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Physical Properties of Dead and Downed Round-wood Fuels in the Boreal Forests of Western and Northern Canada

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Abstract

The quantity of dead and downed woody fuels in forests is commonly estimated using the line intersect method of sampling. Determination of the mass of wood per unit area for each size class requires values for the mean specific gravity, piece tilt angle and piece diameter. We present these values for dead and downed round-wood materials less than 7 cm in diameter based on surveys of slash and naturally fallen materials in six boreal forest regions of western and northern Canada and for eight common species in these regions. There was considerable variation in the three variables: mean specific gravity ranged from 0.34 to 0.65 Mg m^{-3}, tilt ranged from 5° to 33°, and mean squared diameter ranged from 31% below to 71% above the value at class mid-point. Values of each were strongly related to size class, species, fuel type and to region. We conclude that values derived from other study areas or species can give substantial inaccuracies in estimating dead and downed round-wood fuel loads if applied to sites within the study region, although ultimate accuracy obtainable will be more influenced by the length of sampling line. The three variables are combined into a single factor so that fuel loads can be simply calculated by multiplying this factor by the number of intersects per metre of transect.

Keywords:

Dead and downed wood
Fuel load
Line intersect method
Diameter
Tilt
Specific gravity
Pinus
Picea
Abies
Populus
Larix
Boreal forest
Canada
Northwest Territories
Alberta
Saskatchewan
Manitoba.

Introduction

A knowledge of the amount of fine and medium-sized dead and downed round-wood in forests is critical for the understanding and prediction of fire behaviour because such pieces exhibit high surface area-to-volume ratios that in turn determine fuel moisture responses and combustion efficiency (Byram 1959). Inventories commonly utilise the line intersect method of sampling (Warren and Olsen 1964, Van Wagner 1968, 1982, Brown 1971, Brown and Roussopoulos 1974, Brown et al. 1982). For fuel load surveys in Canada, small pieces (those less than 7 cm in diameter) are commonly tallied by round-wood diameter size class using the five classes recommended by McRae et al. (1979). Fuel loads for any size class can be calculated from this formula (after Van Wagner 1982):

$$W = \frac{\pi^2 G \sec(h)\, n\, QMD^2\, c}{8L},$$

where W is mass per unit area or fuel load (Mg ha^{-1} or t ha^{-1}), G is specific gravity (Mg m^{-3}), h is piece tilt angle (degrees), n is the number of intercepts over the length of transect, QMD is the quadratic mean diameter (cm), c is the slope correction factor equal to $\sqrt{1 + (\%\text{ ground slope}/100)^2}$, and L is the length of transect (m). It is necessary, however, to know appropriate values for specific gravity, tilt angle and diameter for each size class.

Locally derived data are important. For example, in the Blue Mountains of Washington and Oregon, Ryan and Pickford (1978) found that locally derived values for QMD and G reduced bias in estimating fuel loads by up to 57% and 44%, respectively, compared with generic values suggested by Brown (1974) for the western United States. Sackett (1980) found that QMD and G values from the south-western United States were up to 62% and 53% different from the values suggested by Brown (1974). In the Sierra Nevada region of California and Nevada, van Wagtendonk et al. (1996) found that the product of QMD, sec(h) and G differed by up to 41% from the values suggested by Brown (1974). Clearly, local data are essential to an accurate assessment of fuel loads but, prior to this study, the only data available for western Canada were from Delisle and Woodard (1988), who measured QMD and G for naturally fallen wood of several species in the Montane forest region of Alberta, and from Bessie and Johnson (1995) who reported G for four species in the Kananaskis region of Alberta. McRae et al. (1979) have suggested multiplication factors incorporating QMD, G and sec(h) for slash fuels of important species for the Canadian size classes, but the applicability of these data are not clear since the sources are varied and include some United States data. To provide more data for western and northern Canada, a 2 year study of the major commercial tree species in six regions of the western Canadian boreal forest was begun in 1995. Brief results from the first year's field survey were reported by Nalder et al. (1997).

Our objectives were to sample naturally fallen dead wood in forest stands and slash on harvested sites, and to make recommendations for values to be used in fuel load inventories in the regions studied. We hypothesised that diameter, tilt and specific gravity were significantly affected by size class, species, fuel type and region. We use the term fuel type to distinguish between forest stands where dead wood is naturally fallen and harvested sites where the wood is predominantly slash.

List of symbols and abbreviations

W	Mass per unit area or fuel load (Mg ha^{-1} or t ha^{-1})
G	Specific gravity (Mg m^{-3} or g cm^{-3})
h	Piece tilt angle (degrees)
MSD	Mean squared diameter (cm^2)
QMD	Quadratic mean diameter (cm)
ACC	Arithmetic class centre, i.e. the arithmetic midpoint of a class (cm)
n	The number of intercepts over the length of transect
c	The slope correction factor
L	The length of transect (m)
M	The fuel load multiplier which combines the effects of G, h and MSD (g cm^{-1})

Methods

We sampled boreal forests of Canada's three prairie provinces and the Northwest Territories (Figure 1). The geographical regions, together with the forest section designations of Rowe (1972), are: (1) central Alberta (B.18a — Mixed Wood), (2) northern Alberta (B.18b — Hay River and B.23a — Upper Mackenzie), (3) central Alberta foothills (B.19 — Foothills), (4) central Manitoba (B.15 — Manitoba Lowlands and B.21 — Nelson River), (5) southern Northwest Territories (B.23a — Upper Mackenzie), and (6) central Saskatchewan (B.18a — Mixed Wood). Within each region we selected several commercially important species for sampling. In total, eight species were selected with the first three being sampled in all regions: (1) *Picea glauca* (Moench) Voss (white spruce), (2) *Picea mariana* (Mill.) B.S.P. (black spruce), (3) *Populus tremuloides* Michx. (trembling aspen), (4) *Pinus banksiana* Lamb. (jack pine), (5) *Pinus contorta* Laws. (lodgepole pine), (6) *Populus balsamifera* L. (balsam poplar), (7) *Abies balsamea* (L.) Mill. (balsam fir), and (8) *Larix laricina* (Du Roi) K. Koch (tamarack). All species were sampled in natural forest stands, and the first four were also sampled on harvested sites.

Stands were chosen by visual inspection aided by preselection from forest inventory maps where available. The primary criterion for selection was that the stands were dom-

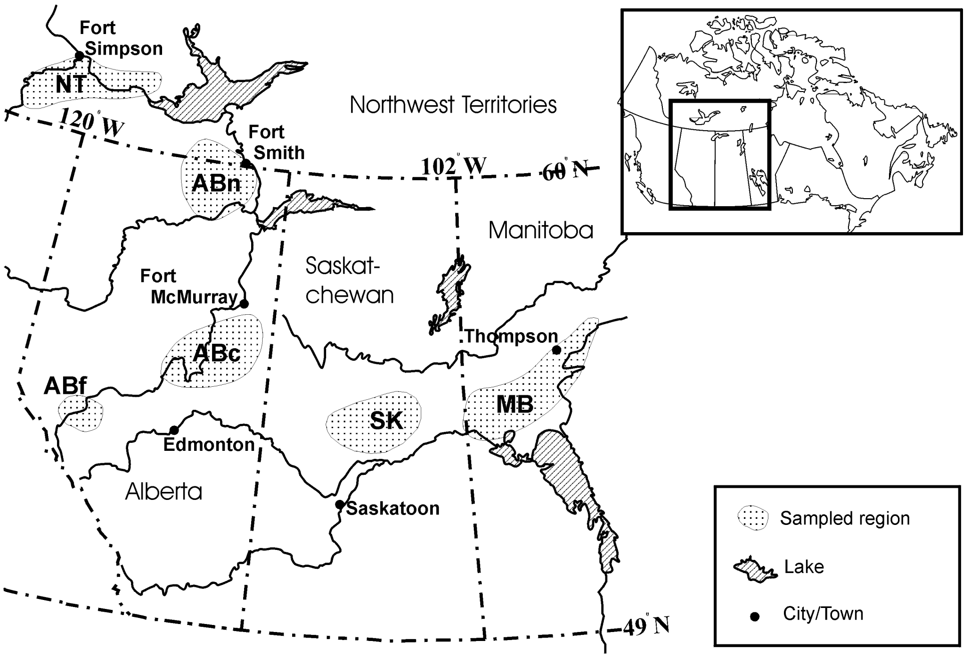

Figure 1. Location of regions sampled. NT, southern Northwest Territories; ABn, northern Alberta; ABc, central Alberta; ABf, central Alberta foothills; SK, central Saskatchewan; MB, central Manitoba.

