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Properties affecting the consumption of sound and rotten coarse woody debris in northern Idaho: a preliminary investigation using laboratory fires

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Abstract. This study evaluates the consumption of coarse woody debris in various states of decay. Samples from a northern Idaho mixed-conifer forest were classified using three different classification methods, ignited with two different ignition methods and consumption was recorded. Intrinsic properties that change with decay were measured including carbon to nitrogen ratio, density, heat content, lignin content, moisture content and surface area-to-volume ratio. Consumption for logs in different stages of decay is reported with characterisation of wood properties. Results indicate very decayed coarse woody debris is likely to be consumed to a substantially greater degree than sound coarse woody debris given similar conditions. High consumption occurred in debris with low-density, high-lignin content and high gravimetric heat content; however, lignin content and density showed the highest correlation with consumption. The Maser classification method grouped very rotten logs with high consumption into decay class 4 and the remainder into class 3. Trends in consumption were similar regardless of ignition; however low-intensity long-duration ignition produced higher consumption values. Focus on physical properties is recommended for predictive purposes over any classification method. Logs of other species and in regions with different decomposition and combustion dynamics may display different property ranges and consumption results.

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Introduction

Wildland fire is a key process in many ecological systems, acting as a disturbance agent that rapidly transfers biogeochemical and hydrological stocks from terrestrial vegetation to the atmosphere (Smith *et al.* 2005; Lentile *et al.* 2006; Roberts and Wooster 2008). Accurately inventorying these emissions requires the best possible knowledge of contributing factors, including the quantity of fuel per unit area or fuel loading (Peterson 2001). An important component of many forest fuel loads is downed coarse woody debris (CWD) over 7 cm in diameter. These logs occur owing to management, succession and disturbance events and are often abundant in forested systems. Estimates of the quantity of this debris are wide, ranging from as much as 9.9 $Mg\,ha^{-1}$ in dry ecosystems (Smith and Hudak 2005) to 134 $Mg\,ha^{-1}$ in more productive systems (Woldendorp and Keenan 2005). In the USA, 92% of the volume of CWD encountered in the Forest Inventory and Analysis national inventory between 2001 and 2010 was in some stage of decay (USDA 2010).

The combustion of CWD generally occurs during smouldering, a phase of combustion that is linked to relatively high emissions of particulate matter (Cahill *et al.* 2008) and volatile organic compounds (Christian *et al.* 2007), which contribute to ozone formation (Aherns 2003) and can affect human health (Dockery *et al.* 1993; Bell *et al.* 2004). For land managers and researchers to account for these emissions, it is crucial to have an accurate estimation of the fuels consumed during wildland fire. However, our current understanding of the quantity of the decayed CWD consumed in wildland fires is poor (Hao and Babbit 2007) and further complicated by the heterogeneous nature of these fuels as they decay. As logs decay, they become less dense (Sollins *et al.* 1987), the composition of the cellulose and lignin ratios change (Dobrý *et al.* 1986), and the overall shape may change as structural integrity is lost (Maser *et al.* 1979). In turn, thermal conductivity is affected by changes in density (Thunman and Leckner 2002), heat loss is affected by surface area-to-volume ratio (Drysdale 1998) and heat content is affected by the lignin and moisture contents (Demirbaş 2001). Combustion of CWD is further complicated by the fact that it is often not uniformly decayed throughout (Hollis *et al.* 2011).

This dynamic quality of CWD presents a challenge for fuel consumption and inventory software such as Consume, the First Order Fire Effects Model (FOFEM) and the Fuel Characteristic Classification method (FCCS). A recent study by Hollis *et al.*

(2010) found consumption of eucalypt CWD to be highly varied and ranging between 9 and 89%; prediction tools such as Consume and the BURNUP model had trouble accurately predicting the consumption of these fuels, especially with regards to rotten fuels between 7 and 23 cm in diameter (Hollis *et al.* 2010). These modelling tools distinguish between sound and decayed CWD using built-in equations to determine consumption (Prichard *et al.* 2005; Reinhardt 2005; Ottmar *et al.* 2007); however, detailed studies evaluating the differences between sound and rotten CWD are not often found in publication. For this reason, there is a need to evaluate both the properties of CWD and methods to stratify logs displaying wide ranges in properties.

To address the influence of decay on consumption of downed CWD, we investigated the effect of several intrinsic wood properties that change with decay on the consumption of CWD in the laboratory using two ignition methods. The wood properties were based on a detailed review by Hyde *et al.* (2011) and include density, heat content, lignin content, moisture content and surface area-to-volume ratio. Decay was characterised using three different numerical classification methods and carbon to nitrogen (C : N) ratio for a subset of samples. The numerical classification methods depend on CWD surface characteristics such as bark and branch presence, structural integrity and colour. Two ignition methods were used to ensure observed results were not simply a product of ignition methods. Three research questions are addressed: (1) are there statistically significant differences in consumption between CWD of similar size and moisture contents in different decay classes? (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 and sound CWD ignited under high-temperature short-duration conditions and low-temperature long-duration methods?

Methods

A four-phased project was designed to address the above research questions (Fig. 1). The initial phase consisted of sampling CWD in various states of decay and assigning it decay classes. In the second phase, intrinsic properties of each sample were characterised including C : N ratio, density, heat content, lignin content, moisture content and surface area-to-volume ratio. The third phase was igniting each sample in a laboratory setting. In the last phase, the wood properties and decay classes were compared with the percentage of mass lost, referred to herein as 'consumption' of CWD.

Study area and field measurements

Coarse woody debris samples were collected from the Priest River Experimental Forest (PREF) located in northern Idaho and administrated by the USDA Rocky Mountain Research Station. This 2758-ha area was chosen because it contained considerable quantities of CWD in varying decay classes. The lack of stumps on collection sites suggests the CWD fell via natural mechanisms rather than harvesting, though the latter cannot fully be ruled out owing to the possibility of past fires. Collection sites for this project were in the *Thuja plicata* habitat series and include the major seral tree species *Pseudotsuga menziesii*, *Abies grandis*, *Pinus monticola*, *Picea engelmannii* and *Larix occidentalis* (Cooper *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 5 cm (Cooper *et al.* 1991).

