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Dead and down woody debris fuel loads in Canadian forests

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Abstract. In Canada, fire behaviour is modelled based on a fuel classification system of 16 fuel types. Average fuel loads are used to represent a wide range of variability within each fuel type, which can lead to inaccurate predictions of fire behaviour. Dead and down woody debris (DWD) is a major component of surface fuels affecting surface fuel consumption, potential crown fire initiation, and resulting crown fuel consumption and overall head fire intensity. This study compiled a national database of DWD fuel loads and analysed it for predictive driving variables. The database included DWD fuel loads for all dominant Canadian forest types at three size classes: fine (<1 cm), medium (1–7 cm) and coarse (>7 cm). Predictive models for DWD fuel load by size classes individually and collectively for various forest types and ecozones were analysed. Bioclimatic regime, age, spatial position, drainage, and structural components including diameter at breast height and stem density were significant variables. This study provides tools to improve our understanding of the spatial distribution of DWD across Canada, which will enhance our ability to represent its contribution within fire behaviour and fire effects models.

Keywords: dead and down woody debris, fire behaviour, fuel load, forest fire, Canada, boreal, surface fuel.

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Introduction

Dead and down woody debris (DWD) is an important component of the forest ecosystem. It forms major structural features important for wildlife habitat (Harmon *et al.* 1986) and plays a fundamental role in carbon (Woodall *et al.* 2013) and other key nutrient cycles (Lambert *et al.* 1980). DWD is a major component of the surface fuel load that contributes to the spread of an active fire (Van Wagner 1977). It is an important contributing factor to forest fire behaviour, particularly as it affects the critical transition phase from surface fire to crown fire. Crown fire threshold is dependent upon the amount of surface fuel consumed within the flame front (flaming combustion), surface fire rate of spread, foliar moisture content and the live crown base height (Van Wagner 1977; Cruz *et al.* 2004). DWD fuel size and load can directly affect the amount of fuel consumed in a moving surface fire (de Groot *et al.* 2007; Ottmar 2014; Prichard *et al.* 2014) and the resulting surface fire intensity (Byram 1959; Alexander 1982). If surface fire intensity reaches the level at which live lower branches of conifer trees are ignited, a point known as the critical surface fire intensity (Van Wagner 1977), a crown fire is initiated. Fire behaviour becomes extreme with the onset of crowning because the fire is exposed to higher wind speeds above the tree canopy (Schroeder and Buck 1970), which increases fire rate of spread, and because total fuel consumption increases due to engagement of crown fuels in the flame front. Both these factors combine to greatly increase overall head fire intensity and fire suppression difficulty (Hirsch and Martell 1996; Alexander and Cruz 2019). When a surface fire becomes a crown fire, head fire intensity can increase by an order of magnitude. Spreading surface fires typically have a head fire intensity of 500–4000 kW/m, whereas crown fires can have 4000–90 000+ kW/m (Alexander and de Groot 1988; Alexander and Lanoville 1989; Stocks *et al.* 2004).

DWD fuel size and load varies greatly both spatially (Keane *et al.* 2012) and temporally (Hély *et al.* 2000) and has many contributing factors. The accumulation of DWD on the forest floor is a balance between tree mortality and breakage versus decomposition (Harmon *et al.* 1986) that changes over the life history of the stand (Woodall *et al.* 2013). It varies depending on the species composition (Bernier *et al.* 2007), disturbance history (Stocks 1987; Keane *et al.* 2012) and site productivity (Woodall *et al.* 2013). DWD increases due to mortality during life cycle processes such as natural thinning as immature stands grow, and stand break-up of over-mature stands. It also increases due to periodic natural disturbances including wind throw, insect outbreaks and snow damage (Brown and See 1981). DWD decomposition, on the other hand, is influenced by patterns of temperature, moisture and substrate quality (Harmon *et al.* 1986). The spatial distribution of DWD varies by size classes where coarse woody debris tends to be close to tree boles and decomposes slowly compared with finer woody debris that is much lighter and more easily dispersed creating a more uniform pattern (Keane *et al.* 2012). Another important agent of DWD reduction is fire, which can consume a great proportion of DWD depending on fire intensity and fire weather conditions (Forestry Canada Fire Danger Group 1992).

As mentioned earlier, DWD fuel load and the amount consumed by fire directly affect fire intensity (Byram 1959), and the rate of combustion influences emissions (Cofer *et al.* 1990). These variables are influenced by DWD size class, moisture content and combustion phase (i.e. flaming, smouldering and residual), although most models do not currently differentiate between the latter two phases (Ottmar 2014). Quantification of DWD by size class is important as the surface to volume ratio affects drying rates and therefore ignition and consumption. Smaller diameter fuels require less heat to ignite and are generally consumed faster. DWD fuel load is defined as the total dry weight biomass per unit area (Keane 2013) and is an input in fire behaviour prediction (e.g. Albini 1976), effects (Reinhardt *et al.* 1997; de Groot 2010) and carbon emission models (Kurz *et al.* 2009). To date, DWD fuels have not been modelled explicitly in the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), one of the major subsystems in the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989), which is the primary source of daily fire intelligence in Canada. Instead, DWD is combined with forest floor and understorey vegetation fuels to represent the entire surface layer as a single fuel component, due to the capabilities of model development at the time. However, advances have been made since then to separate surface fuels into forest floor and DWD fuel layers, each with multiple components (Amiro *et al.* 2009; de Groot *et al.* 2009, 2013). Specifically, DWD is modelled explicitly as a distinct fuel layer comprised of individual diameter size-classes in the Canadian Fire Effects Model (CanFIRE; de Groot 2010), which has shown significant improvement in fire behaviour predictions (de Groot *et al.* 2013) and carbon emission assessment (de Groot *et al.* 2007) owing to these changes.

Standard fuel models have been developed for fire behaviour prediction in Canada using a classification system of 16 fuel types in the FBP System (Forestry Canada Fire Danger Group 1992), which are based on dominant forest vegetation types found across Canada. The FBP System calculates fire behaviour attributes including fuel consumption, rate of spread and head fire intensity for each FBP System Fuel Type. These models are driven primarily by components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), representing the effect of fire weather on dead fuel moisture content and fire behaviour.

FBP System standard fuel models have components of surface and canopy fuels, which were assigned with an average fuel load to each component for every fuel type. As part of a project to build the next generation CFFDRS (CFFDRS-2025), research efforts to update the FBP System include adding the ability to quantitatively represent fuel structural components, which allows surface and ground fuels to be separated into individual fuel layers (i.e. litter, duff, DWD) (Canadian Forest Service Fire Danger Group 2021). This greatly increases ground and surface fuel model flexibility to more accurately reflect the diverse range of surface fuel conditions in Canada. Similar changes are planned for the aboveground tree fuel component, which will greatly expand the range of standing timber fuel types that are represented in the FBP System, including special cases such as the damaged or disturbed forests with increased DWD fuel loads. By incorporating an adjustable fuel load dimension for individual layers, like DWD, fire behaviour prediction becomes more robust and dynamic. In order to implement these changes in the next generation FBP System and extension models like CanFIRE, reliable DWD fuel load information representing forest stands across the country is required. Currently, neither a national DWD fuels database nor DWD fuel load models are available in Canada.

Assessing wildland surface fuels in general is difficult (Keane 2013), especially when DWD fuels are considered due to their high degree of spatial variability over relatively small areas (Gould *et al.* 2008; Woodall and Liknes 2008). Regression models predicting DWD fuel loads have been established based on species, age, temperature and moisture regimes, and disturbance, but they are limited to selected forest types or regions in Canada (e.g. Lee *et al.* 1997; Hély *et al.* 2000; Pedlar *et al.* 2002; Ter-Mikaelian *et al.* 2008; Allard and Park 2013). The objectives of this study were to (1) assemble existing Canadian datasets to characterise DWD fuel load, (2) examine the geographical variation of DWD, and (3) analyse potential factors to predict DWD fuel loads across the country.

Materials and methods

Data sources

Numerous Canadian datasets were examined to identify those containing DWD information as well as information on dominant tree species, ecozone and/or spatial coordinates of the sampling plots. There were five datasets that met these criteria for inclusion in this study (Table 1): the National Forest Inventory (NFI), the Forest Ecosystem Carbon Database (FECD), the FBP System experimental fire database (FIRE dataset hereafter), the Energy from the Forest Program of Canadian Forest Service (ENFOR) dataset, and the Canada-Ontario Forest Resource Development Agreement (COFRDA) forest fuels database. All datasets fall within the predominately forested landmass of Canada as defined by the Ecological Stratification Working Group (ESWG 1995) (Fig. 1).