inated by a single species, ideally greater than 80% on a live biomass basis. Most stands were close to roads for ease of access, but within this constraint we obtained a range of stand ages and wide geographic dispersion within each region. For each stand or site we determined age from increment cores or from fire and harvest records. We also recorded latitude, longitude, slope, aspect, elevation and a general site description. To characterise tree cover in forest stands, we recorded the species, height and diameter at breast height of all trees in three variable-sized fixed area plots, e.g. 43 m^2 for dense stands and 173 m^2 for open stands, spaced along the main transect (see next paragraph) and calculated basal area, stem density, biomass and species dominance (defined as live tree biomass of dominant species as a percentage of total live tree biomass). Live biomass was calculated from standard allometric equations (Evert 1985).

Dead and downed wood was sampled using similar procedures to Delisle (1986). To facilitate sampling, a 75 m randomly oriented main transect was run through the approximate centre of each stand or site. We sampled along the main transect as well as along subsidiary, randomly oriented transects which were run at 10 m intervals off the main transect. For each piece of dead and downed wood that intersected the transect, we measured its diameter with digital callipers to ±0.01 mm and its tilt, i.e. its angle of inclination relative to horizontal, with a carpenter's slope gauge to the nearest 5 degrees. In each stand or site, we measured the first 20–25 pieces in each size class (0–0.5 cm, 0.5–1 cm, 1–3 cm, 3–5 cm and 5–7 cm, referred to as classes I to V, respectively) and generally sampled at least four stands/sites to obtain at least 100 pieces for each species/fuel type/region combination that we sampled. We also recorded the distances required to obtain the samples, which varied from a few metres for Class I to hundreds of metres for Class V.

For specific gravity determination, we cut a segment from every third piece of wood sampled and returned it to the laboratory for measurement using the mass of water displaced in accordance with ASTM D2395-93 Method B-II (Anonymous 1994). Very rotten pieces, or pieces that would not remain intact during handling, were rejected because it was impossible to get valid measurements of specific gravity. For the same reason, any loose bark was removed prior to analysis. We determined the oven-dry mass of each piece by drying to constant mass at 105°C (Roussopoulos and Johnson 1973), after which the volume of each piece was measured. Each oven-dried piece was water-proofed by dipping in liquid paraffin at 180°C (see Discussion for rationale for this temperature), then its volume was determined by immersing it in a beaker of water placed on a top-loading balance.

For each stand/site and size class, we calculated the mean tilt, mean specific gravity and mean squared diameter (*MSD*) which is equal to the sum of the squared diameters divided by the number of pieces. We followed Sackett (1980) in calculating *MSD* rather than quadratic mean diameter (*QMD*) because it is a direct measure of cross-sectional area and

Table 1. Age and percentage dominance (live biomass basis) of sampled stands. Data are means ± SD.

Species	*n*	Stand age (years)	Dominance (%)
Picea glauca	29	126±31	87±13
Populus tremuloides	27	73±27	96± 5
Picea mariana	26	139±66	93±10
Pinus banksiana	22	87±29	96± 8
Larix laricina	8	79±28	82±16
Populus balsamifera	6	79±15	97± 3
Pinus contorta	4	100±10	98± 4
Abies balsamea	3	108±45	64±13

therefore directly related to fuel volume or mass. Consequently, *MSD* gives a better indication of important differences between species, fuel types and regions. For example, two species with *QMD*s of 2.0 cm and 2.2 cm have a 10% difference in *QMD*s, but the difference in *MSD*s would be 21% which is the difference in fuel loads calculated from these *QMD*s.

The stand means for tilt, specific gravity and *MSD* were used as observations for the statistical analysis, with size class, species, fuel type and region as factors. In regard to size classes, we were interested not in their absolute effect but in their effect relative to class midpoint. Consequently, we divided each *MSD* value by the square of the arithmetic class centre (*ACC*) of the appropriate size class, e.g. for Class II, all *MSD* values were divided by 0.75^2. The results were log-transformed to meet the assumptions of ANOVA. Specific gravity was also log-transformed to meet these assumptions. Because of unequal replication and missing cells, we used a general linear model type IV analysis (SAS Institute 1988) to analyse the stand data. Where the ANOVA showed significant differences within factors, we tested for effect with multiple comparison tests using a 5% significance level. Scheffé tests were utilised to give a conservative result (Boardman and Moffit 1971). Three analyses were carried out, one for each of the dependent variables, specific gravity, tilt and mean squared diameter.

Results

We sampled a total of 126 forest stands and 45 harvested sites, measuring diameter and tilt on 22 835 pieces of dead and downed wood and specific gravity on 7539 pieces out of the 22 835. Table 2 provides summary values of specific gravity, tilt angle, and *MSD* along with the number of stands sampled for each species, fuel type and region. Sampled stands were mature to over-mature and 98 of the 126 stands met the 80% dominance target (Table 1). The stands that had less than 80% dominance were principally *A. balsamea*, *L. laricina* and *P. glauca*. Basal areas and stem densities ranged from 8 to 66 m^2 ha^{-1} and 430 to 17 000 stems ha^{-1}, respectively. Time-since-harvest for harvested sites was 18 months or less, except for two *P. glauca* sites in southern Northwest Territories and four *P. glauca* sites in northern Alberta, which had been harvested 3–5 years prior.

Specific Gravity

There was a large variation in specific gravity, from a high of 0.65 Mg m^{-3} for Class II *P. mariana* in the central Alberta foothills to a low of 0.34 Mg m^{-3} for Class V *P. tremuloides* in central Alberta (Table 2). Our statistical analysis examined the effect on specific gravity of the five size classes, six regions, eight tree species and two fuel types. All independent factors were highly significant (Table 3). Species and class were also significant in interaction terms with all other variables. Scheffé pairwise comparison tests showed that: (1) all classes were different; (2) forested stands were different from harvested sites; (3) species comparisons were different when the species were of different genera, with two exceptions: *Larix* was not different from *Picea* (possibly due to the small sample size of *Larix*) and *Pinus* and was not different from *Populus*; and (4) the only regionally significant comparisons were that central Manitoba was different from southern Northwest Territories and northern Alberta.

Tilt

Tilt angles ranged from 5 to 33 degrees with the lowest angles occurring in Class V (Table 2). Our statistical analysis examined the effect on tilt angle of the five size classes, six regions, eight tree species and two fuel types. All independent factors were strongly significant as well as the species–region and species–class interaction terms (Table 3). Scheffé pairwise comparison tests showed that: (1) all size classes were different; (2) harvested sites were different from

Table 2. Mean specific gravity (G), mean tilt angle (h) and mean squared diameter (MSD) of dead and downed wood pieces by size class, species, fuel type and region; "n" refers to the number of stands or sites sampled and "H" refers to harvested site.