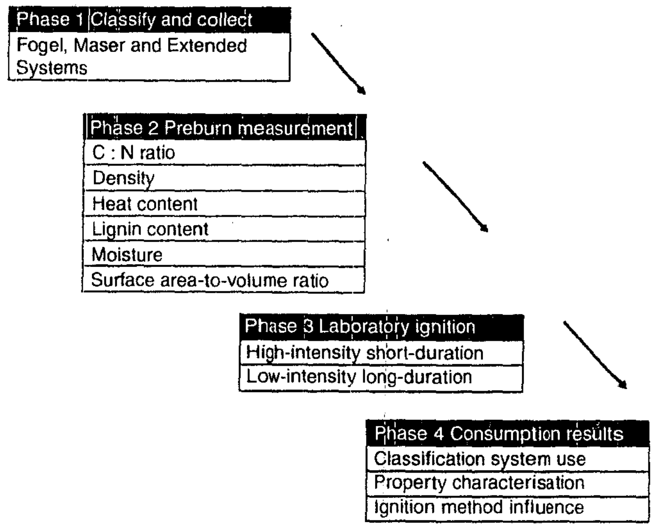

Fig. 1. This project was designed in four phases: (1) sample classification and collection; (2) sample characterisation evaluating C : N ratio, density, heat content and lignin content; (3) laboratory ignition using high- and low-intensity ignition methods and (4) analysing the consumption of each sample and linking this information back to sample properties.

Field collection sites (Fig. 2) were selected at four locations within PREF to capture variability in the CWD physical properties, not to represent spatial variability in abundance or landscape heterogeneity. Following past studies where CWD sampling was conducted using the line intersect method (Kangas and Maltimo 2006), we assumed that the debris was arranged in random directions. A transect of 50 m was placed at a random azimuth at each site. Two additional transects were placed 120° apart and the procedure was repeated. This sampling protocol is similar to that of the downed woody materials indicator used by the US Forest Service Forest Inventory and Analysis (FIA) program (Woodall and Williams 2005).

The CWD size range chosen for this study was a diameter between 7 and 23 cm and a length of greater than 1 m; this captures the 1000-h time-lag fuels widely used in many fire fuels inventory applications (Brown 1974; Keane and Dickinson 2007; Ottmar *et al.* 2007). As this is the smaller of CWD size classes, it also allowed for samples that were easy to harvest and transport. Representative samples 40 cm in length were collected using a chainsaw. This length provided a sample that was easily manageable and contained enough material for all property analysis and burn trials. A sample was collected from each log either at its point of intersection with the transect tape or from the nearest section indicative of the decay state of the CWD. Logs with more than 50% surface charring or that had a visibly abnormal abundance of pitch were omitted from sampling. Although we acknowledge these factors would likely

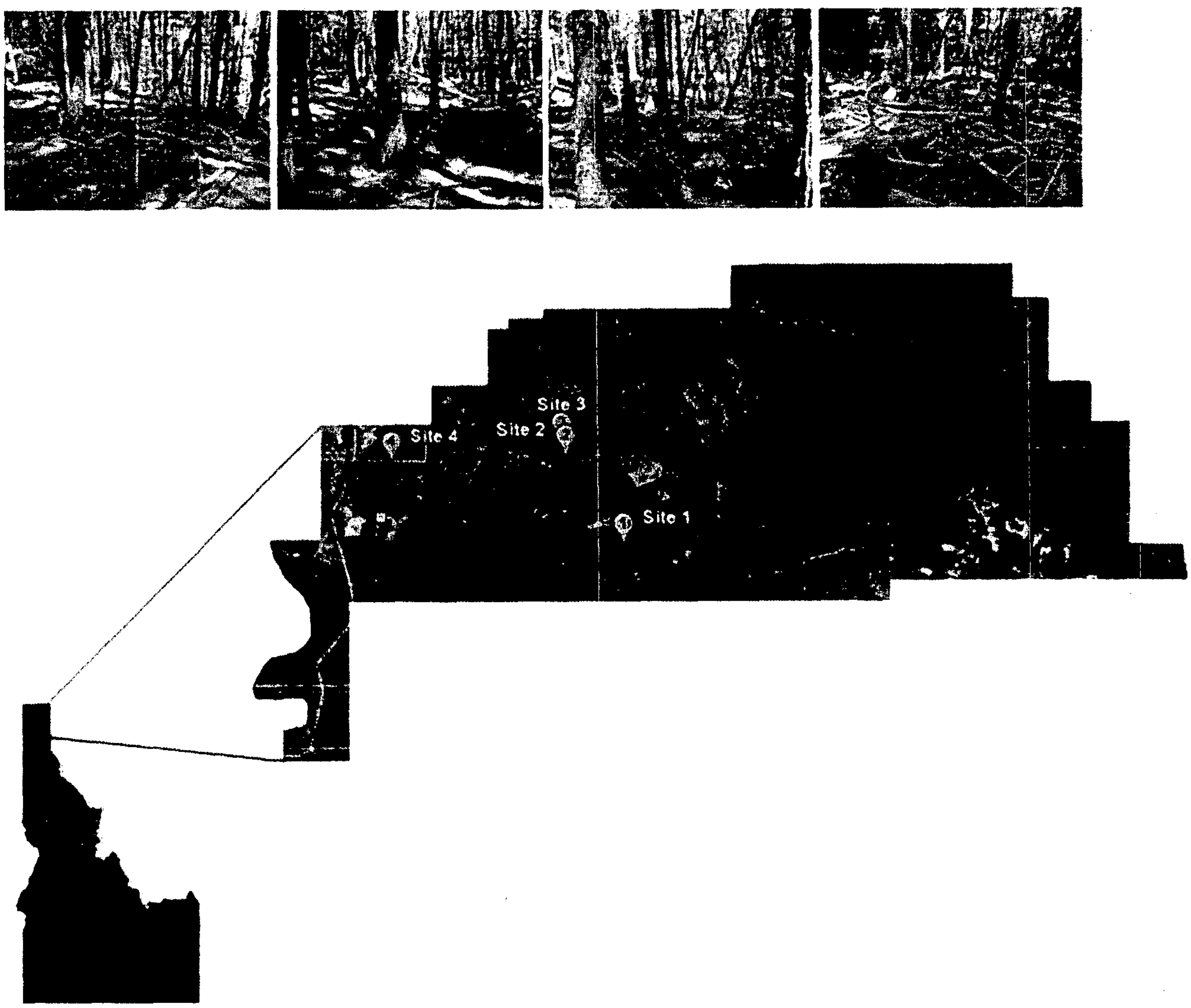

Fig. 2. Priest River Experimental forest. Collection sites 1 through 4 are displayed from left to right.