The NFI is a collection of national permanent sample plots across Canadian forests (Gillis *et al.* 2005) maintained by the Canadian Forest Service. Attributes are obtained from ground plots, photo plots and remote sensing data. DWD of various size classes were sampled from the ground plots using both transects and microplots (Table 2). The NFI is the most complete dataset within the study area containing 766 plots across the country that met the study requirements (Fig. 1); latitude, longitude, stand age, drainage class, tree species, diameter at breast height and stand density (both live and dead standing) were also measured (Table 1). In this dataset, drainage class is a measure of how quickly water is drained from the soil ranging from very rapid, rapid, well, moderately well, imperfect, poor, to very poor (Ontario Institute of Pedology 1985). DWD fuel loads were measured for three size classes as fine (<1.0 cm), medium

Table 1. Number of plots (*n*) by dataset

DWD size class and explanatory variables for Database I are unshaded. Those explanatory variables shaded in grey are included in Database II, in addition to all those from Database I. Diameter size classes are as follows: fine woody debris (FWD) <1 cm, medium woody debris (MWD) 1–7 cm, coarse woody debris (CWD) >7 cm, and total DWD includes all size classes. NFI, National Forest Inventory; FECS, Forest Ecosystem Carbon Database; FIRE, Fire Behaviour Prediction System experimental database; ENFOR, Energy from the Forest Program; COFRDA, Canada-Ontario Forest Resource Development Agreement

Dataset	Total *n*	FWD fuel load	MWD fuel load	CWD fuel load	Total DWD fuel load	Dominant tree species	Ecozone	Drainage class	Stand age	DBH	Density
NFI	766	766	653	766	766	766	766	766	722	501	501
FECD	94		85	94	94	94	94	89	93		
FIRE	48	48	45	48	48	48	48		4		
ENFOR	120	120	82	120	120	120	96		93		
COFRDA	257			257	257	257	65				
Total	1285	934	865	1285	1285	1285	1069	855	912	501	501

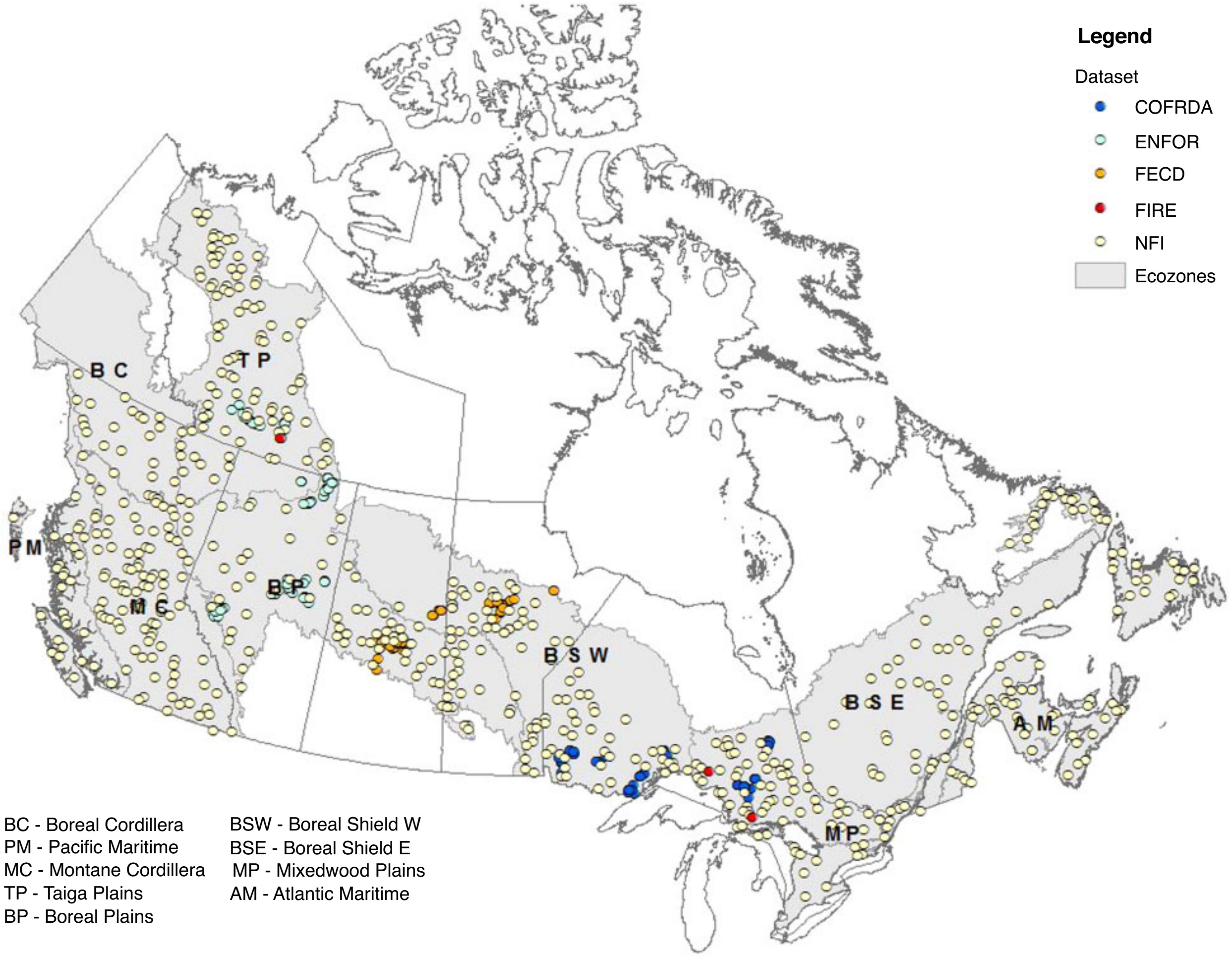

Fig. 1. Map of plot locations in the DWD fuel load dataset across ecozones. The datasets include the NFI, FECD, FIRE, ENFOR and COFRDA.

(1.0–7.5 cm), coarse (>7.5 cm) and total woody debris (all sizes) (Table 2).

The FECD was part of a series of projects designed to address the data needs of modellers studying the impacts of changing climate and site characteristics on forest carbon stocks and fluxes (Shaw *et al.* 2005). The FECD focussed on compiling existing plot-level data to be used in the estimate of aboveground and belowground carbon pools. A total of 706 plots from eight sources were included in the dataset collected from 1986 to 2002 (Fig. 1). Only 94 plots met the minimum required attributes of this study. The dataset includes latitude, longitude, dominant tree species, stand age and drainage class (Table 1).

Table 2. Datasets complied for the study, including their source, field method for collection and DWD size class distributions

NFI, National Forest Inventory; FECS, Forest Ecosystem Carbon Database; FIRE, Fire Behaviour Prediction System experimental database; ENFOR, Energy from the Forest Program; COFRDA, Canada-Ontario Forest Resource Development Agreement

Dataset	Reference	Biomass collection method	FWD (cm)	MWD (cm)	CWD (cm)
NFI	Gillis *et al.* (2005)	Line-intersect[A] for MWD and CWD-microplot for FWD	<1.0	1.0–7.5	>7.5
FECD	Shaw *et al.* (2005)	Line-intersect[A]		0–7.0	>7.0
FIRE	Forestry Canada Fire Danger Group (1992)	Line-intersect[A]	0–0.49 0.5–0.99	1.0–2.99 3.0–4.99 5.0–7.0	>7.0
ENFOR	Nalder *et al.* (1997, 1999)	Line-intersect[A]	0–0.49 0.5–0.99	1.0–2.99 3.0–4.99 5.0–7.0	>7.0
COFRDA	Stocks *et al.* (1990)	Line-intersect[A]		0–2.99 3.0–7.0	>7.0

[A] Van Wagner (1968).

Table 3. Uncorrelated standard bioclimatic variables produced with Canadian and North American surfaces by McKenney *et al.* (2013) (http://cfs.nrcan.gc.ca/projects/3. See https://fennerschool.anu.edu.au/research/products/anuclim for information about ANUCLIM.)

Bioclimatic variables (*Abbreviation*)	Definition
Mean Annual Temperature (*Annual μ T*)	Mean of all the monthly mean temperatures
Mean Diurnal Range (*μ Diurnal Range*)	Mean of all the monthly diurnal temperature ranges
Isothermality 2/7 (*Isothermality*)	Mean diurnal range divided by the annual temperature range
Mean Temperature of Wettest Quarter (*μ T Wettest Q*)	The wettest quarter of the year is determined and the mean temperature of this period is calculated
Mean Temperature of Driest Quarter (*μ T Driest Q*)	The driest quarter of the year is determined and the mean temperature of this period is calculated
Mean Temperature of Warmest Quarter (*μ T Warmest Q*)	The warmest quarter of the year is determined and the mean temperature of this period is calculated
Precipitation of Wettest Period (*P Wettest Period*)	Precipitation of the wettest month
Precipitation Seasonality (CofV) (*P Seasonality*)	Coefficient of variation (CofV) is the standard deviation of the monthly precipitation expressed as a percentage of the mean of those estimates
Precipitation of Warmest Quarter (*P Warmest Q*)	The warmest quarter of the year is determined and the total precipitation over this period is calculated

DWD fuel loads were collected for two size classes in this database, less than all other datasets (Table 2).