Species and fuel	n	G (Mg m^{-3})					h (degrees)					MSD (cm^2)				
type		I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Central Alberta																
P. banksiana	4	0.43	0.45	0.49	0.52	0.47	15	16	12	17	10	0.0767	0.500	2.70	14.1	34.6
P. banksiana-H	4	0.50	0.52	0.52	0.51	0.48	12	19	10	10	7	0.0920	0.519	3.07	14.2	34.4
P. glauca	3	0.56	0.58	0.62	0.51	0.43	24	23	17	15	8	0.0620	0.517	2.46	15.4	35.5
P. glauca-H	4	0.46	0.61	0.62	0.59	0.45	18	20	14	10	6	0.0653	0.526	3.17	12.9	34.4
P. mariana	4	0.51	0.59	0.57	0.49	0.49	18	22	18	11	7	0.0483	0.414	3.46	16.8	34.0
P. tremuloides	4	0.46	0.42	0.40	0.35	0.34	15	18	15	11	5	0.0949	0.474	3.24	14.8	35.3
P. tremuloides-H	4	0.46	0.48	0.43	0.43	0.43	16	15	12	8	8	0.1189	0.540	3.06	14.0	36.7
Northern Alberta																
P. balsamifera	4	0.43	0.42	0.39	0.36	0.36	20	19	16	10	8	0.1338	0.525	2.95	15.3	34.6
P. banksiana	6	0.49	0.54	0.48	0.47	0.42	13	15	10	7	5	0.0842	0.500	3.20	15.2	35.6
P. glauca	10	0.50	0.59	0.57	0.47	0.45	20	23	19	12	11	0.0718	0.511	3.04	15.8	35.6
P. glauca-H	4	0.52	0.62	0.61	0.53	0.45	17	16	12	10	9	0.0808	0.537	2.93	14.6	35.9
P. mariana	7	0.50	0.57	0.58	0.49	0.49	20	20	16	13	9	0.0499	0.494	3.34	15.5	34.5
P. tremuloides	7	0.50	0.46	0.43	0.44	0.40	14	18	14	11	10	0.0996	0.497	3.30	14.5	35.0
Central Alberta Foothills																
P. contorta	4	0.45	0.52	0.50	0.44	0.44	17	22	15	8	8	0.1245	0.457	3.05	17.2	35.1
P. glauca	4	0.53	0.63	0.61	0.49	0.45	22	29	23	16	14	0.0493	0.503	2.79	15.1	35.2
P. mariana	4	0.54	0.65	0.62	0.50	0.49	19	33	19	14	13	0.0568	0.491	2.85	16.3	34.8
P. tremuloides	4	0.48	0.45	0.41	0.37	0.37	18	17	15	13	11	0.0962	0.554	3.14	16.1	35.0
Central Manitoba																
L. laricina	4	0.49	0.54	0.54	0.51	0.54	13	14	14	9	8	0.0356	0.506	2.33	14.6	35.4
P. banksiana	4	0.43	0.51	0.47	0.42	0.41	15	16	13	6	5	0.0694	0.486	3.57	15.9	34.0
P. banksiana-H	4	0.49	0.56	0.52	0.47	0.47	15	12	9	6	5	0.0783	0.502	3.28	15.4	35.7
P. glauca	4	0.44	0.56	0.51	0.45	0.44	13	17	15	14	8	0.0390	0.469	2.55	16.1	38.5
P. mariana	4	0.46	0.58	0.52	0.48	0.47	16	19	11	7	6	0.0457	0.504	3.53	15.3	33.8
P. mariana-H	4	0.43	0.61	0.64	0.52	0.46	14	16	12	5	6	0.0496	0.481	2.49	17.0	35.1
P. tremuloides	4	0.50	0.43	0.39	0.39	0.39	13	17	16	10	7	0.0973	0.504	2.90	16.1	34.8
P. tremuloides-H	4	0.54	0.48	0.47	0.48	0.47	12	14	11	8	6	0.1043	0.506	2.91	14.9	34.7
Southern Northwest Territories																
P. banksiana	4	0.49	0.50	0.46	0.48	0.45	14	17	9	8	12	0.0890	0.463	3.756	14.3	33.9
P. glauca	4	0.51	0.56	0.54	0.49	0.45	15	21	19	12	10	0.0621	0.498	3.248	15.5	36.5
P. glauca-H	3	0.50	0.63	0.59	0.56	0.50	14	17	15	11	8	0.0690	0.559	2.80	14.5	35.7
P. mariana	4	0.56	0.62	0.59	0.55	0.52	20	19	15	12	6	0.0668	0.491	3.573	15.0	34.7
P. tremuloides	4	0.50	0.44	0.39	0.41	0.43	17	19	15	9	10	0.1117	0.528	3.38	15.3	33.8
Central Saskatchewan																
A. balsamea	3	0.45	0.43	0.41	0.39	0.38	12	15	12	16	13	0.0598	0.511	3.29	13.2	33.8
L. laricina	4	0.51	0.51	0.51	0.49	0.55	22	21	17	14	7	0.0503	0.475	2.60	14.1	40.6
P. balsamifera	2	0.47	0.38	0.43	0.38	0.35	16	21	16	9	6	0.1372	0.510	3.07	15.1	38.1
P. banksiana	4	0.45	0.47	0.50	0.45	0.42	17	14	14	9	5	0.0716	0.529	2.78	15.0	35.0
P. banksiana-H	4	0.51	0.56	0.55	0.50	0.47	14	14	12	7	5	0.0667	0.521	2.90	16.0	36.1
P. glauca	4	0.43	0.54	0.54	0.46	0.41	19	18	14	9	7	0.0390	0.528	3.28	15.8	34.2
P. glauca-H	5	0.48	0.60	0.59	0.52	0.48	12	13	11	9	5	0.0480	0.538	2.85	15.2	35.4
P. mariana	4	0.51	0.56	0.51	0.49	0.49	19	21	19	13	12	0.0501	0.487	3.49	15.7	33.8
P. tremuloides	4	0.51	0.42	0.40	0.36	0.37	15	18	13	7	6	0.0857	0.522	3.51	15.5	34.0
P. tremuloides-H	5	0.58	0.51	0.49	0.46	0.45	12	13	11	9	7	0.1139	0.567	3.12	15.4	34.3

Table 3. ANOVA table for specific gravity (transformed to log[1+ *G*]), tilt and mean squared diameter (transformed by log[1+*MSD*/*ACC*^{2}]); *ACC*, arithmetic class centre.

Source	DF	Type IV SS	F Value	Pr. > F
Specific Gravity (*G*)				
Class	4	0.05974	15.7	0.0001
Species	7	0.24526	36.7	0.0001
Fuel type	1	0.08537	89.5	0.0001
Region	5	0.03642	7.6	0.0001
Species*Fuel type	3	0.01244	4.4	0.0048
Species*Region	16	0.06093	4.0	0.0001
Class*Species	28	0.24532	9.2	0.0001
Class*Fuel type	4	0.01128	3.0	0.0193
Class*Region	20	0.03274	1.7	0.0264
		Tilt angle (*h*)		
Class	4	4205.65	62.4	0.0001
Species	7	1109.81	9.4	0.0001
Fuel type	1	588.57	35.0	0.0001
Region	5	1382.92	16.4	0.0001
Species*Region	16	1032.81	3.8	0.0001
Class*Species	28	788.01	1.7	0.0166
		Mean Squared Diameter (*MSD*)		
Class	4	2.07767	96.6	0.0001
Species	7	1.07737	28.6	0.0001
Fuel type	1	0.02802	5.2	0.0227
Region	5	0.10864	4.0	0.0013
Class*Species	28	3.77961	25.1	0.0001
Class*Fuel type	4	0.18089	8.4	0.0001
Class*Region	20	0.46347	4.3	0.0001

forest stands; (3) central Alberta foothills differed from all other regions, central Manitoba differed from all regions except central Saskatchewan, and central Saskatchewan was different from northern Alberta; and (4) *P. tremuloides* was different from *Picea*, *P. balsamifera* and *P. banksiana*, and *P. banksiana* also differed from *Picea* and *Larix*.