Table 1. Decay classifications based on Fogel *et al.* (1973)
TSHE, *Tsuga heterophylla* (western hemlock)

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	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, 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 2. Coarse woody debris decay classes 1 through 5 based on Maser *et al.* (1979)

Feature	Log decay class 1	2	3	4	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
Colour of wood	Original colour	Original colour	Original to faded colour	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 touching ground	Log is touching ground or partially buried	Log is nearly completely buried

Table 3. Extended classification method based on 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 or 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 colour	Original colour	Original colour	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

influence CWD consumption, they rarely occurred in the sample area and fall outside the scope of this study. A total of 77 samples were used in this study.

Coarse woody debris samples were mixed conifer species. *Thuja plicata* CWD was omitted from sampling as it tends to dry and rot at different rates than other species; this would have created difficulties in drying the samples to similar moisture contents. Each CWD sample was assigned a decay class, 1 through 4, using three different numeric classification methods based on Fogel *et al.* (1973) (Table 1), Maser *et al.* (1979) (Table 2) and an extended classification method derived from a combination of examples from Fogel *et al.* (1973), Maser *et al.* (1979), Sollins (1982) and Triska and Cromack (1980) (Table 3). All three systems have five decay classes, but class 5 logs were omitted from the present study as they occurred too infrequently and tended to be buried under duff and litter, preventing the location and collection of a representative sample size. Once classified, samples were wrapped in wire mesh (chicken wire or hardware cloth) and removed from the field.

Properties analysis and sample preparation

Our protocol yielded log samples with mean and median diameters of 10.4 and 11.4 cm respectively. Log sizes did not significantly differ among any of the decay classes evaluated in this study. Density, heat content, lignin content, moisture content and surface area-to-volume ratio were measured for each sample. A subset of C : N ratio measurements was also taken to provide another method by which the researchers could determine degree of decay (Swift *et al.* 1979). These properties were chosen for investigation based on a detailed review of wood properties and CWD combustion conducted by Hyde *et al.* (2011). Samples were dried to a moisture content of between 6 and 13% to prevent further decay that may have influenced the wood properties, and to reduce the variability in moisture contents that may have influenced consumption. Following drying, all samples were placed in a closed chamber with ≤35% humidity and temperatures ranging between 25 and 37°C. Before analysis, the ends of a sample were cut off with an unlubricated electric reciprocating saw to remove any wood contaminated by the oiled chainsaw blade during field collection. A 10–15-cm section was removed from each sample for property analyses while retaining enough wood for moisture sampling and 25-cm section for burn trials.

Carbon to nitrogen ratio was analysed for a subset of samples using a CE Instruments NC 2500 elemental analyser (Wigan, United Kingdom). 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 analyser and carbon and nitrogen contents recorded. This measurement was collected for approximately half of the logs sampled. Project resources prevented the acquisition of this measurement for all samples.

Dry wood density was determined using a water-displacement method similar to that outlined in Means *et al.* (1985). Four samples were collected from a cross-section of the CWD sample to capture the density on the surface and in the interior. The mean of these values was calculated to produce an average density for each sample. Each subsample was dried at 104°C until its weight stabilised. To prepare for the water-displacement procedure, each subsample was waterproofed with melted paraffin wax. The layer of paraffin on the outside of the subsample was assumed to minimally affect its volume.

Heat content was determined for the mass and volume of samples. The sample was ground into ≤2-mm granules, pressed into a 1-g gram pellet and oven-dried to remove moisture. The dried pellet was placed into a Parr oxygen bomb calorimeter (Moline, IL) and analysed to obtain the gravimetric heat content. Volumetric heat content was calculated by multiplying gravimetric heat content by the average dry wood density of each sample. Lignin content was determined using the Klason method (Milne *et al.* 1989) on powdered wood samples in which extractives had been removed using dichloromethane solvent. Prior to each burn trial, a moisture sample was cut, dried at 104°C and weighed. The 25-cm sections remaining after moisture content procedures were used for burn trials.

Surface area-to-volume ratio of CWD was determined by measuring the length and end diameters of each burn sample. These numbers were entered into the surface area and volume equations for a frustum (Eqns 1 and 2). This yielded a surface area-to-volume measurement for the portion of the sample that was to be burned.

$$\text{Area} = \pi(R + r)\sqrt{(R - r)^2 + L^2} \tag{1}$$

$$\text{Volume} = \frac{\pi}{3}L\left(R^2 + r^2 + R \times r\right) \tag{2}$$

where R, large radius; L, length; r, small radius.

Sample combustion

The CWD samples were ignited using two methods to simulate a (1) high-intensity short-duration and (2) low-intensity long-duration combustion environment. All samples were ignited and allowed to burn on a flat fireproof surface outdoors and sheltered from wind. Temperature and relative humidity were measured using a Kestrel 3000 Series meter (Birmingham, MI). Prior to ignition, each sample was weighed to determine its initial mass. We followed methods previously implemented by the US Forest Service at the Missoula Fire Sciences Laboratory (J. Reardon, pers. comm., 2009) and the Pacific Wildland Fire Sciences Laboratory. For the high-intensity short-duration method, we used a Detroit Radiant model PT-32 high-intensity infrared heater (Detroit, MI) attached to a propane tank with an acetylene regulator. The sample was placed on a bed of sand 18 cm away from the face of the heater. Temperature at ignition was measured at the ignition source with a Mikron infrared camera (Santa Clara, CA). A concrete heat shield was placed between the sample and the heater while the heating element reached its peak temperature, at which point the shield was removed and the log was exposed to heat for 120 s. The log was allowed to smoulder until the reaction ceased. The low-intensity long-duration ignition was achieved by placing the sample on a bed of dried peat moss with two 0.5-cm diameter, 12 cm-long dowel rods placed below the surface of the moss. This simulated conditions in the collection areas: a combination of litter or duff (simulated by the peat moss) and small-diameter woody debris (simulated by dowels). The simulated duff moistures ranged from 6 to 12% and the dowel rod moistures were ~3%. This simulated duff layer was ignited using a strip of excelsior (finely shredded aspen wood) lit with a propane torch. The sample was allowed to smoulder until the reaction ceased. Consumption of CWD was determined by weighing the remains of the sample following extinction and comparing this with the initial sample weight.