Fuel load data in the FIRE dataset were collected on six experimental burning projects conducted by the Canadian Forest Service over 40 years to build the FBP System (Forestry Canada Fire Danger Group 1992) (Fig. 1). These experimental burning projects were conducted at Hondo (Quintilio *et al.* 1991) and Darwin Lake (Quintilio *et al.* 1977) in Alberta; Sharpsand Creek (Stocks 1987) and Kenshoe Lake (Stocks 1989) in Ontario; and Fort Providence (Stocks *et al.* 2004) and Porter Lake (Alexander *et al.* 1991) in the North-west Territories (Fig. 1). DWD fuel loads in this dataset were measured by multiple size classes (Table 2) but included a limited number of attribute variables (Table 1).

Nalder *et al.* (1997, 1999) and others[1] created the ENFOR dataset for DWD fuels in the boreal forests of western and northern Canada (Alberta and North-west Territories; Fig. 1). Fuel loads were measured for multiple size classes (Table 2) and included information by dominant tree species and stand age (Table 1).

Lastly, the COFRDA forest fuels dataset is a detailed inventory of close to 300 stands across the Boreal and Great Lakes–St. Lawrence forest regions of northern Ontario (Stocks *et al.* 1990) (Fig. 1). DWD fuel loads were measured in three size classes at each plot with dominant tree species information of the plot (Table 2).

Database management and analysis

DWD fuels

Two fuels databases were compiled to characterise Canadian DWD fuel loads, and to analyse potential factors predicting DWD fuel loads across the country (objectives 1 and 2). One DWD fuels database contained the plot-level data from all five different datasets (Table 1) (Database I), and the second was a subset containing only the NFI dataset (Database II). Although Database I was larger, because it included all five DWD

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[1] Unpublished CWD data, collected under ENFOR Project NO-00-04/P-491in 2000 and 2002 by University of Alberta for Canadian Forest Service, Northern Forestry Centre, Edmonton.

datasets, the number of variables was limited by data not available for drainage and stand structure characteristics in some DWD datasets. In contrast, Database II contained only the NFI dataset, which was smaller than Database I, but it included a large amount of data for all variables of interest (i.e. structural attributes). Database I and Database II were both national in scope. Although Database II included a more extensive list of variables than Database I and it contained more than half (59.6%) of all available DWD plot data (Table 1), Database II was still lacking in data for certain species or species groups. Therefore, Database I was included in this study to provide analysis over a broader range of species with a larger dataset.

All DWD data in this study was collected using the line intersect method (Van Wagner 1968). When compiling the databases, DWD fuel load and dominant tree species were the primary attributes of interest. In order to be consistent, the DWD data were grouped into three diameter size classes: fine (0–0.99 cm) (FWD), medium (1–7 cm) (MWD) and coarse (7+ cm) (CWD). The diameter distribution of the NFI plots was slightly different for the top end of MWD (i.e. 7.5 cm) and lower end of CWD (Table 2). The FECD dataset did not have a separate FWD class and COFRDA sampled FWD up to 2.99 cm (Table 2); these were aggregated into the MWD class. The assumption was that these small discrepancies would have minimal influence on the final fuel loading outcomes (Hollis *et al.* 2010). Total DWD fuel load was calculated as the total fuel load of all size classes. There were some instances where zero fuel load was measured for a size class, which usually occurred in the FWD size class, although zero fuel load was not a common occurrence in the dataset. In the case of no entry for a given fuel size class, the record was removed from the analysis.

Plots from all sources were assigned to the ecozone level of the national ecological framework (ESWG 1995) (Fig. 1). For this study, only predominately forested ecozones were included and the Boreal Shield was split into east and west subzones (Stocks *et al.* 2003). Hudson Plains and Taiga Shield were excluded due to a lack of plots, resulting in a total of nine ecozones represented. In addition to the sampled plot-level covariates of tree species, soil drainage and stand age, 36 bioclimatic variables (McKenney *et al.* 2013), longitude and elevation were extracted for each plot based on spatial coordinates, to provide additional explanatory power. An initial exploratory analysis using only the sampled plot-level covariates were all found to have a significant effect on DWD fuel loads based on ANOVA and regression analysis. However, the best models using only plot-level covariates could only explain 30–40% of the variance for all DWD size classes. In order to improve the prediction power of these models, additional bioclimate variables were added to the analysis to expand on the climatic differences within the ecozone delineations. The majority of the initial 36 bioclimatic variables were highly correlated with each other based on Pearson's correlation coefficient ($r \geq 0.7$; Dormann *et al.* 2013; Blouin *et al.* 2016). As a result, only nine bioclimatic variables were selected for the final analysis where $r < 0.7$ (Table 3). In addition, species were grouped into genera to increase sample sizes for less common species (Tables S1–S4, Supplementary Material) with limited spatial extent across the country, that is, maple (*Acer*), birch (*Betula*), Douglas-fir (*Pseudotsuga*) and hemlock (*Tsuga*).

Spatial distribution of DWD and its prediction modelling

Based on Database II, one-way ANOVA was used to compare the DWD fuel loads by ecozone and DWD size classes across the study area. We used Database II for the comparison because the sampling plots in the NFI database were designed to represent various forest ecosystems, which may increase the reliability of the comparisons. To compensate for the skewed nature of the data to low fuel loads, the data were square root transformed. We also compared DWD fuel loads by DWD size classes for forest stands dominated by various species and species groups across the country.

We developed the predictive models of DWD at various sizes with all sampling plots from Database I. Explanatory variables including age and drainage class in addition to elevation, longitude and bioclimatic variables (Table 3) were considered in these models when available (Table 1). For its simplicity, a multiple linear regression model was carried out on all uncorrelated variables by size class for the entire database and for each dominant species or genus group when sample size was limited, respectively. An R package *leaps* was used for model selection by conducting an exhaustive search of the minimum number of variables that resulted in the simplest model using main factors with the optimal adjusted R^2 ($P < 0.05$). By checking the residual plot of each model, a quadratic term of the predictors was tested in the modelling procedure. Proportional contribution of each variable was calculated based on the proportional variation explained by the variable to the total.

For species or species groups where no statistically significant models could be built based on Database I, the same multiple linear regression analysis was performed using Database II in order to use the additional plot-level structural variables to improve the goodness of fit. We built the regression models by species level for the whole study area and for each ecozone (which was shown to be significant based on ANOVA results) where plot numbers were sufficient. To compensate for the reduction in the number of plots, a basic rule of thumb was followed where analysis was not performed with fewer than seven plots and a minimum of one explanatory variable could be included for every five plots, which is suggested as the minimum number of records necessary to build a reliable model (Tabachnick and Fidell 2019).

Results

The largest average TWD (total woody debris) fuel loads were found in western Canada in the Pacific Maritime and Montane Cordillera ecozones (Fig. 2). Based on our exploratory analysis, ecozone was found to be a significant variable explaining up to 85% of the variability in fuel load for some dominant tree species and all size classes. The lowest TWD fuel loads were found in the far northern ecozone of the Taiga Plains and more southern Mixedwood Plains, which is dominated by more temperate tree species. Mean TWD is relatively consistent across the boreal ecozones into the Atlantic Maritime (Fig. 2), although it is important to note that there is a lot of variability in fuel loads for all size classes, where standard deviations are often equal to or greater than the mean fuel load (Tables S1–S4, Supplementary Material). CWD makes up the greatest proportion of TWD fuel load in all ecozones (Fig. 2). The distribution