Mean Squared Diameter

MSD varied considerably across species, fuel type and regions, with values for Classes I–V ranging from 0.036 to 0.137, 0.41 to 0.57, 2.3 to 3.8, 13 to 17 and 34 to 41 cm^2 respectively (Table 2). Our statistical analysis examined the effect on *MSD* of the six regions, eight tree species, two fuel types as well as the five size classes. All dependent variables were highly significant, as well as the interaction terms of class with the other variables (Table 3). Scheffé pairwise comparison tests showed that: (1) size classes were different except IV–V; (2) harvested sites were different from forest stands; (3) differences between species were generally due to differences between genera: *Populus* differed from *Picea*, *Larix*, *Abies* and *P. banksiana,* and *Picea* differed from *Pinus*, *Larix* and *Abies*, but differences between species within the same genus were not significant; and (4) the only regional differences were central Manitoba differing from northern Alberta and southern Northwest Territories.

Discussion

Specific Gravity

Clear patterns emerged in the variation of specific gravity. The strong variation across size classes, genera and fuel types is illustrated by Figure 2, which combines data from all regions to show the major trends. Specific gravity was generally highest in Class II and declined to a minimum in Class V. Roussopoulos and Johnson (1973) also observed that specific gravity decreases with larger pieces and attribute this to

Table 4. MSD values for Class 1 (0–0.64 cm), Class 2 (0.64–2.54 cm), Class 3 (2.54–7.62 cm) used in the United States and combined Canadian class I–II, i.e. 0–1 cm, for each species and fuel type (cm^2); "H" refers to harvested site.

Species and fuel type	Size Class 1	2	3	I–II
A. balsamea	0.078	1.83	16.1	0.122
L. laricina	0.055	1.24	25.0	0.085
P. balsamifera	0.200	1.59	25.0	0.353
P. banksiana	0.093	1.66	19.7	0.131
P. banksiana-H	0.090	1.72	21.9	0.129
P. contorta	0.139	1.24	26.7	0.168
P. mariana	0.068	1.68	20.8	0.102
P. mariana-H	0.080	1.22	24.8	0.142
P. tremuloides	0.125	1.67	19.7	0.206
P. tremuloides-H	0.139	1.62	18.9	0.244
P. glauca	0.072	1.42	22.9	0.116
P. glauca-H	0.086	1.62	20.0	0.169

"higher concentrations of pitch and extractives, and the larger proportion of volume occupied by bark in the smaller particles." It is not clear to us that there is in fact a larger proportion of bark in the smaller pieces, because the bark in small pieces tends to be very thin. Even if this was true, it would require the bark to be more dense than the stem wood; the reverse seems to be the case from our observations. The specific gravity differences are more likely due to the highly compressed growth rings in the smaller pieces and a consequent higher proportion of cell walls in the small cells of this wood.

Specific gravity also varied considerably between genera, with *Picea* being the highest, followed by *Pinus* and then *Populus*. It might be expected that this would be a reflection of the specific gravity of tree stem wood, but this is only partially true. From data reported by Singh (1984, 1986) for the prairie provinces and Northwest Territories, the average stem wood specific gravity for the same *Picea*, *Pinus* and *Populus* genera was 0.459, 0.448 and 0.425 Mg m^{-3}, respectively (n = 229, 176 and 229). This is the same ranking as our dead and downed wood data shown in Figure 2, but shows much less difference between genera. In the case of *Populus*, our relatively low values for specific gravity are almost certainly attributable to their high rate of decomposition. For *Pinus* and *Picea*, the specific gravity of dead and downed wood was generally much higher than stem wood, and this is likely due to highly compressed growth rings in small pieces. Regardless, it is clear that use of live stem wood specific gravity values for dead and downed wood fuel load studies would be inappropriate.

Specific gravity was significantly higher for slash than for naturally fallen material. This is to be expected because the slash was less than 5 years old and therefore was subjected to decomposition for a shorter time period.

Variation across the six regions was less than for the other variables, but was still significant. We suspected that this variation was related to climatic effects on growth and/or decomposition rates. To test this, we calculated monthly temperature and precipitation for each stand using a simple interpolation method (Nalder and Wein 1998) with 1951–1980 Normals (Environment Canada 1983), calculated annual precipitation and growing degree days (5°C base), then for each of the three species sampled in all six regions we carried out regressions of G_{avg} against the two climatic variables, where G_{avg} is the specific gravity of dead and downed wood collected in a stand averaged across all size classes. There was no significant relationship for *P. mariana* but G_{avg} was negatively related to annual precipitation for *P. tremuloides* (r^2 = 0.29, P = 0.004, n = 27) and negatively related to growing degree days for *P. glauca* (r^2 = 0.25, P = 0.005, n = 29). The presence of these relationships suggests first a possible

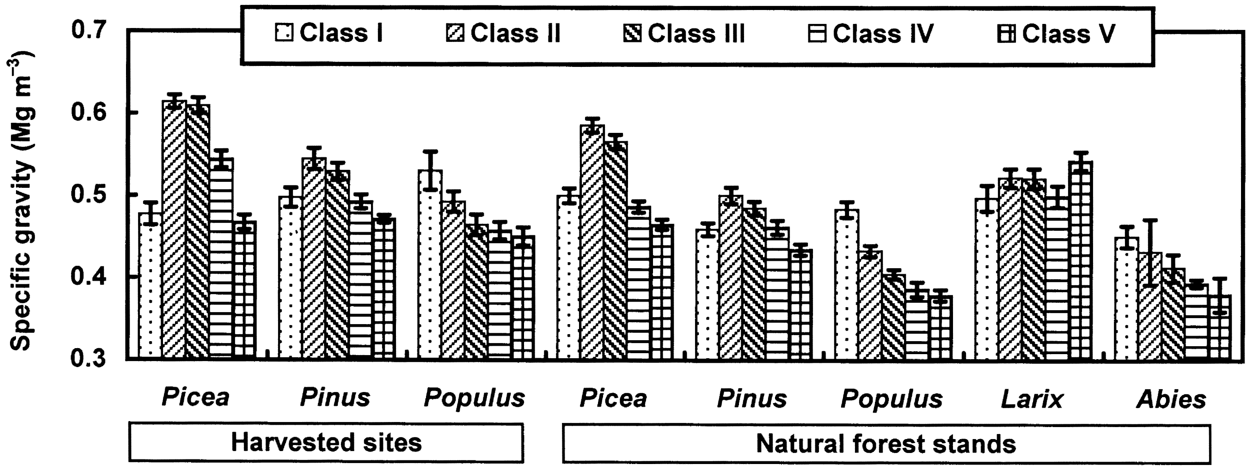

Figure 2. Mean specific gravity and standard error by diameter size class, genus and fuel type. Data are averaged across regions. See text for class sizes.