Statistical analysis

Statistical analysis was performed following the application of a log-transformation to consumption values, which created a normal distribution for these. An exploratory analysis of consumption for each of the three classification methods was performed using a two-way analysis of variance (ANOVA) with CWD decay class and ignition type as predictor variables. The normality assumption for ANOVA was checked by plotting a normal quantile–quantile plot of the ANOVA residuals, which was inspected visually. Bartlett's test for homoscedasticity (Bartlett 1937) was also performed. If any of the classification methods did not meet the assumptions of ANOVA, it is noted and described herein based on visual evaluation. If the assumptions for an ANOVA were met, further examination of ignition and consumption differences was conducted using Tukey's honestly significant difference (HSD) method.

Correlation of wood properties was evaluated using the Spearman method (Spearman 1904). Beta regression (Cribari-Neto and Zeileis 2010) and the log-likelihood ratio test (Neter *et al.* 1996) were used to compare the relationship between consumption and the wood properties. Beta regression is designed for response variables such as consumption that are proportions ranging between zero and one. All methods were performed in *R*, ver. 2.12.2 (R Development Core Team 2011). Sample sizes for each class and ignition method are shown in Table 4.

Results

Consumption by class and classification method

CWD in class 4 experienced substantially greater consumption than the others, and logs in class 1 experienced the least

Table 4. Sample sizes for all classification and ignition methods

Class	High-temperature short-duration				Low-temperature long-duration	
	Fogel		Maser		Extended	
	High temperature	Low temperature	High temperature	Low temperature	High temperature	Low temperature
1	20	11	11	8	13	8
2	5	8	9	9	10	7
3	4	6	10	9	10	13
4	12	11	11	10	8	8
Total	41	36	41	36	41	36

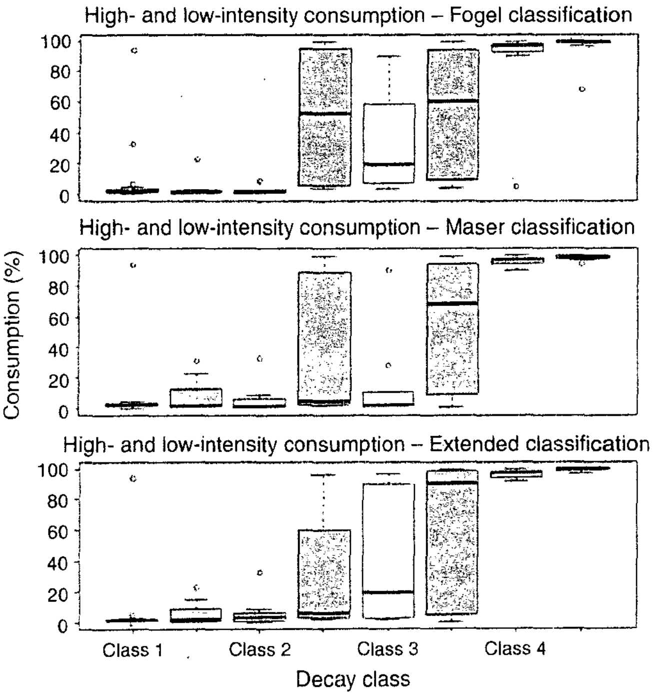

Fig. 3. Bar plot of consumption by ignition method for each of the decay classes within the Fogel, Maser and Extended method. White corresponds to high-intensity short-duration ignition and grey to low-intensity long-duration ignition. Circles represent outliers, whiskers represent greatest values and bar indicates median.

consumption; both of these trends held true regardless of classification method or ignition method (Fig. 3). In analysing the three classification methods, data organised by the Maser method met the prerequisites required for an analysis of variance. Analysis of this system indicated class 4 was consumed significantly more than logs in other classes regardless of ignition method at the $\alpha = 0.05$ level of significance (Table 5). Classes 1 through 3 did not statistically differ from each other with the exception of class 3 logs ignited using low-intensity long-duration methods when compared with class 1 logs ignited with high-intensity short-duration methods.

Data for the Fogel and Extended methods did not meet the statistical assumptions required for analysis; hence observations on these two systems are based on review of raw data and not statistical analysis. One potential reason for this could be the

Table 5. An ANOVA table displaying the degrees of freedom (d.f.), sum of squares, mean sum of squares and test values (*P*) for class and ignition within the Maser classification method

Variable	d.f.	Sum of squares	Mean sum of squares	*P*
Class	3	27.79	9.26	>0.001
Ignition	1	1.91	1.91	0.024
Class : Ignition	3	1.29	0.43	0.317

different distribution of logs in each class using these different systems. For example, the specific gravity criteria used by the Fogel system placed more samples into decay class 1 that would have otherwise fallen into classes 2 or 3. The Extended classification method, a combination of several classification methods, tended to group samples into class 3 that had been placed in class 4 by the other classification methods.

Consumption by intrinsic properties

We evaluated density, lignin content, heat content, surface area-to-volume ratio and moisture content. Consumption and wood property means for each system are displayed by decay class (Fig. 4). Increased consumption was associated with high lignin content, high gravimetric heat content, low density and low volumetric heat content. Surface area-to-volume ratio and moisture content did not differ with consumption. High consumption values occurred in very rotten logs for both ignition methods and were associated with low C : N ratios.

Because many of these wood properties change with increasing decay, several of them were found to be correlated (Table 6). Beta-regression modelling shows percentage lignin content significantly predicted consumption at the $\alpha = 0.001$ significance level, whereas density significantly predicted consumption at $\alpha = 0.01$ (Table 7). Adding other characteristics such as heat content, moisture content and surface area-to-volume ratio did not significantly improve the regression model as indicated by a log-likelihood ratio test (Neter *et al.* 1996). The same test indicated interactions between properties did not add to the predictive capabilities of this model. Although the relationship between moisture content and surface area-to-volume ratio and sustainable combustion is well documented, these properties were not critical factors limiting consumption at low moisture contents and diameters of 7–23 cm in this study. No detectable

