (10.3)	34.0 (45.6)	6.6 (9.6)	33.0 (41.9)
3	33.1(39.2)	54.8 (44.8)	14.8 (27.6)	53.4 (44.7)	42.4 (44.3)	58.9 (45.5)
4	88.2(26.4)	96.1 (1.4)	95.7 (2.9)	98.5 (1.3)	96.3 (2.7)	99.0(1.2)

Table 11. Median coarse woody debris properties for decay classes one through four.

Median fuel property values by class							
Class	Moisture	Surface to volume ratio	Percent lignin content	Density	Joules per gram	Joules per cm^3	C/N ratio
1	7.77	0.33	31.25	0.496	20150.4	9818.7	1374.22
2	7.75	0.31	32.28	0.503	20232.5	10199.8	1554.86
3	7.75	0.37	34.03	0.481	20517.6	9266.3	1110.54
4	8.05	0.33	70.79	0.328	22149.1	6950.55	379.44

Table 12. Correlation coefficients for all ignition patterns, high temperature ignition, and low temperature ignition. The trend of strong correlations with consumption and lignin content, density, and joules per volume can be seen in all ignition methods, however the high temperature ignition samples also had C/N ratio measured, where the latter had the highest correlation with consumption.

Correlation coefficients for CWD properties

Factor	Consumption: All Ignition Types	Consumption: High Intensity Heater	Consumption: Smoldering Duff
C/N Ratio	N/A	-0.86923214	N/A
Density	-0.76329088	-0.71340199	-0.82185456
Joules per gram	0.59999760	0.61995738	0.52010003
Joules per cm^{-3}	-0.74152935	-0.66965907	-0.79784575
Lignin	0.79720582	0.79713167	0.79899982
Moisture content	0.18431067	0.15337459	0.24913369
Surface/volume ratio	-0.02563826	-0.09174012	0.04347826

Table 13. Range of CWD propertied studied. Shaded area indicates a consumption value of 50% or higher.

Property	High consumption								Low consumption	
C/N ratio	180	360	540	720	900	1080	1260	1440	1620	1800
Consume (%)	97% (1)	94% (4)	95% (4)	40% (39)	4% (1)	8% (4)	3% (2)	3% (1)	2% (1)	2% (1)
Density (g cm^{-3})	0.240	0.291	0.342	0.393	0.444	0.495	0.546	0.597	0.648	0.7+
Consumption	97% (1)	98% (3)	85% (30)	75% (38)	33% (42)	6% (10)	11% (24)	9% (25)	14% (19)	2
Heat content (J g^{-1})	23400	22948	22492	22036	21580	21124	20668	20212	19756	19300+
Consumption	96% (4)	93% (12)	98% (1)	83% (36)	94%	36% (97)	22% (35)	13% (28)	3% (2)	3% (1)
Heat content (J cm^{-3})	5200	6178	7156	8134	9112	10090	11068	12046	13024	14000+
Consumption	98% (0.3)	97% (3)	77% (38)	85% (29)	34% (42)	9% (25)	15% (26)	10% (27)	28%	1% (1)
Lignin content (%)	90+	84	77	70	63	56	49	42	35	28
Consumption	99% (1)	99% (2)	97% (3)	99% (1)	82% (36)	94%	56% (42)	60% (40)	7% (15)	3% (2)
Surface/vol ratio	0.23	0.282	0.334	0.392	0.444	0.496	0.548	0.600	0.652	0.7+
Consumption	96%	27% (41)	38% (43)	51% (47)	42% (45)	16% (36)	1	1	1	17% (17)
Water holding capacity (%)	120+	113.6	106.9	100.2	93.5	86.8	80.1	73.4	66.7	60
Consumption	97% (1)	94% (4)	96%	96%	48% (65)	9% (11)	3% (1)	2% (0)	3% (3)	2% (0)

Standard deviations in parenthesis