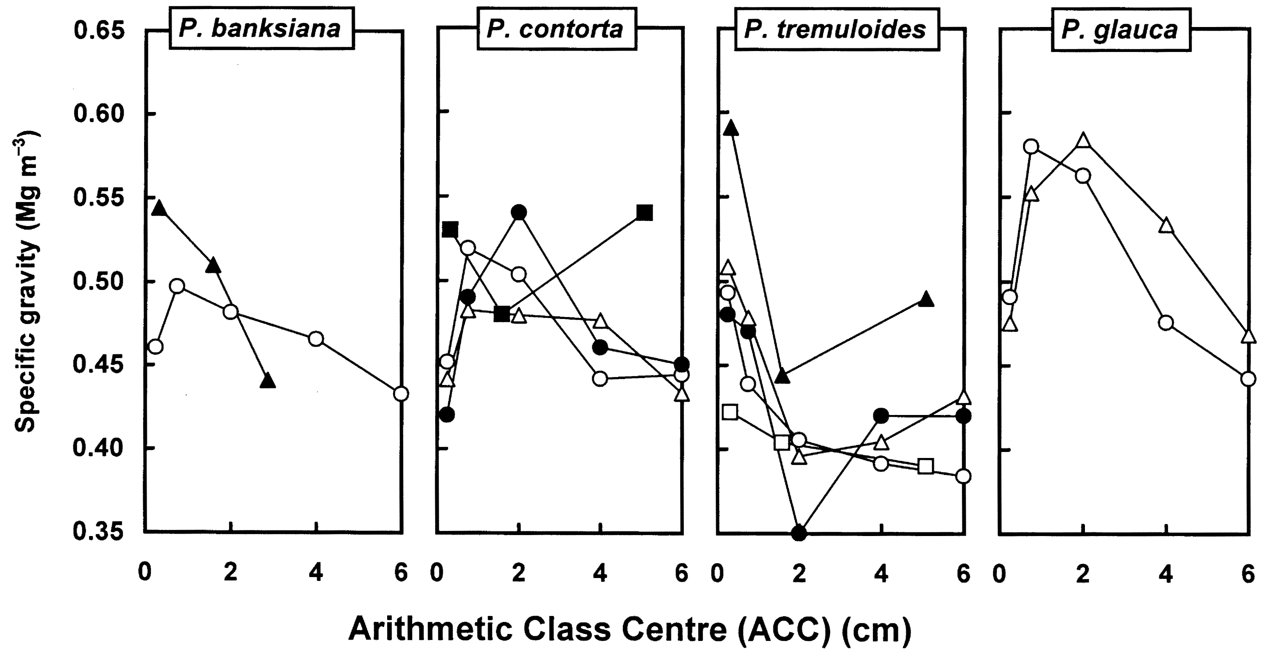

Figure 3. Comparison of specific gravity values from this study with those from other studies. Open circles, this study; filled circles, Bessie and Johnson (1995), whose data were for *P. contorta* and *P. tremuloides* in the Kananaskis region of Alberta; open triangles, Delisle and Woodard (1988), whose data were for *P. contorta, P. glauca* and *P. tremuloides* in the Montane region of Jasper National Park; filled triangles, Roussopoulos and Johnson (1973), whose data were for *P. banksiana*, *Picea* spp. and *P. tremuloides* in the Great Lakes states of the United States; open squares, Sackett (1980), whose data were for *P. tremuloides* in SW United States; filled squares, van Wagtendonk et al. (1996), whose data were for *P. contorta* in the Sierra Nevada region of California and Nevada.

method of extrapolating specific gravity to other regions, and second, that the use of data from climatically dissimilar regions would be inappropriate.

Specific gravity values from other regions are compared with ours in Figure 3. The difference in placement of data points along the X-axis is due to the use of different size classes in the United States or in early Canadian studies. All specific gravity values were determined with oven-dry volume (rather than green volume), except for Sackett (1980) who used air-dry volume. Our results correspond closely with those of Delisle and Woodard (1988) from Jasper National Park, Alberta: the patterns that we found across size classes, as well as the differences among *Picea*, *Pinus* and *Populus,* are closely reflected in their results. The differences, which range up to 12%, may have a regional component. Data from the Kananaskis country of Alberta (Bessie and Johnson 1995) also reflect the difference between *Pinus* and *Populus*, but have a less consistent pattern across size classes, perhaps due to their smaller sample size. Averaged across size classes, however, their values are quite close; their specific gravity for *P. contorta* is 0.1 % lower than our value and 1.3% lower for *P. tremuloides*. When compared with United States studies, the discrepancy in specific gravity values tend to be greater, suggesting that regional effects are important when the regions are sufficiently different. This again tends to confirm the need for regionally specific data.

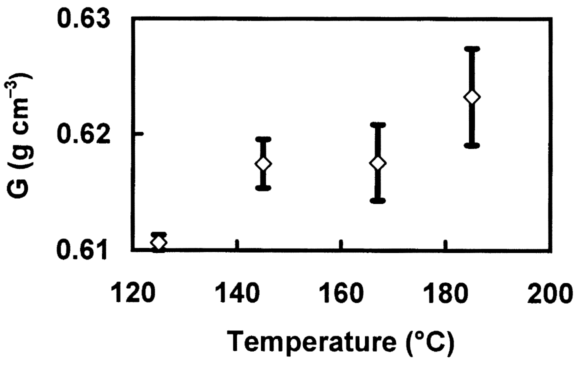

Figure 4. Mean and standard error (n=7) of calculated specific gravity (G) for test pieces of 6.4 mm wooden doweling as a function of the temperature of the paraffin used for coating the doweling.

We must emphasise, however, that determination of dead and downed wood specific gravity is not a precise science. First, the values presented in Table 2 will be slightly higher than true field values because some pieces were too rotten to

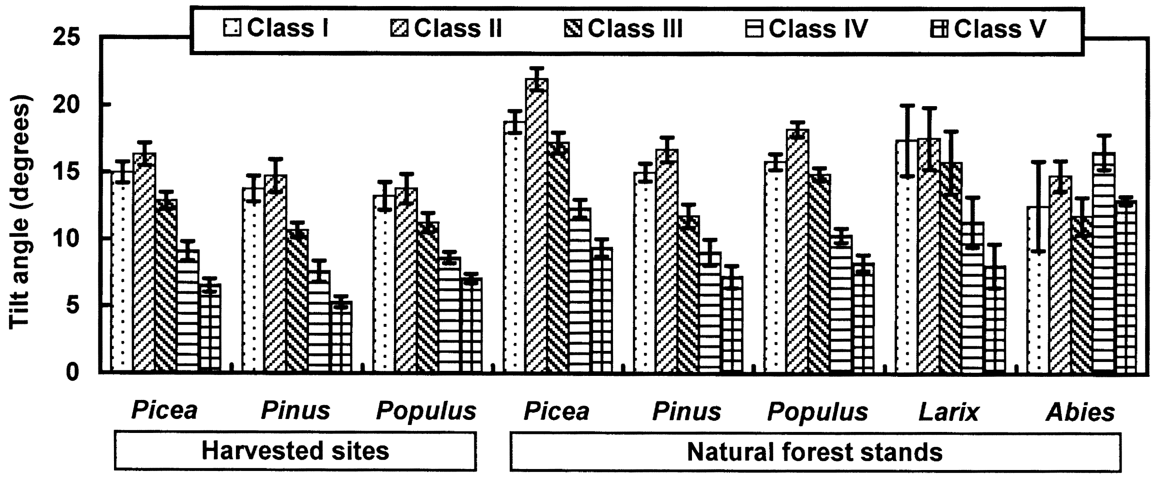

Figure 5. Mean and standard error of piece tilt angles by size class, genus and fuel type.

measure their volume. By size class, 0.6%, 1.0%, 2.9%, 8.9% and 13.6% of pieces were rejected for Class I, II, III, IV and V, which would mean an overestimate of G of 0.3%, 0.5%, 1.5%, 4.0% and 5.6%, respectively, assuming rejected pieces had a specific gravity of 0.25. Second, the process of coating pieces in paraffin tends to underestimate specific gravity due to its finite thickness. We found that this effect was dependent on the paraffin temperature (Figure 4). Since temperature is not specified by ASTM D2395-93 Method B-II, we used 180°C to minimise the error. Third, measured specific gravity will also depend on the number and size of cracks because paraffin tends to bridge small cracks thus leading to an overestimate of oven-dry volume. Fourth, uptake of moisture between removal of the pieces from the drying oven and the measurement of their volume is unavoidable which results in a slight increase in volume. Considering these and other factors, we would expect that our values could vary from "true" by up to 5%.