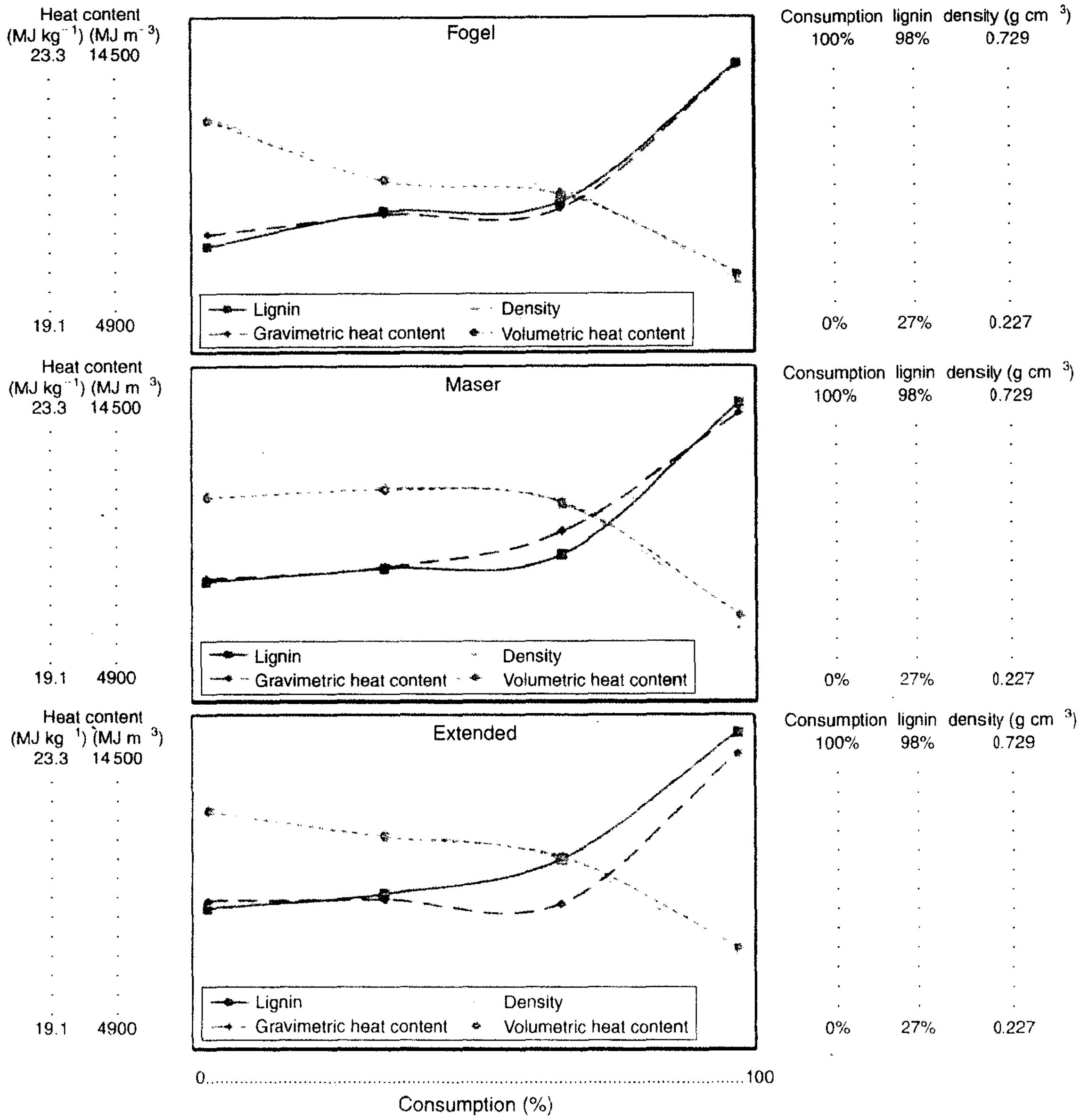

Fig. 4. Mean densities, lignin contents and heat contents from 0 to 100% consumption within each of the three classification methods.

Table 6. Correlation table for CWD properties and consumption

	Consume	Surface area-to-volume ratio	Moisture content	Lignin	Gravimetric heat content (MJ kg^{-1})	Density (g cm^{-3})	Volumetric heat content (MJ m^{-3})
Consume	1.000	−0.026	0.184	0.797	0.600	−0.763	−0.742
Sav		1.000	−0.135	0.044	−0.073	−0.031	−0.047
Moisture			1.000	0.273	0.148	−0.201	−0.193
Lignin				1.000	0.714	−0.695	−0.653
MJ kg^{-1}					1.000	−0.588	−0.501
Density						1.000	0.990
MJ m^{-3}							1.000

relationship was observed between consumption and the temperature and humidity values recorded during the burn trials. Ranges of property values by decay class may be seen in Table 8.

Consumption by ignition method

During high-intensity short-duration ignition, flaming of the log surface typically occurred within 10 to 30 s of exposure; the CWD was exposed to temperatures of ~800–900°C. For

Table 7. Beta regression showing the estimated coefficient, standard error, log-likelihood and log-likelihood *P* value
P values of 0.05 or less represent significant additions to the model (Neter *et al.* 1996)

Variable	Estimated coefficient	Standard error	Log-likelihood	Log-likelihood test *P* value
Intercept	6.8160	13.560	Initial model	Initial model
Ignition	0.3315	0.2775		
Density	−29.960	31.400	68.61	
Lignin content	0.0582	0.01626	78.92	0.001
Heat content (gravimetric)	−0.0002	0.0006	79.49	0.450
Heat content (volumetric)	0.0011	0.0015	79.63	0.708
Surface area-to-volume ratio	−0.8762	1.2420	79.84	0.647
Moisture content	−0.1186	0.1300	80.32	0.488

Table 8. Mean consumption and properties for all classification and ignition methods
Standard deviations are shown in parentheses