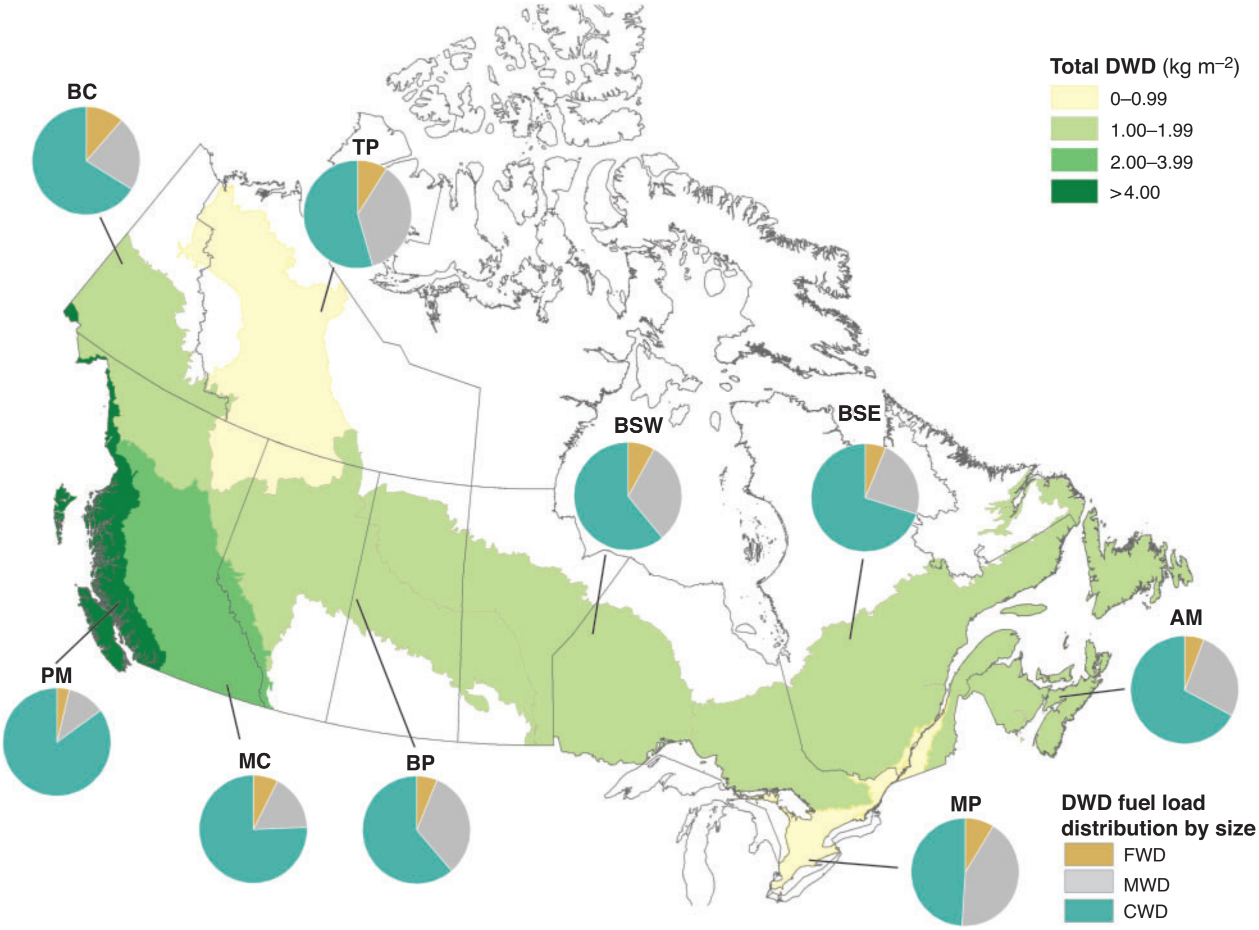

Fig. 2. Average TWD (including all diameter size classes) by ecozone with the pie charts of proportional woody debris by size class; FWD (<1 cm), MWD (1–7 cm) and CWD (>7 cm). Ecozones are as follows: BC (Boreal Cordillera), PM (Pacific Maritime), MC (Montane Cordillera), TP (Taiga Plains), BP (Boreal Plains), BSW (Boreal Shield West), BSE (Boreal Shield East), MP (Mixedwood Plains) and AM (Atlantic Maritime).

of other DWD size classes varied among ecozones where the Atlantic Maritime had the lowest values for FWD and the Pacific Maritime, Montane Cordillera and Boreal Cordillera had the lowest proportional MWD fuel loads (Fig. 2).

When grouped by genera, median FWD fuel loads were all under 0.5 kg/m^2 (Fig. 3), with the exception of a few outliers. FWD fuel loads were greatest for coastal Douglas-fir (*Pseudotsuga menziesii var. menziesii*) and hemlock (*Tsuga*), due to the high FWD loads of Douglas-fir (mean 0.68 kg/m^2) and western hemlock (*Tsuga heterophylla*) (mean 0.44 kg/m^2) in the Pacific Maritime ecozone (Table S1). MWD loads were higher than FWD loads, upwards of 1 kg/m^2 (Fig. 3), again dominated by large western coniferous tree species including both Douglas-fir and western hemlock (Table S2). CWD fuel loads were very low for larch (*Larix*), mean 0.26 kg/m^2 (Table S3, Fig. 3), and under 1 kg/m^2 on average for sugar maple (*Acer saccharum*), eastern white pine (*Pinus strobus*) and balsam poplar (*Populus balsamifera*). TWD fuel loads were greatest for hemlock (*Tsuga*) (Fig. 3), dominated by coastal western hemlock (Table S4).

Multiple linear regressions fitted by genus, using Database I, resulted in significant models for six of the genera tested (Table S5, Supplementary Material) explaining 35–75% of the fuel load variability (Table 4). Of the initial 14 explanatory variables considered, the most commonly significant were temperature-based variables (i.e. annual mean temperature, isothermality, mean diurnal temperature or mean temperature of the wettest quarter), but they rarely explained more than 30% of the variability in DWD fuel load. Age and soil drainage were not as often found to be significant but when they were significant could explain up to 50% of the variability (i.e. MWD for Douglas-fir and hemlock, which are high drought and water tolerant species, respectively). The same explanatory variables were often significant across different size classes within the same genera (Table 4).

No significant models were found for larch and for the three most widespread genera found in Canada, spruce (*Picea*), pine (*Pinus*) and poplar/aspen (*Populus*) based on Database I (Table 4). Models fitted with additional structural explanatory variables, DBH and stand density (both live and dead) using Database II showed significant improvement (Table 5 and Table S6, Supplementary Material) for pine only. Models for pine CWD and TWD were significant ($P < 0.05$) with adjusted-R^2 of 0.37 and 0.35, respectively (Table S6). In both cases

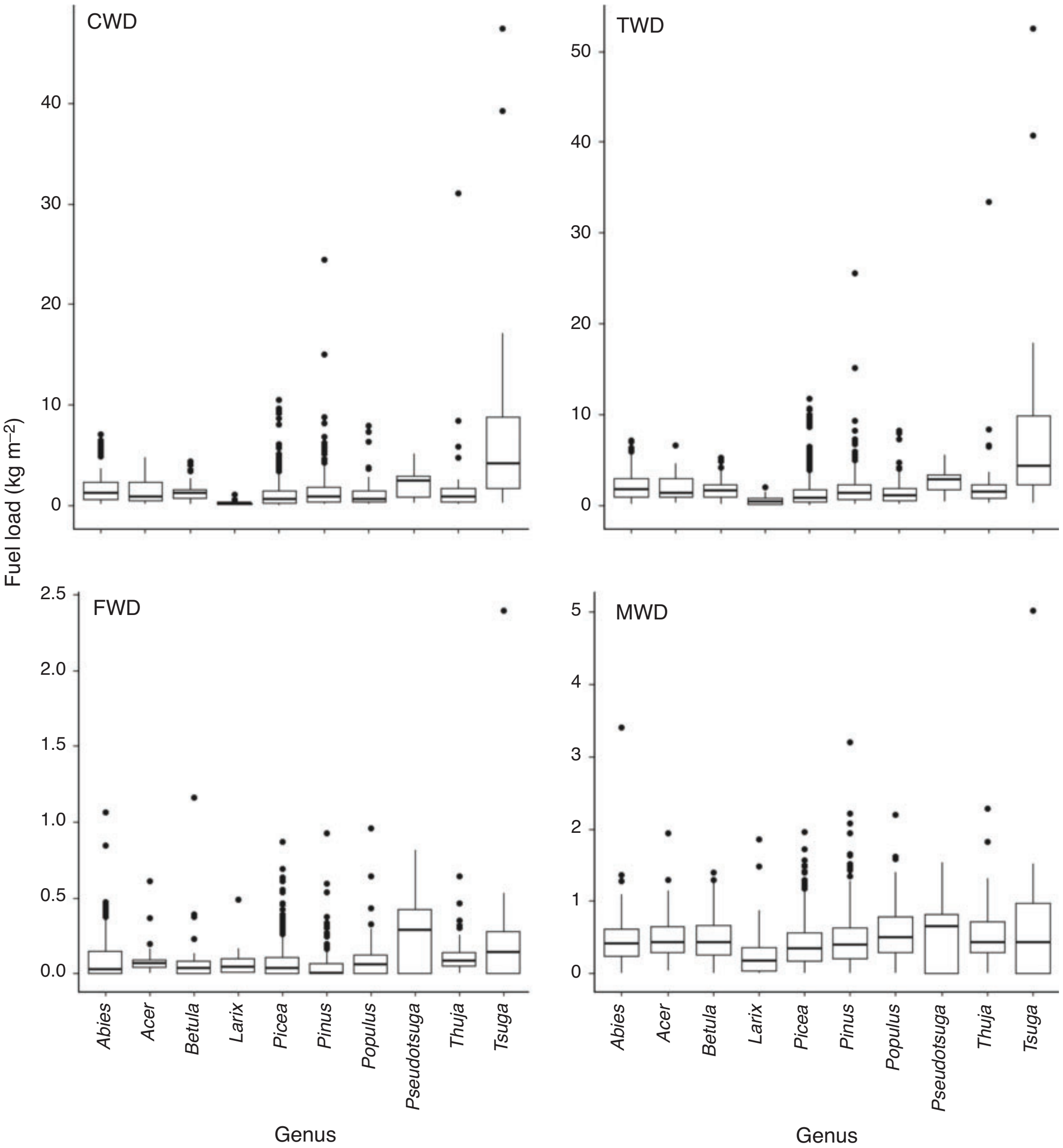

Fig. 3. Box plot comparisons of fuel loading by size class (FWD, MWD, CWD and TWD) by genus.

elevation and DBH were the only significant explanatory variables included in the final model, where most of the variability was explained by elevation differences (Table 5).