Despite these limitations, this study represents the most extensive measurements of dead and downed wood specific gravity in the western and northern boreal forest of Canada. The large variation, from a high of 0.65 Mg m^{-3} to a low of 0.34 Mg m^{-3}, represents a significant potential source of error in calculating fuel loads if not incorporated into calculations.

Tilt

As shown by the statistical analysis, all independent variables had a significant effect on tilt. However, the effect of region was minimal compared with that of species, size class and fuel type. Also, the effect of species was due mainly to differences among genera rather than differences between species within a genus. The patterns of variation can be most easily seen by averaging across regions and grouping species by genus as shown in Figure 5. Tilt angles are highest for *Picea* and lowest for *Pinus*, with harvested sites having slightly lower angles as would be expected with slash. By far the greatest variation is with size class as shown by the Sums of Squares in Table 3. This pattern of variation by class is remarkably consistent: with the exception of *Abies*, for which we had relatively few samples, Class II has the highest tilt angles and angles decrease to a minimum in Class V.

Tilt angle also varies across regions (Figure 6), although not all the differences were significant under the multiple comparison test. Remembering that the tilt of each piece was measured relative to horizontal rather than relative to the ground, it is likely that the main reason for the regional variation is the difference in ground slope between regions. Ground slope is also shown in Figure 6 and was closely correlated with mean piece tilt angle (Pearson correlation coefficient = 0.95). It is also possible that the degree of settling contributed to the regional differences because freshly harvested sites were difficult to access in the two most northerly regions and consequently time-since-harvest for some sites was 3–5 years compared with less than 1½ years for the remaining regions.

Very few data have been published for tilt angles of dead and downed wood. The only comparable data are from Brown and Roussopolous (1974) and van Wagtendonk *et al.* (1996). Both studies reported the average secant of tilt angles, the former for jack pine slash in Northern Minnesota and Michigan's lower peninsula and lodgepole pine naturally fallen material in western Montana, and the latter for naturally fallen lodgepole pine material in the Sierra Nevada region of California. Their results are compared with secant values calculated from our data averaged across all regions in Figure 7. The substantial differences again suggest the need for regionally specific data. It should be noted, however, that the differences between our results and those

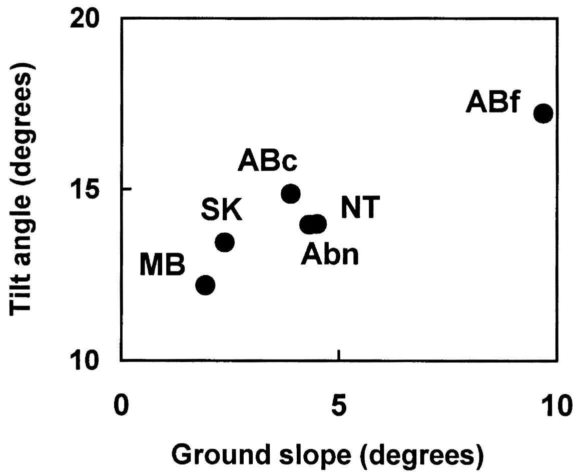

Figure 6. Mean piece tilt angle compared with mean ground slope for stands/sites sampled within each region. Tilt angle for each region is the mean of all size classes and those species common to all regions (*P. banksiana*/*P. contorta*, *P. tremuloides*, *P. mariana*, *P. glauca*). Ground slope for each region is the mean for all stands/sites sampled in that region.

from Brown and Roussopolous (1974) may be partially due to the different time-since-harvest of sampling: the Brown and Roussopolous values were for slash less than 1 year old whereas our pine data were for slash less than 1½ years old.

Brown and Roussopolous (1974) pointed out that failure to account for tilt angle could result in large underestimates of fuel loads. To adjust for piece tilt, the volume or mass per unit area calculated from the line intersect method is multiplied by a tilt correction factor equal to the secant of the average piece tilt angle (Van Wagner 1982). From our data, the correction factor can be large, e.g. 1.199 for *P. mariana* size class II in central Alberta foothills, but the average across all size classes, regions, species and fuel types is much less, being 1.035. By size class, the correction factor is 1.047, 1.060, 1.037, 1.020 and 1.013 for Classes I–V, respectively. The tilt correction factor is important for minimising bias but in the regions we sampled it is generally not large.

Mean Squared Diameter

As noted earlier, we have presented our diameter data as mean squared diameter because this is the variable that is used in calculating fuel loads. It is clear from Table 3 that measured *MSD* relative to its value at class midpoint is strongly affected by size class and species. The effects of region and fuel type are much less. Differences between species within each genus are generally not significant. Consequently, the major sources of variation are size class and genus: their effects are shown in Figure 8, expressed as the deviation of *MSD* from the square of arithmetic class centre (*ACC*).

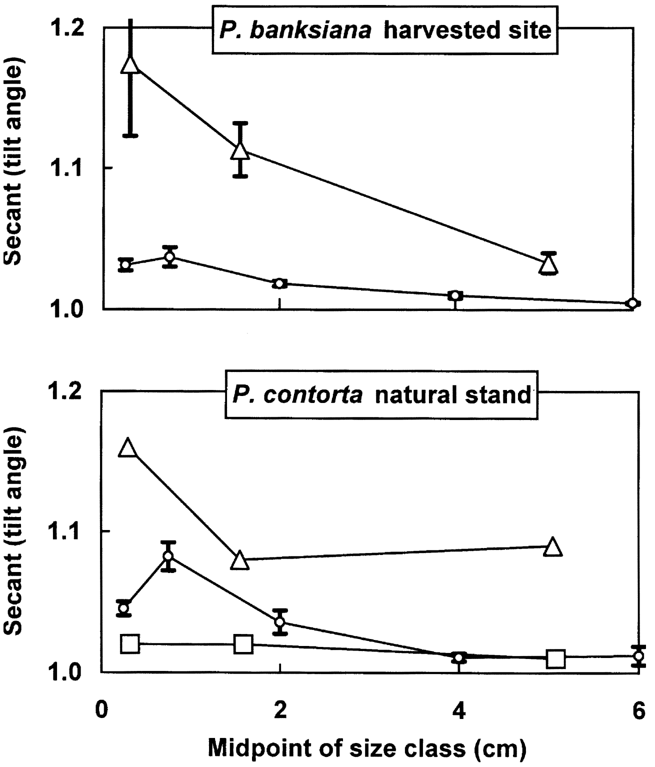

Figure 7. Comparison of tilt data from this study with data from other studies. Data are presented as average secants of measured tilt angles with standard error bars where available. Circles, data from this study; triangles, Brown and Roussopolous (1974); squares, van Wagtendonk et al. (1996).