Class	Consumption high-temperature short-duration	Consumption low-temperature long-duration	Moisture percentage by weight	Surface area-to-volume ratio	Lignin percentage by weight	Density (g cm^{-3})	Heat content (MJ kg^{-1})	Heat content (MJ m^{-3})	C : N ratio
Fogel									
1	8.6 (21.2)	3.7 (6.4)	7.8 (0.8)	0.3 (0.1)	33 (7)	0.512 (0.084)	20.2 (0.6)	10341 (1648)	1366 (402)
2	3.6 (3.1)	51.1 (46.7)	7.7 (0.5)	0.3 (0.1)	39 (12)	0.447 (0.084)	20.5 (0.7)	9100 (1568)	1270 (302)
3	33.1 (39.2)	54.8 (44.8)	8.1 (1.2)	0.4 (0.2)	41 (12)	0.431 (0.094)	20.5 (0.9)	8828 (1861)	632 (284)
4	88.2 (26.4)	96.1 (1.4)	8.3 (1.6)	0.3 (0.1)	66 (16)	0.331 (0.078)	22.1 (1.0)	7293 (1555)	397 (168)
Maser									
1	10.9 (27.4)	8.0 (11.9)	0.8 (1.0)	0.4 (0.1)	34 (8)	0.480 (0.083)	20.2 (0.6)	9666 (1583)	1232 (453)
2	6.5 (10.3)	34.0 (45.6)	7.7 (0.5)	0.4 (0.1)	36 (11)	0.485 (0.084)	20.3 (0.6)	9831 (1589)	1402 (428)
3	14.8 (27.6)	53.4 (44.7)	7.8 (0.9)	0.4 (0.1)	39 (13)	0.464 (0.113)	20.7 (1.0)	9576 (2165)	1081 (432)
4	95.7 (2.9)	98.5 (1.3)	8.4 (1.6)	0.3 (0.1)	68 (14)	0.324 (0.079)	22.2 (1.0)	7155 (1613)	363 (124)
Extended									
1	9.2 (25.3)	5.9 (8.3)	7.8 (0.7)	0.3 (0.1)	32 (7)	0.509 (0.094)	20.2 (0.5)	10236 (1798)	1440 (396)
2	6.6 (9.6)	33.0 (41.9)	8.0 (0.9)	0.4 (0.2)	35 (8)	0.475 (0.058)	20.2 (0.5)	9583 (1185)	1184 (446)
3	42.4 (44.3)	58.9 (45.5)	7.7 (0.9)	0.3 (0.1)	44 (14)	0.434 (0.105)	21.0 (1.0)	9060 (2015)	858 (380)
4	96.3 (2.7)	99.0 (1.2)	8.7 (1.7)	0.3 (0.1)	73 (11)	0.299 (0.054)	22.4 (1.1)	6694 (1281)	311 (97)

low-intensity long-duration ignition, the peat moss was allowed to smoulder under the log, exposing CWD to temperatures of ~500°C for several minutes with temperatures cooling to ~300°C. A general trend of increasing consumption with advancing decay class held true for all classification and ignition methods (Fig. 5). Only the Maser class met statistical assumptions for analysis. Consumption for logs ignited using the low-intensity long-duration method was higher at the $\alpha = 0.05$ significance level. Further analysis with using Tukey's HSD did not produce statistical differences among specific Maser decay classes (Fig. 5).

Discussion

Classification methods

The three classification methods showed similar consumption values for class 1 and 4 logs. There was a wide range of consumption values for logs in decay classes 2 and 3. This is in part due to the reliance of these methods on surface characteristics. These classification methods also appear to have a propensity for capturing a wide variety of characteristics in the middle classes, a phenomenon that has been noted by previous researchers (Pyle and Brown 1999). For the original intent of these systems, this may not create complications; however, when they are applied to a fuels inventory application, these surface characteristics do not always represent the entire log accurately. Examples of this may be seen by observing the cross-sections of three logs that experienced higher than expected consumption given their decay class (Fig. 6). These cross-sections show special cases where small pockets of decay or cracks existed or the presence of wood that was far more decayed within the log than on its surface. The small channels of decay were weakly represented in the overall wood properties for each of the samples; however, they provided a suitable environment for a sustained smoulder. This smouldering ultimately ignited the sound wood and led to consumption values closer to those for a class 4 log than other classes. As a result, these samples accounted for a portion of the observed variation in consumption in classes 2 and 3.

Although the Maser classification method easily separated out decay class 4 logs with high consumption, a finer degree of accuracy is difficult to attain using these methods, and they

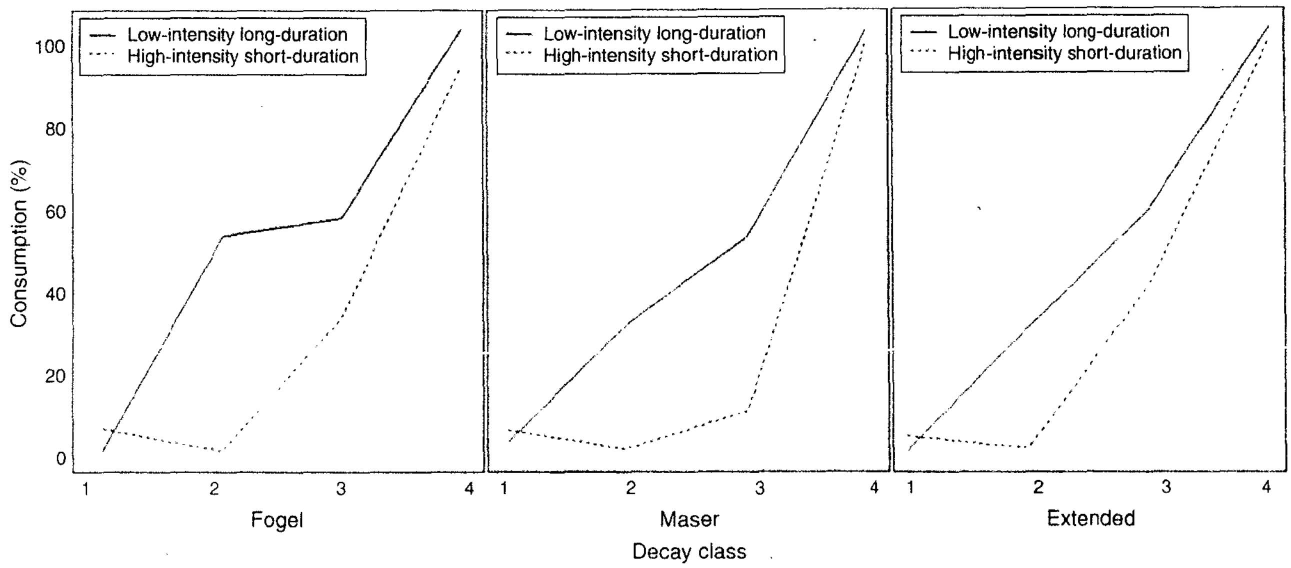

Fig. 5. Linear plots comparing consumption in each class by ignition method. Results for the Fogel method (left), Maser method (centre) and Extended method (right).

Fig. 6. The logs pictured left and centre 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 smouldering in the sound sections was initiated. The log on the right showed a relatively sound outer portion and completely decayed inner portion. The pictured ruler is 15 cm for scale.

should be considered a method of coarse approximation. In attempting to determine if the wood properties significantly changed in Maser class 4 compared with the other classes, complications arose as not all the properties met the assumptions of normality and homoscedasticity required to make comparisons between classes. To further understand the influence of decay on CWD properties and consumption, the CWD properties must be considered independently of any classification method.