Additional variability in common boreal genera could be explained by separate dominant tree species (Table 6 and Table S7, Supplementary Material), except for those most commonly found across the country (which is addressed in the following paragraph). Although the number of plots were reduced, models for many DWD size classes were improved. For example, the explained variability for the spruce genus was 30.3% of TWD fuel load (Table 6), but separating by species the explained variability in TWD fuel load for Engelmann spruce (*Picea engelmannii*) increased to 55.1% (Table 6). Similar examples can be seen for spruce and poplar/aspen (Table S7 and Table 6). Significant models were found for all size classes for eastern white pine (*Pinus strobus*), where the density of standing live trees was the only covariate that remained for MWD, CWD and TWD and explained greater than 50% of the variability in fuel load for each size class (Table 6). Explanatory variables that related to temperature were again the most commonly selected in the regression models, although often did not contribute much in explaining the variability. When included, age and structural variables (in Database II), DBH and density of standing live trees were more important. Significant models that explained greater than 30% of the variability were found for seven of the nine dominant tree species in just under half of the size class/species combinations.

For the remaining two common boreal tree species for which no significant models could be found for any size class (Jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*)), as well as the two species for which only one size class was available to develop prediction models (white spruce (*Picea

Table 4. Summary of multiple linear regression models by genus using Database I, including significant explanatory variables and their estimated coefficients, proportional variability explained (Exp Var) and adjusted (Adj) R^2

T, temperature; P, precipitation; Q, quarter; SD, soil drainage (categorical); µ, mean; DBH, diameter at breast height. Only significant ($P < 0.05$) models are included

		FWD			MWD			CWD			TWD		
Genus	Variable	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2
Fir (*Abies*)	Intercept	–5.913		0.54									
	P Wettest Period	0.004	43.5										
	Longitude	–0.004	10.2										
	µ T Driest Q	–0.015	1.5										
	P Seasonality	–0.005	1.2										
Maple (*Acer*)	Intercept	0.123		0.35				14.412		0.68	15.724		0.67
	µ T Driest Q	0.010	37.1					–0.113	37.1		–0.138	42.0	
	Factor (SD) 2	–						–4.931	22.5		–5.282	18.9	
	Factor (SD) 3	–						–5.358			–5.422		
	Factor (SD) 4	–						–5.096			–4.859		
	Factor (SD) 5	–						–5.281			–5.144		
	Factor (SD) 6	–						–5.716			–5.469		
	Longitude	–						0.089	14.8		0.096	26.2	
Birch (*Betula*)	Intercept	–1.203		0.76				17.128		0.58			
	Isothermality	10.101	33.7					–91.256	8.7				
	P Seasonality	0.003	20.0					0.091	21.6				
	P Warmest Q	–0.002	19.8					–	–				
	Age	–0.001	5.4										
	µ Diurnal Range	–0.078	2.9					2.668	0.0				
	µ T Driest Q	–	–					0.170	0.6				
	µ T Warmest Q	–	–					–1.612	0.0				
	Annual µ T	–	–					1.339	0.1				
	Factor (SD) 2	–	–					–1.096	50.1				
	Factor (SD) 3	–	–					–0.993					
	Factor (SD) 4	–	–					–1.138					
	Factor (SD) 5	–	–					–0.715					
	Factor (SD) 6	–	–					2.297					
Douglas-fir (*Pseudotsuga*)	Intercept	–6.350		0.73	0.176		0.49	2.835		0.41			
	Longitude	–0.052	28.2		–	–		–	–				
	P Warmest Q	0.002	26.9		–	–		–	–				
	P Wettest Period	0.001	20.9		–	–		–	–				
	µ T Warmest Q	–	–		0.033	14.5		–	–				
	µ T Wettest Q	–	–		–	–		–0.128	29.2				
	µ T Driest Q	–	–		–	–		–0.112	20.7				
	Factor (SD) 2	0.258	8.8		–0.405	50.0		–	–				
	Factor (SD) 3	0.060			–0.221			–	–				
	Factor (SD) 4	–0.111			–0.059			–	–				

Cedar (*Thuja*)	Intercept	–0.231		0.49				–42.816		0.57	–43.744		0.55
	Elevation	0.0004	32.4					–0.023	10.6		–0.022	11.9	
	Isothermality	0.045	22.0					375.125	22.3		373.570	21.7	
	Factor (SD) 2	–	–					–7.708	18.7		–9.312	18.9	
	Factor (SD) 3	–	–					–15.231			–15.471		
	Factor (SD) 4	–	–					–9.798			–13.157		
	Factor (SD) 5	–	–					–10.754			–11.143		
	Factor (SD) 6	–	–					–14.480			–15.785		
	Factor (SD) 7	–	–					–18.183			–18.839		
	Annual µ T	–	–					–4.887	8.1		–4.816	7.4	
	Age	–	–					–0.075	19.6		–0.064	16.5	
Hemlock (*Tsuga*)	Intercept				2.530		0.77						
	Age				–0.002	50.1							
	Elevation				0.001	22.1							
	Isothermality				–10.000	9.1							
	Annual µ T				0.259	1.8							
	µ T Wettest Q				–0.032	1.6							

Table 5. Summary of multiple linear regression models by genus using Database II, including significant explanatory variables and their estimated coefficients, explained variability (Exp Var) and adjusted (Adj) R^2

DBH, diameter at breast height. Only significant ($P < 0.05$) models are included

Genus	Variable	FWD Estimate	Exp Var (%)	Adj R^2	MWD Estimate	Exp Var (%)	Adj R^2	CWD Estimate	Exp Var (%)	Adj R^2	TWD Estimate	Exp Var (%)	Adj R^2
Pine (*Pinus*)	Intercept							–1.777		0.37	–1.254		0.35
	Elevation							0.002	29.6		0.002	31.1	
	DBH							0.110	8.9		0.092	5.6	

Table 6. Summary of multiple linear regression models by dominant species using Database II, including significant explanatory variables and their estimated coefficients, explained variability (Exp Var) and adjusted (Adj) R^2

T, temperature; P, precipitation; Q, quarter; SD, soil drainage (categorical); µ, mean; DBH, diameter at breast height; DSD, density standing dead; DSL, density standing live. Only significant ($P < 0.05$) models are included

		FWD			MWD			CWD			TWD		
Species	Variable	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2
Picea engelmannii	Intercept	–0.185		0.55				–4.632		0.48			
	Age	0.004	60.3					–	–				
	DBH							0.470	44.9				
	µ T Driest Q							0.424	14.4				
Picea glauca	Intercept							2.004		0.47			
	µ T Warmest Q							–0.873	15.0				
	P Seasonality							–0.057	8.5				
	Elevation							–0.004	7.2				
	Isothermality							59.610	6.7				
	µ T Driest Q							–0.131	1.6				
Picea mariana	Intercept				–0.647		0.32						
	DSD				0.001	23.5							
	µ Diurnal Range				0.079	9.5							
Pinus contorta var. latifolia	Intercept				0.074		0.56	–5.692		0.93	–5.847		0.95
	DBH				–	–		0.471	94.0		0.508	96.1	
	Age				0.003	63.6		–	–		–	–	
Pinus contorta var. contorta	Intercept				–5.1981		0.55	–253.00		0.42	–115.00		0.37
	DSD				0.0005	25.8		0.0017	5.8		–	–	
	Factor (SD) 3				–0.3542	20.4		–	–		–	–	
	Factor (SD) 4				–0.4663			–	–		–	–	
	Longitude				–0.0446	10.3		–1.8100	12.4		–0.832	14.7	
	DBH				–0.0205	6.6		0.0958	4.7		–	–	
	P Wettest Period				0.0074	2.5		0.1080	2.1		0.077	0.7	
	µ T Wettest Q				0.0204	1.7		0.1430	3.4		–	–	
	Elevation				–	–		0.0117	14.0		0.006	14.9	
	Annual µ T				–	–		2.5800	20.6		1.410	16.0	
	P Seasonality				–	–		0.0978	1.2		–	–	
Pinus strobus	Intercept	–0.1755		0.89	–0.2422		0.52	–0.5414		0.52	–0.7405		0.52
	P Wettest Q	0.0020	72.3		–			–	–		–	–	
	µ T Wettest Q	0.0101	20.1		–			–	–		–	–	
	DSL	–	–		0.00005	59.2		0.0008	57.3		0.0013	58.8	
Populus balsamifera	Intercept	–2.7658		0.64	–0.0620		0.45	1.4610		0.80			
	Longitude	–0.0173	45.9		–	–		–	–				
	µ T Driest Q	–0.0293	19.7		–	–		–	–				
	P Seasonality	–0.0107	4.9		–	–		–	–				
	µ T Warmest Q	0.0577	4.1		–	–		–0.2004	35.4				
	P Warmest Q	0.0014	2.3		–	–		–	–				
	µ Diurnal Range	–	–		–	–		0.5756	51.6				
	Age	–	–		0.0056	49.9		–	–				
	Elevation	–	–		–	–		–0.0020	0.4				

glauca) and trembling aspen (*Populus tremuloides*)), higher levels of explained variability in DWD fuel loads were achieved when the prediction models were developed by ecozone, that is, where the number of plots permitted this (Table 7 and Table S8, Supplementary Material). This was possible for black spruce, white spruce, Jack pine and trembling aspen. Significant models that explained a good proportion of fuel load variability were found within each species for each ecozone, with the exception of black spruce in the Boreal Shield East (Table 7). The key explanatory variables in the models were again more similar between DWD size classes than between ecozones within a species or between species. These included age, temperature, longitude and structural variables (DBH, DSD) as well as soil drainage, which were most important based on high proportions of variability explained in the resultant models.