Some fuel load surveys have used *ACC* as an approximation of *QMD*. Figure 8 shows that this is not always a good assumption. *MSD* values are often very different from the square of *ACC*, particularly for Classes I and III. In Class I, *MSD* can be up to 71% higher than the midpoint assumption, as in the case of *Populus*, or 31% less as in the case of *Larix*. Class III *MSD*s are approximately 20% less than the midpoint assumption. Unlike tilt or specific gravity, there is no consistent pattern across classes.

To provide a wider application for these data and to facilitate comparisons, we have estimated *MSD* for United States size classes (0–0.64, 0.64–2.54 and 2.54–7.62 cm, referred to as Classes 1–3, respectively) and also for 0–1 cm, termed Class I–II (Table 4). The latter class is sometimes used instead of Classes I and II where it is not necessary to emphasise fine fuels (Van Wagner 1982). To do this, we created frequency distributions of piece diameters for Classes I–V using increments of 0.2 mm, converted these to frequency

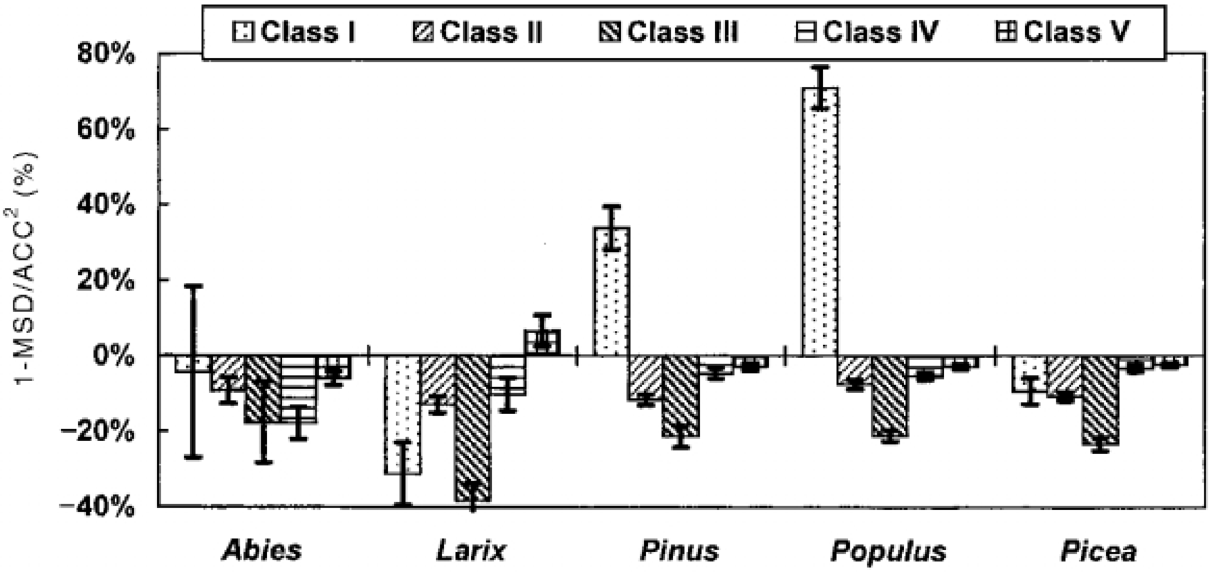

Figure 8. Mean and standard error for the percentage deviation of the *MSD* value from the square of *ACC*. Data are averaged across regions and fuel types. See text for class sizes.

per unit distance by dividing each frequency by the sampling distance for that class, then combined the five size classes into one distribution. *MSD*s for the new size classes were calculated from the combined distribution as:

$$MSD = \sum_{i=j}^{k} f_i * d_i^2 \div \sum_{i=j}^{k} f_i,$$

where f_i is the frequency per unit distance for size increment i, d_i is the mid-point of size increment i, and j and k are the lower and upper limits of the new size class. To provide sufficient points for stable distributions, data for the six regions were combined. We had no data for pieces above 7 cm diameter, therefore the distribution from 7 to 7.62 cm was extrapolated from Class V data (5–7 cm) by assuming that f_i was linearly related to d_i. Cumulative frequency plots for Class 3 gave a smooth curve, suggesting that the assumption was a reasonable one. As a check of the method, we used it to re-calculate *MSD*s for Classes I–V for each species/fuel type and compared the results with those from Table 2. Some differences are to be expected, mainly because *MSD*s calculated from raw data are slightly different from those calculated from stand means, but the differences were minimal (mean absolute difference = 0.8%) indicating the method gives reasonable results.

There can be considerable differences between our data and those derived from other regions as shown by Table 5. For this comparison, we averaged our *MSD* values across regions; our values for Classes 1, 2 and 3 were taken from Table 4 and the values from studies that presented their results as *QMD*s have been squared. Our values range from 141% above to 44% below those of comparable studies. Given the low standard errors from our study (Figure 8) for *Pinus*, *Populus* and *Picea*, it seems likely that the differences for these genera are due either to regional differences or to low precision estimates from other studies, some of which had much smaller sample sizes. In either case, it is clear that use of *MSD* values derived from other regions may give large biases in estimating fuel loads in the boreal forests of western and northern Canada.

Fuel Load Estimates

The data from this study supports our hypotheses that specific gravity, tilt and *MSD* are affected by size class, species, fuel type and region. This suggests that fuel load estimates should use values specific to these four factors. The required values for use in the formula given in the Introduction of this paper can be taken from Table 2. When calculating volumes, only data for tilt and *MSD* will be required. To simplify fuel load calculations the values for specific gravity, tilt and *MSD* can be combined into one single multiplication factor that can be applied to the formula:

$$W = \frac{n * M}{L},$$

where $M = G * \sec(h) * MSD * \pi^2 / 8 / 100$ (g cm^{-1}). Values for M for each size class, species, fuel type and region that we sampled are given in Table 6. For each size class, fuel loads in Mg ha^{-1} or t ha^{-1} are obtained by multiplying the appropriate M value from Table 6 by the number of intersec-

Table 5. Differences between *MSD* values from this study and those from other comparable studies by size class, species and fuel type. Size classes I–V (Canadian system) and 1–3 (United States system) are defined in the text; "H" refers to harvested site.

Species and fuel type	Study	Percentage difference for Size Class:				
		I	**II**	**III**	**IV**	**V**
P. banksiana-H	McRae 1982	–8	20	15	8	–5
P. contorta	Delisle and Woodard 1988	10	–6	–16	14	0
P. glauca	Delisle and Woodard 1988	–42	0	–10	9	3
P. mariana -H	McRae 1982	14	15	3	14	–2
P. tremuloides	Delisle and Woodard 1988	–14	14	–1	0	1
P. tremuloides-H	McRae 1982	19	30	–8	6	9
		1	**2**	**3**		
A. balsamea	Roussopoulos and Johnson 1973	141	—	—		
P. banksiana	Roussopoulos and Johnson 1973	20	—	—		
P. banksiana-H	Brown and Roussopoulos 1974	–12	0	6		
P. contorta	Brown and Roussopoulos 1974	7	–44	44		
P. contorta	Ryan and Pickford 1978	21	–13	—		
P. contorta	van Wagtendonk et al. 1996	39	–14	100		
P. tremuloides	Roussopoulos and Johnson 1973	–12	—	—		
P. tremuloides	Sackett 1980	–29	–20	–12		
P. tremuloides-H	Sackett 1980	–9	–4	32		

tions per metre of transect.