Consumption and intrinsic properties

High consumption of logs in this study was associated with high lignin content and gravimetric heat content, and low density and volumetric heat content. The ranges of intrinsic properties in the CWD we observed, especially lignin content, is likely due to the specific decay organisms associated with CWD in the western United States. Logs in this study were predominantly affected by brown rot fungi, organisms that utilise cellulose much more readily than lignin (Schmidt 2006). This results in wood with high lignin content. High lignin content results in higher heat content (Demirbaş 2001) and would explain the high gravimetric heat content observed in the decayed class 4 samples. Higher heat content in rotten logs was also observed by van Wagtendonk *et al.* (1998). 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 values would likely be different as brown rot preferentially attacks cellulose and white rot attacks both lignin and cellulose (Schmidt 2006). Owing to the selection of a specific size class and the efforts to look at logs under similar moisture conditions, our inferences on the effect of surface area and moisture 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 an effect on the consumption of CWD in this study.

Rotten logs are best described as a low-density body (equating to lower heat conductivity) of high-heat-content material. This lower density or high heat content may be the cause for increased consumption. Another potential cause could be oxygen availability, a key factor in smouldering consumption of CWD (Carvalho *et al.* 2002). During density analysis, there were visibly larger air spaces in the rotten CWD samples. These

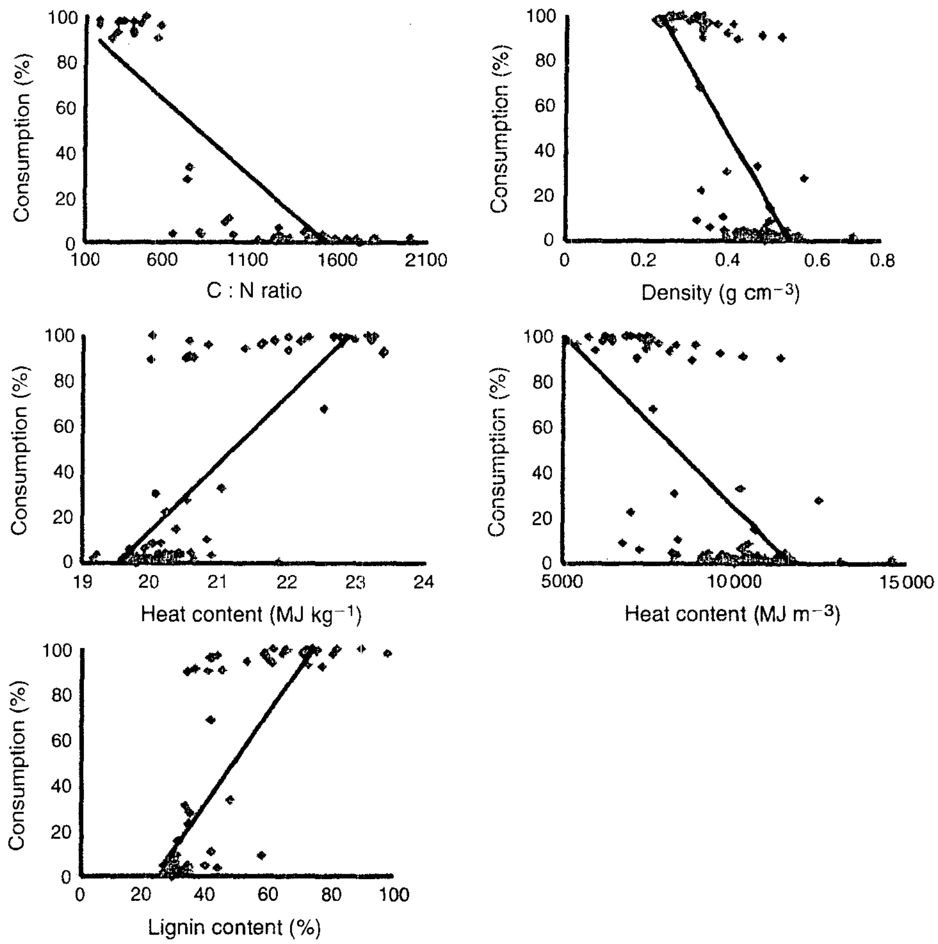

Fig. 7. Bimodal percentage consumption plotted for each of the intrinsic properties.

air spaces or pores could be providing gaps through which oxygen could be made available to the combustion front (E. Alvarado, pers. comm., 2009); pore size is also important for the rate of combustion (Rabelo *et al.* 2004).

Consumption data was bimodal in nature (Fig. 7). Approximately 75% of the samples grouped together in the low-consumption region of the graphs whereas the last 25% (most decayed samples) grouped in the highest-consumption regions. This may indicate a threshold beyond which properties of CWD make it more available for consumption. It may also be an artefact of management practices. Further investigation is recommended in the ranges of wood property values in which this split appears; this includes logs with C : N ratios starting at 600, densities of 0.3–0.4 $g\,cm^{-3}$, gravimetric heat content between 20 and 21 $MJ\,kg^{-1}$, volumetric heat content between 8000 and 9000 $MJ\,m^{-3}$ and 40–60% lignin content. It is suggested the future studies investigate samples within these ranges when examining properties that facilitate sustained consumption in CWD.

Ignition

Consumption values were generally higher for logs in classes 2 and 3 of all classification methods given low-intensity long-duration ignition methods (Fig. 5). Class 1 logs tended to have low consumption regardless of classification and ignition methods, and class 4 logs tended to experience high consumption values. Temperature ranges involved in both ignition methods, ~800–900 and 300–500°C for high-intensity and low-intensity ignition respectively, were both above those required to ignite wood in previous studies (Babrauskas 2002). One possibility for the increased consumption in low-intensity long-duration examples may be the extended period of time for which the samples were exposed to heat. Another possibility for this increased consumption could be the insulating effect of the peat moss used to carry the smouldering front that ignited these samples.