Discussion

This study represents the first research in Canada to develop DWD fuel load models for most dominant forest types across the country. Because it is difficult and expensive to monitor and sample, DWD fuel load data is typically sparse. The national datasets presented herein are themselves of great value, particularly to fire managers across the country (see Table S9 in the Supplementary Material to crosswalk results to the current benchmark FBP System Fuel Types). Recent studies on sensitivity analysis have shown that variations in fuel load can have significant impact on fuel consumption and therefore fire behaviour and emission predictions (Kennedy *et al.* 2020). Any information that allows modellers to tailor fuel load estimates is helpful. Using regression modelling techniques, we developed models with high predictive power for 80% of the dominant Canadian forest types/DWD size classes, which improves our ability to characterise DWD fuels for improved fire behaviour, fire effects and fire emission models used within research and operational fire management (see Table S9 in the Supplementary Material for general guidelines on how results can be applied). Where explanatory variables are not available, mean and standard deviation values of DWD by species and ecozone provide a much needed starting point to calibrate models.

The databases analysed in this study revealed a wide range in DWD fuel loads, as also shown in other studies (Keane 2016). As previously mentioned, species and climatic gradients strongly influence DWD production (Bernier *et al.* 2007), accumulation (Allard and Park 2013) and decomposition (Harmon *et al.* 2000). DWD variability across climatic gradients in this study are similar to findings by Woodall *et al.* (2013), which showed greatest loadings in the Pacific North West of the USA, an area of cool wet climate and infrequent fire very similar to Canada's Pacific Maritime ecozone. Bioclimatic variables, especially those derived from temperature, were significant in almost all predictive models for all DWD size classes. Although, these were often not as important as variables such as age, drainage, elevation or structural attributes when included. Overall, there was more consistency in terms of explanatory variable selections between size classes than between genera or species. For some genera, further division into species groups was necessary to achieve a better fitted model, which may relate to greater differences in tree morphology within some genera, that is, white spruce and black spruce have very different structural growth patterns and occupy different niches. Species has been found to be a significant variable also in other models of DWD (Hély *et al.* 2000; Allard and Park 2013).

Drainage class and age have also been shown to influence DWD load, particularly for CWD (Gould *et al.* 2008; Allard and Park 2013). Although these were significant variables in less than half of the regression models fitted in this study, when age was a significant variable, it could in some cases explain over half of the variability (i.e. FWD Engelmann spruce and MWD hemlock). We assume that drainage class may show significant influence on DWD when the species are more tolerant to soil moisture changes, because drainage class may not vary much for species with less tolerance to soil moisture regime changes. The lack of consistency of age influencing DWD has also been found elsewhere (Ter-Mikaelian *et al.* 2008), whereas others have found disturbance, which can be synonymous with age, to be important (Hély *et al.* 2000; Moroni 2006). It is not clear why age has not been consistent in predicting DWD; however, we found that age appeared to be significant only to species that are adapted to mesic or drier habitats (e.g. Jack pine), not to species that are adapted to wetter habitats (e.g. black spruce). Furthermore, a lack of age data for all plots may be the other reason that age did not show significant influence in some models.

Summarising DWD fuel loading is complicated, and additional factors including small scale disturbance events and silvicultural practices further confound national scale summaries (Woodall and Liknes 2008). Disturbance patterns that occur at the stand level can strongly influence DWD accumulation rates (Moroni 2006), which may result in weak DWD relationships to landscape scale ecosystem characteristics like species type and climate (Brown and See 1981). This may be why some forest types required classification to the ecozone level to capture added variability due to either the widespread distribution of some species or greater influence of stand scale processes across Canadian forested lands.

With the exception of the Pacific Maritime ecozone (which has some DWD fuel loads >11 kg/m^2), average Canadian TWD fuel loads are low (<6 kg/m^2, with most ecozones having <3 kg/m^2) in comparison to typical fuel loads in the forest floor (5–20 kg/m^2, Letang and de Groot 2012) and standing timber (5–16 kg/m^2, Penner *et al.* 1997). However, DWD fuels are important because they are an influential factor on fuel consumption, surface fire intensity and potential fire behaviour overall. A high proportion of FWD and MWD (and a small proportion of CWD) are consumed by surface fire during the flaming combustion phase (Hollis *et al.* 2010; Prichard *et al.* 2014), directly contributing to surface fire intensity. In contrast, the organic forest floor fuel layer, which is the other primary fuel stratum contributing to surface fire intensity, has a very different pattern. Forest floor fuel loads are much higher than DWD and consumption values can be high, but the amount consumed is wide-ranging and dependent on the level of long-term drying (de Groot *et al.* 2009). However, even when forest floor fuel consumption is very high, only the surface layer of litter, lichen and mosses is consumed at a high rate in the flaming combustion phase (90–95%), and very little of the subsurface duff fuels (F and H layers) are consumed during flaming combustion (10% for upper duff, 0% for lower duff) (Prichard *et al.* 2007). As a result, only a small amount of the total organic soil layer burned

Table 7. Summary of multiple linear regression models by ecozone (Figs 1 and 2) and species using Database II, including significant explanatory variables and their estimated coefficients, explained variability (Exp Var) and adjusted (Adj) R^2

T, temperature; P, precipitation; Q, quarter; SD, soil drainage (categorical); µ, mean; DBH, diameter at breast height; DSD, density standing dead; DSL, density standing live. Only significant ($P < 0.05$) models are included

		FWD			MWD			CWD			TWD		
Ecozone	Variable	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2	Estimate	Exp Var (%)	Adj R^2
Jack pine (*Pinus banksiana*)													
TP	Intercept							0.3495		0.53			
	µ T Wettest Q							–0.3368	62.2				
	P Seasonality							0.0924	1.2				
BP	Intercept	–0.1506		0.41	–1.2827		0.40						
	Age	–0.0011	47.7		–0.0071	39.2							
	Longitude	–0.0060	0.78		–	–							
	µ Diurnal Range	–0.0323	0.52		0.2000	4.9							
	Annual µ T	–	–		–0.1878	1.0							
BSW	Intercept	1.8654		0.46	6.7558		0.44						
	Longitude	–0.0137	27.3		–	–							
	µ T Wettest Q	–0.1904	15.2		–0.3458	27.5							
	Annual µ T	0.1003	12.7		–	–							
	Age	–	–		–0.0104	19.7							
BSE	Intercept				–0.1338		0.69				16.7306		0.40
	Annual µ T				0.1626	74.4					0.5696	30.4	
	µ Diurnal Range				–	–					0.9418	14.7	
	P Seasonality										0.2867	7.0	
White spruce (*Picea glauca*)													
TP	Intercept							–8.3258		0.63	–3.5330		0.49
	DBH							0.2845	13.0		0.2152	38.8	
	µ T Warmest Q							–0.5310	10.8				
	P Wettest Period							–0.1902	1.9		–0.0972	0.04	
	Isothermality							102.5123	0.5				
	P Seasonality										0.1314	17.2	
BSW	Intercept										–0.4761		0.87
	P Wettest Period										–	–	
	Age										0.0181	89.1	
Black spruce (*Picea mariana*)													
TP	Intercept							0.3596		0.89	–1.9385		0.32
	µ T Warmest Q							–0.3969	48.4		–	–	
	Isothermality							28.8277	42.0		–	–	
	Elevation							–0.0010	1.2		–	–	
	DBH							–	–		0.2206	34.5	
BP	Intercept	–1.5420		0.62	–3.1901		0.57	–0.8172		0.71	–0.8833		0.64
	µ T Driest Q	0.0257	40.5		–	–		–	–		–	–	
	DSL	0.0001	24.2		–	–		–	–		–	–	
	µ T Wettest Q	0.1196	5.0		–	–		–	–		–	–	
	µ Diurnal Range				0.3009	33.4		–	–		–	–	
	DSD				0.0011	30.5		0.0034	65.0		0.0045	57.8	
	DBH				–	–		0.0620	11.0		0.0836	11.3	

BSW	Intercept				0.2870		0.55				4.9400		0.41
	DSD				0.0008	56.9					0.0026	17.3	
	DSL				−0.0001	0.80					−0.0005	3.1	
	DBH				–	–					0.2970	25.1	
	Isothermality				–	–					−35.400	1.8	
Trembling aspen (*Populus tremuloides*)													
BP	Intercept	−0.42860		0.49	−6.4778		0.38						
	Factor (SD) 2	0.02948	53.4		–	–							
	Factor (SD) 3	−0.03652			–	–							
	Factor (SD) 4	−0.03520			–	–							
	Factor (SD) 5	0.10330			–	–							
	Factor (SD) 6	0.03436			–	–							
	µ T Wettest Q	0.03286	4.1		0.2015	3.0							
	DSL	0.00005	3.3		–	–							
	Longitude	–	–		−0.0371	27.4							
	Annual µ T	–	–		−0.2059	13.3							
BSW	Intercept							−2.3019			−2.5380		0.52
	DBH							0.1859	49.4		0.2243	20.1	

contributes to surface fire intensity. By separating these strata in the next generation CFFDRS fuels (Canadian Forest Service Fire Danger Group 2021), the contribution of DWD to overall surface fuel loads becomes more important. These data are a starting point to help initialise fuel loads in resultant DWD consumption models currently in development.