To our knowledge, these are the best available data on physical properties for fuel load surveys in the regions we sampled and represent a substantial improvement on typical values or values from other regions that have been used previously. For instance, in the absence of regionally derived data the Alberta Land and Forest Service (ALFS)[*] have used a horizontal correction factor of 1.13, specific gravities of 0.46, 0.44 and 0.42 g cm^{-3} for size classes III, IV and V, respectively, and *MSD* values of 4.3333, 16.3333 and 36.3333 cm^2 for the same size classes (Anonymous 1984). When calculated from these values, *M* varies substantially from the species/fuel type/region specific values of Table 6 (mean difference = –16%, mean absolute difference = 17%, maximum difference = 48%). For 69 of the 120 comparisons, the ALFS values fall outside ± two standard errors of our means, indicating that use of *M* values from Table 6 will significantly improve fuel load estimates.

The limitations of these data, however, must be recognised. First, the values from these tables have not been tested against independent data sets, so the absolute accuracy is unknown. Second, our selection of stands was representative rather than random and thus the results may apply only to stands of similar characteristics. This could be of particular concern in regard to stand age because we did not sample immature or regenerating stands (Table 1). In studies of 22 conifer species in California and Nevada, however, development stage was found to have no significant effect on diameter, tilt or specific gravity (van Wagtendonk et al. 1996) therefore it is likely that our results are applicable to other ages. Third, we sampled relatively pure stands (Table 1) and, in the few stands that were less so, we sampled wood only of the dominant species, and therefore the results apply only to dead and downed wood of the indicated species. For fuel load studies in mixed stands, pieces would need to be tallied by species to apply our values, but this is sometimes impracticable. The alternative would be to interpolate values based on the estimated proportions of the two or three most common species (Brown 1974); the interpolation could be done on the basis of measured live-plus-dead biomass of each species, but we have no data on the validity of such an approach. Lastly, any improvements in accuracy that may accrue from using these values, rather than values from other regions or typical values, may be small relative to the precision of fire fuel load estimates. For instance, 20% relative standard error (RSE) has been suggested as adequate for most fuel load surveys (Brown 1974, Van Wagner 1982); to achieve this RSE in stands of *P. contorta* using triangular

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[*] This manual constituted a collaborative effort between T.A. Van Nest of the Alberta Forest Service and M.E. Alexander of the Canadian Forest Service. The physical properties assigned to the various dead and downed round-wood diameter size classes in order to compute fuel loads using the line intersect equation constituted a "state-of-the-art" approach relying solely on existing information available at the time; the present study was prompted by a desire to provide users with better information. In the interest of the operational nature of the fuel surveys to be carried out by the Alberta Forest Service, size class I and II, i.e. 0–1 cm, were combined for increased efficiency and values of *G* (0.48 g cm^{-3}) and *MSD* (0.333 cm^2) accordingly assigned.

Table 6. Recommended fuel load multiplier factor (*M*) to apply in the second equation on page 95 for calculating fuel loads from the line intersect method of sampling in western and northern Canada (g cm^{-1}). "H" refers to harvested site.

Species and fuel type	Value of *M* for Size Class				
	I	II	III	IV	V
Central Alberta					
P. banksiana	0.042	0.292	1.69	9.46	20.3
P. banksiana-H	0.058	0.352	2.00	9.05	20.7
P. glauca	0.047	0.403	1.97	9.98	19.4
P. glauca-H	0.039	0.423	2.49	9.64	19.3
P. mariana	0.032	0.326	2.57	10.41	20.7
P. tremuloides	0.056	0.256	1.65	6.43	14.7
P. tremuloides-H	0.069	0.334	1.65	7.59	19.5
Northern Alberta					
P. balsamifera	0.076	0.287	1.47	6.86	15.5
P. banksiana	0.053	0.346	1.87	8.89	18.6
P. glauca	0.048	0.406	2.28	9.36	20.4
P. glauca-H	0.053	0.429	2.25	9.68	20.1
P. mariana	0.033	0.370	2.55	9.53	21.1
P. tremuloides	0.063	0.299	1.82	8.00	17.5
Central Alberta Foothills					
P. contorta	0.073	0.319	1.98	9.48	19.5
P. glauca	0.038	0.451	2.31	9.60	19.9
P. mariana	0.041	0.475	2.27	10.41	21.7
P. tremuloides	0.060	0.320	1.63	7.51	16.4
Central Manitoba					
L. laricina	0.022	0.346	1.60	9.32	24.3
P. banksiana	0.039	0.317	2.13	8.22	17.4
P. banksiana-H	0.049	0.354	2.11	8.93	20.6
P. glauca	0.022	0.340	1.64	9.38	21.0
P. mariana	0.028	0.377	2.02	11.02	20.2
P. mariana-H	0.026	0.388	2.33	9.21	19.6
P. tremuloides	0.061	0.284	1.45	7.73	16.8
P. tremuloides-H	0.072	0.312	1.72	8.83	20.3
Southern Northwest Territories					
P. banksiana	0.056	0.300	2.18	8.47	19.2
P. glauca	0.040	0.371	2.30	9.52	20.7
P. glauca-H	0.044	0.453	2.10	10.24	22.5
P. mariana	0.048	0.394	2.68	10.45	22.4
P. tremuloides	0.072	0.303	1.70	7.87	18.2
Central Saskatchewan					
A. balsamea	0.035	0.280	1.69	6.66	16.3
L. laricina	0.035	0.322	1.72	8.87	27.8
P. balsamifera	0.082	0.258	1.68	7.17	16.5
P. banksiana	0.041	0.315	1.77	8.38	18.3
P. banksiana-H	0.043	0.372	2.00	9.99	20.8
P. glauca	0.022	0.370	2.22	9.12	17.5
P. glauca-H	0.029	0.411	2.12	9.89	20.9
P. mariana	0.033	0.357	2.32	9.83	20.9
P. tremuloides	0.056	0.282	1.76	7.03	15.6
P. tremuloides-H	0.083	0.366	1.91	8.87	19.3

plots with 30 m sides (McRae et al. 1979) required 8, 11, 27, 22 and 21 plots for classes I–V respectively (Delisle et al. 1988). Lower RSEs require more sampling effort and could become prohibitively expensive. Consequently, the accuracy of estimates may tend to be limited more by the length of line used for sampling than by accuracy of specific gravity, tilt and *MSD* estimates.

Conclusions

This 2 year study collected data on specific gravity, piece tilt angle and mean squared diameter of dead and downed woody fuels less than 7 cm in diameter for a wide range of conditions in the western and northern Canadian boreal forest. These variables are necessary for estimates of fuel loads using the line intersect method. The variables were significantly related to size class, species, fuel type and region, confirming our initial hypothesis. A large part of the variation, however, can be explained by size class and genus. Although region did not have a large effect in our study area, it was still significant and comparisons with other studies confirmed previous findings of the need for regionally specific data.

We have combined the three variables into a single multiplier, *M*, (Table 6) which can be used to calculate fuel load (Mg ha^{-1}) in any of the five size classes by applying it to the number of piece intersections per metre of transect. These size class, species, fuel type and region specific multipliers differ by up to 48% from values previously used by ALFS, and should provide reduced bias and improved accuracy for fuel load estimates. However, it must be borne in mind that disposition of dead and downed wood is highly variable, and obtaining accurate fuel load estimates may depend more on the length of sample line than on the accuracy of the above variables.

In instances where it is necessary to extrapolate from this or other studies, a number of our findings should be considered: (1) across size classes, the patterns of tilt and specific gravity variation are quite consistent; (2) piece tilt angle is closely related to ground slope; (3) for some species the specific gravity of dead and downed wood is related to climate; (4) stem wood specific gravity is a poor approximation for that of dead and downed wood; and (5) assuming *QMD* is equal to *ACC* can lead to large errors.

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