Management implications

The FIA program reports 24% of CWD surveyed in the United States fell into decay class 4 or above (USDA 2010). Based on the results of the present study, this debris is prone to ≥90% consumption given low moisture conditions whereas sound logs experience less than 3–10% consumption. It is more difficult to draw conclusions about the remaining logs in classes 2 and 3 owing to high variation. The Maser classification grouped logs in the present study into two groups, classes 1 through 3 being considered sound and class 4 being considered rotten. This captures a binary trend in sound and very decayed logs, and of the three systems evaluated in this study is the one recommended by the authors for a coarse approximation of

Table 9. Wood property-based look-up table for consumption
Dark shaded area indicates a consumption value of 50% or higher. Light shaded area indicates consumption of 20–50%. The remaining 19% or less consumption is not shaded

	High consumption								Low consumption
C : N ratio	180	360	540	720	900	1080	1260	1440	≥1620
Consumption	97%	94%	95%	40%	4%	8%	3%	3%	2%
Density (g cm^{-3})	0.240	0.291	0.342	0.393	0.444	0.495	0.546	0.597	≥0.648
Consumption	97%	98%	85%	75%	33%	6%	11%	9%	2%
Heat content (MJ kg^{-1})	23.4	22.9	22.5	22.0	21.6	21.1	20.7	20.2	≤19.8
Consumption	96%	93%	98%	83%	94%	36%	22%	13%	3%
Heat content (MJ m^{-3})	5200	6178	7156	8134	9112	10 090	11 068	12 046	≥13 024
Consumption	98%	99%	97%	99%	82%	94%	56%	60%	7%
Lignin content (%)	≥90	84	77	70	63	56	49	42	≤35
Consumption	99%	99%	97%	99%	82%	94%	56%	60%	7%
Surface area-to-volume ratio	0.23	0.282	0.334	0.392	0.444	0.496	0.548	0.600	≥0.652
Consumption	96%	27%	38%	51%	42%	16%	1	1	17%

consumption. Based on this work, the authors propose a more detailed tool to approximate consumption that incorporates wood properties to provide a more accurate representation of these fuels for use in physical-based models. One example of such a tool is proposed herein (Table 9). In this table, the authors divided the property values into equal ranges and applied shading based on average percentage consumption for each range using our data. Average consumption values were sorted into three categories, 0–19, 20–50 and 50–100% consumption, and the corresponding wood properties are displayed. Such a table may be seen as a starting point to linking consumption to ranges of wood properties. Adapting this table to a visual estimation technique is likely to be limited by the same constraint as the classification methods evaluated in this paper: the reliance on surface characteristics that may not represent the entire log accurately. However, this tool may increase in utility should any of the represented metrics become easily measured in a field setting, thus allowing a log to be allocated to a region of the table where its properties could then be better characterised for modelling purposes.

Combining CWD decay classes into sound and rotten categories in modelling systems such as Consume and FOFEM will likely capture the bimodal nature of consumption observed in this study. Further studies, such as the one by *Hollis et al.* (2010), are warranted to evaluate how well the predictions in these modelling systems match consumption of decayed CWD in field conditions. In the case of Consume, incorporation of log property data from studies such as this would require the addition of physical parameters such as density or lignin content as its CWD consumption algorithms rely more on surrounding fuel conditions and moisture rather than intrinsic properties of CWD. 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 gravimetric heat content or lignin content.

Limitations

This work evaluates the effect of decay on consumption of mixed conifer logs 7–23 cm in diameter influenced by brown rot under low moisture conditions. This narrowed scope allowed the authors to focus on the influence of decay on CWD consumption, but limited the inferences that could be made regarding the influence of moisture and surface area-to-volume ratio. Water-holding capacity is a property this study was unable to evaluate that could produce different results than those here. It is unclear to what degree moisture content may affect logs with low density and different composition due to decay. Other researchers have found sustained smouldering in soils to occur at over 140% moisture content (Reardon *et al.* 2007); whether or not these CWD could sustain smouldering at high moisture contents merits further investigation. Perhaps higher moisture contents would show more of an interaction among CWD intrinsic properties and consumption.

The surface area-to-volume ratio was estimated using equations for the area and volume of a frustum. Although quick, this method provides only a coarse view of the actual surface area owing to its inability to capture surface texture. Sound CWD samples are often found without bark and with a relatively smooth surface as compared with decay class 4 CWD. In decayed samples, brown cubicle rot had created a pattern of cracking and tiny protrusions formed by fragmenting during the decay and weathering process. A method that accurately captures these differences in surface textures may provide a stronger relationship between surface area-to-volume ratio and consumption than that reported here. For solid wood particles, the method by Fernandes and Rego (1998) may be a better indicator of actual surface area; however, its application to decayed samples is problematic owing to the frailty of the most decayed samples and their propensity to absorb and retain water.

Our understanding of the combustion of rotten wood would benefit greatly if it is evaluated in multiple field settings to determine if the relationships between decay and consumption found in this study hold true in other regions and conditions. Areas where different decay organisms are present may yield different consumption values, as some the wood properties evaluated in this work may change in wood affected by a different class of decay organisms.

Conclusion

With regards to classification methods, decay class 4 experienced statistically higher consumption than classes 1 through 3. As consumption increased with decay class, density and volumetric heat content decreased and lignin content and gravimetric heat content increased. Although we held moisture and surface area-to-volume ratio relatively constant so that the study could focus on other wood properties, these variables are likely to influence consumption and should be evaluated in the future. Ignition method was statistically significant and tended to be higher for logs ignited using the low-intensity long-duration method.

This study demonstrates that decayed CWD with diameters 7–23 cm is likely to be consumed completely under low fuel moisture conditions. Logs in sound or mostly sound condition are likely to be less consumed, 1–60%, and with greater variability. As 24% of CWD surveyed under the FIA program is highly decayed, CWD is likely to create substantial amounts of emissions during wildland fires in low-moisture conditions as these logs are prone to a greater degree of consumption than sound logs. There was a noticeably wide range in consumption values of decay classes 2 and 3, in part because of cracks and pockets of decay that allowed fire to breach the solid surface and reach the interior, creating variability in the consumption. Such circumstances are difficult to account for when making consumption predictions. In characterising the physical properties of decaying CWD, lignin content and density were highly correlated with consumption regardless of ignition method. For the subset of samples that had C : N ratios calculated, this number was highly correlated with consumption, further indicating the linkage between advancing decay and increasing consumption.

Examining the split between low and high consumption and the wood property ranges where this split occurs will provide future research opportunities for those investigating a potential threshold beyond which the sustained combustion of logs is likely to occur. The bimodal nature of the consumption data appears to be in agreement with the current convention used by Consume and FOFEM of combining CWD into two broad categories of 'sound' and 'rotten'. However, the algorithms of each should be evaluated for their adequacy in predicting consumption of highly decayed CWD. This was a laboratory study and fuel consumption data measured in the field should be used to validate the results of this study and determine field applicability. Consumption predictions may be improved by incorporating the physical metrics specified above into predictive models.

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