As with most scientific analyses this study was not without limitations. Spatially, many of the sample plots, particularly in more southern parts of the country were clustered, with fewer plots in more northern areas; there were no plots in the Taiga Shield and Hudson Plains ecozones. Some genera had fewer than 40 plots across the country including maple, birch, larch, Douglas-fir, hemlock and cedar, and low plot numbers restricted the analysis for these forest types. In addition, structural variables of DBH and stem density (live or dead) were only available in Database II and may have explained further variability in the models created using Database I. Consistency in data collection standards may also influence results, that is, using the same size classes may have contributed to higher variability within some of the regression models. Future field studies should use consistent size classes and collect more in-situ data like age, disturbance regimes (i.e. time since fire) and structural attributes. Future research could also use other forms of modelling techniques such as non-linear models or machine learning, although multiple linear regression did have good results in most cases as shown in our study and allowed exploration of explanatory variables. The compiled databases provide a much needed starting point for eventual mapping of DWD that could be done with more sophisticated machine learning techniques and combined with remote sensing information like Lidar (light detection and ranging) across the landscape to obtain more plot level data (Keane *et al.* 2012; Queiroz *et al.* 2019).

Conclusions

DWD fuel loads in natural forest stands across Canada are highly variable. The relationship between bioclimatic variables, elevation, drainage, age and tree structure with woody debris fuel load is complicated, and DWD fuel loads therefore cannot be described/quantified nationally based on a simple set of variables. The in-situ measured variables, dominant tree species and ecozone, were significant predictive factors but only explain 30% of variation on their own. Age and drainage class were also significant factors but only increase explained variance by an additional 1–9%, depending on DWD size class. Addition of bioclimatic variables and structural attributes to the models improved models in most cases. Overall, the models and datasets developed in this study capture a good portion of the inherent variability of DWD fuel loads, which provides a first approximation of DWD fuel loads in standing timber fuel types across Canada. Based on this study, the fuel loads are consistent with other regional scale analyses across Canada and broad scale patterns are similar to other national analyses. These results together with forest floor fuel loads from Letang and de Groot (2012) give a thorough picture of surface and ground dead fuel loading across Canada, with only the live understorey vegetation component missing to complete a national surface fuel loading database required for wildland fire modelling and implementation of planned changes to the next generation CFFDRS

(Canadian Forest Service Fire Danger Group 2021). These data and models provide a foundation on which to build quantitative fuel load and consumption models for improved prediction of fire behaviour, fire effects and forest carbon dynamics.

Conflicts of interest

The authors declare no conflicts of interest.

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References

Albini FA (1976) Computer-based models of wildland fire behavior: a user's manual. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture. (Ogden, UT, USA)

Alexander ME (1982) Calculating and interpreting forest fire intensities. *Canadian Journal of Botany* **60**, 349–357. doi:10.1139/B82-048

Alexander ME, Stocks BJ, Lawson BD (1991) Fire behavior in black-spruce lichen woodland: the Porter Lake project. Information Report NOR-X-310. Forestry Canada, Northwest Region. (Edmonton, AB)

Alexander ME, Cruz MG (2019) Fireline intensity. In 'Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires'. (Ed. SL Manzello) pp. 1–8. (Springer: Cham). doi:10.1007/978-3-319-51727-8_52-1

Alexander ME, de Groot WJ (1988) Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Canadian Forest Service/Northern Forestry Centre (Edmonton, AB). Poster w/text.

Alexander ME, Lanoville RA (1989) Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. Forestry Canada, Northern Forestry Centre/Government of Northwest Territories, Department of Renewable Resources, Territorial Forest Fire Centre (Edmonton, AB/Fort Smith, NWT). Poster w/text.

Allard J, Park A (2013) Woody debris volumes and carbon accumulation differ across a chronosequence of boreal red pine and jack pine stands. *Canadian Journal of Forest Research* **43**, 768–775. doi:10.1139/CJFR-2013-0100

Amiro BD, Cantin A, Flannigan MD, de Groot WJ (2009) Future emissions from Canadian boreal forest fires. *Canadian Journal of Forest Research* **39**, 383–395. doi:10.1139/X08-154

Bernier PY, Lavigne MB, Hogg EH, Trofymow JA (2007) Estimating branch production in trembling aspen, Douglas-fir, jack pine, black spruce, and balsam fir. *Canadian Journal of Forest Research* **37**, 1024–1033. doi:10.1139/X06-284

Blouin KD, Flannigan MD, Wang X, Kochtubajda B (2016) Ensemble lightning prediction models for the province of Alberta, Canada. *International Journal of Wildland Fire* **25**, 421–432. doi:10.1071/WF15111

Brown JK, See TE (1981) Downed dead woody fuel and biomass in the northern Rocky Mountains. USDA Forest Service, Intermountain Forest and Range Experimental Station, GTR-INT-117. (Ogden, UT, USA)

Byram GM (1959) Combustion of forest fuels. In 'Forest fire: Control and use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York, NY)

Canadian Forest Service Fire Danger Group (2021) The vision for the Next-Generation of the Canadian Forest Fire Danger Rating System. Information Report GLFC-X-26. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre. (Sault Ste. Marie, ON)

Cofer WR, III, Levine JS, Winstead EL, Stocks BJ (1990) Gaseous emissions from Canadian boreal forest fires. *Atmospheric Environment* **24**, 1653–1659. doi:10.1016/0960-1686(90)90499-D

Cruz MG, Alexander ME, Wakimoto RH (2004) Modeling the likelihood of crown fire occurrence in conifer forest stands. *Forest Science* **50**, 640–658.

de Groot WJ (2010) Modeling fire effects: Integrating fire behaviour and fire ecology. In 'Proceedings of 6th International Conference: Forest Fire Research', 15–18 November 2010, Coimbra, Portugal. (Ed. DX Viegas). ADAI University of Coimbra. (Coimbra, Portugal). CD-ROM.

de Groot WJ, Landry R, Kurz WA, Anderson KR, Englefield P, Fraser RH, Hall RJ, Banfield E, Raymond DA, Decker V, Lynham TJ, Pritchard JM (2007) Estimating direct carbon emissions from Canadian wildland fires. *International Journal of Wildland Fire* **16**, 593–606. doi:10.1071/WF06150

de Groot WJ, Pritchard JM, Lynham TJ (2009) Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. *Canadian Journal of Forest Research* **39**, 367–382. doi:10.1139/X08-192

de Groot WJ, Cantin AS, Flannigan MD, Soja AJ, Gowman LM, Newbery A (2013) A comparison of Canadian and Russian boreal forest fire regimes. *Forest Ecology and Management* **294**, 23–34. doi:10.1016/J.FORECO.2012.07.033

Dormann CF, Elith J, Bacher S, Buchmann C, Carl G, Carre G, García Marquéz JR, Gruber B, Lafourcade B, Leitão PJ, Münkemüller T, McClean C, Osborne PE, Reineking B, Schröder B, Skidmore AK, Zurell D, Lautenbach S (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography* **36**, 27–46. doi:10.1111/J.1600-0587.2012.07348.X

Ecological Stratification Working Group (1995) A National Ecological Framework for Canada. Agriculture and Agric.-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, (Ottawa, Ontario). Report and national map at 1:7 500 000 scale.

Forestry Canada Fire Danger Group (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada Information Report ST-X-3.

Gillis MD, Omule AY, Brierley T (2005) Monitoring Canada's forests: the National Forest Inventory. *Forestry Chronicle* **81**, 214–221. doi:10.5558/TFC81214-2

Gould WA, Gonzálex G, Hudak AT, Nettleton Hollingsworth T, Hollingsworth J (2008) Forest structure and downed woody debris in boreal, temperate, and tropical forest fragments. *Ambio* **37**, 577–587. doi:10.1579/0044-7447-37.7.577

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Jr, Cummins KW (1986) Ecology of course woody debris in temperate ecosystems. *Advances in Ecological Research* **15**, 133–302. doi:10.1016/S0065-2504(08)60121-X

Harmon ME, Krankina ON, Sexton J (2000) Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. *Canadian Journal of Forest Research* **30**, 76–84. doi:10.1139/X99-187

Hély C, Bergeron Y, Flannigan MD (2000) Coarse woody debris in the southeastern Canadian boreal forest: composition and load variations in relation to stand replacement. *Canadian Journal of Forest Research* **30**, 674–687. doi:10.1139/X99-256

Hirsch KG, Martell DL (1996) A Review of Initial Attack Fire Crew Productivity and Effectiveness. *International Journal of Wildland Fire* **6**, 199–215. doi:10.1071/WF9960199

Hollis JJ, Matthews S, Ottmar RD, Prichard SJ, Slijepcevic A, Burrows ND, Ward B, Tolhurst KG, Anderson WR, Gould JS (2010) Testing woody fuel consumption models for application in Australian southern eucalypt forest fires. *Forest Ecology and Management* **260**, 948–964. doi:10.1016/J.FORECO.2010.06.007

Keane RE (2013) Describing wildland surface fuel loading for fire management: a review of approaches, methods and systems. *International Journal of Wildland Fire* **22**, 51–62. doi:10.1071/WF11139

Keane RE (2016) Spatiotemporal variability of wildland fuels in US Northern Rocky Mountain Forests. *Forests* **7**, 129. doi:10.3390/F7070129

Keane RE, Gray K, Bacciu V, Leirfallom S (2012) Spatial scaling of wildland fuels for six forest and rangeland ecosystems of the northern Rocky Mountains, USA. *Landscape Ecology* **27**, 1213–1234. doi:10.1007/S10980-012-9773-9

Kennedy MC, Prichard SJ, McKenzie D, French NH (2020) Quantifying how sources of uncertainty in combustible biomass propagate to prediction of wildland fire emissions. *International Journal of Wildland Fire* **29**, 793–806. doi:10.1071/WF19160

Kurz WA, Dymond CC, White TM, Stinson G, Shaw CH, Rampley GJ, Smyth C, Simpson BN, Neilson ET, Trofymow JA, Metsaranta J, Apps MJ (2009) CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* **220**, 480–504. doi:10.1016/J.ECOLMODEL.2008.10.018

Lambert RL, Lang GE, Reiners WA (1980) Loss of mass and chemical change in decaying boles of a subapline balsam fir forest. *Ecology* **61**, 1460–1473. doi:10.2307/1939054

Lee PC, Crites S, Nietfeld M, Van Nguyen H, Stelfox JB (1997) Characteristics and origins of deadwood material in aspen-dominated boreal forests. *Ecological Applications* **7**, 691–701. doi:10.1890/1051-0761(1997)007[0691:CAOODM]2.0.CO;2

Letang DL, de Groot WJ (2012) Forest floor depths and fuel loads in upland Canadian forests. *Canadian Journal of Forest Research* **42**, 1551–1565. doi:10.1139/X2012-093

McKenney D, Pedlar J, Hutchinson M, Papadopol P, Lawrence K, Campbell K, Milewska E, Hopkinson RF, Price D (2013) Spatial climate models for Canada's forestry community. *Forestry Chronicle* **89**, 659–663. doi:10.5558/TFC2013-118

Moroni MT (2006) Disturbance history affects dead wood abundance in Newfoundland boreal forests. *Canadian Journal of Forest Research* **36**, 3194–3208. doi:10.1139/X06-195

Nalder IS, Wein RW, Alexander ME, de Groot WJ (1997) Physical properties of dead and downed round-wood fuels in the boreal forests of Alberta and Northwest Territories. *Canadian Journal of Forest Research* **27**, 1513–1517. doi:10.1139/X97-083

Nalder IA, Wein RW, Alexander ME, de Groot WJ (1999) Physical properties of dead and downed round-wood fuels in the Boreal forests of western and Northern Canada. *International Journal of Wildland Fire* **9**, 85–99. doi:10.1071/WF00008

Ontario Institute of Pedology (1985) 'Field Manual for Describing Soils, 3rd edition'. (Guelph Agriculture Centre and University of Guelph: Guelph, ON, Canada)

Ottmar RD (2014) Wildland fire emissions, carbon, and climate: Modeling fuel consumption. *Forest Ecology and Management* **317**, 41–50. doi:10.1016/J.FORECO.2013.06.010

Pedlar JH, Pearce JL, Venier LA, McKenney DW (2002) Course woody debris in relation to disturbance and forest type in boreal Canada. *Forest Ecology and Management* **158**, 189–194. doi:10.1016/S0378-1127(00)00711-8

Penner M, Power K, Muhairwe C, Tellier R, Wang Y (1997) Canada's Forest Biomass Resources: Deriving Estimates from Canada's Forest Inventory. Canadian Forest Service Information Report BC-X-370. (Victoria, British Columbia)

Prichard SJ, Ottmar RD, Anderson GK (2007) Consume User's Guide. Pacific Wildland Fire Sciences Laboratory, USDA Forest Service. 239 pp. (Seattle, WA)

Prichard SJ, Karau EC, Ottmar RD, Kennedy MC, Cronan JB, Wright CS, Keane RE (2014) Evaluation of the CONSUME and FOFEM fuel consumption models in pine and mixed hardwood forests of the eastern United States. *Canadian Journal of Forest Research* **44**, 784–795. doi:10.1139/CJFR-2013-0499

Queiroz GL, McDermid GJ, Castilla G, Linke J, Rahman MM (2019) Mapping course woody debris with random forest classification of centrimetric aerial imagery. *Forests* **10**, 471. doi:10.3390/F10060471

Quintilio D, Fahnestock GR, Dubé DE (1977) Fire behaviour in upland jack pine: the Darwin Lake Project. Canadian Forest Service, Northern Forestry Centre. Information Report NOR-X-174. (Edmonton, AB)

Quintilio D, Alexander ME, Ponto RL (1991) Spring fires in a semimature trembling aspen stand in central Alberta. Forestry Canada, Northwest Region, Northern Forestry Centre. Information Report NOR-X-323. (Edmonton, AB)

Reinhardt ED, Keane RE, Brown JK (1997) First Order Fire Effects Model: FOFEM 4.0, User's Guide. USDA Forest Service, Intermountain Research Station, General Technical Report INT-GTR-344. (Ogden, UT, USA)

Schroeder M, Buck C (1970) Fire weather: a guide for application of meteorological information to forest fire control operations. USDA Forest Service, Agriculture Handbook 360. (Washington, DC)

Shaw CH, Bhatti JS, Sabourin KJ (2005) An ecosystem carbon database for Canadian forests. National Resources Canada, Canadian Forest Service, Northern Forestry Centre Information Report NOR-X-403. (Edmonton, Alberta)

Stocks BJ (1987) Fire behaviour in immature jack pine. *Canadian Journal of Forest Research* **17**, 80–86. doi:10.1139/X87-014

Stocks BJ (1989) Fire behaviour in mature jack pine. *Canadian Journal of Forest Research* **19**, 783–790. doi:10.1139/X89-119

Stocks BJ, Lawson BD, Alexander ME, Van Wagner CE, McAlpine RS, Lynham TJ, Dubé DE (1989) Canadian Forest Fire Danger Rating System: an overview. *Forestry Chronicle* **65**, 450–457. doi:10.5558/TFC65450-6

Stocks BJ, McRae DJ, Lynham TJ, Hartley GR (1990) A photo series for assessing fuels in natural forest stands in northern Ontario. Forestry Canada, Great Lakes Forestry Centre, Canada–Ontario Forest Resource Development Agreement (COFRDA) Report No. 3304. (Sault Ste. Marie, Ontario)

Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2003) Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research* **108**, 8149. doi:10.1029/2001JD000484

Stocks BJ, Alexander ME, Lanoville RA (2004) Overview of the International Crown Fire Modelling Experiment (ICFME). *Canadian Journal of Forest Research* **34**, 1543–1547. doi:10.1139/X04-905

Tabachnick BG, Fidell LS (2019) 'Using Multivariate Statistics, Seventh Edition'. (Pearson: Boston, MA)

Ter-Mikaelian MR, Colombo SJ, Chen J (2008) Amount of downed woody debris and its prediction using stand characteristics in boreal and mixedwood forests of Ontario, Canada. *Canadian Journal of Forest Research* **38**, 2189–2197. doi:10.1139/X08-067

Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* **14**, 20–26.

Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23–34. doi:10.1139/X77-004

Van Wagner CE (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35. (Canadian Forestry Service: Ottawa, ON)

Woodall CW, Liknes GC (2008) Climatic regions as an indicator of forest course and fine woody debris carbon stocks in the United States. *Carbon Balance and Management* **3**, 5. doi:10.1186/1750-0680-3-5

Woodall CW, Walters BF, Oswalt SN, Domke GM, Toney C, Gray AN (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. *Forest Ecology and Management* **305**, 48–59. doi:10.1016/J.FORECO.2013.05.030