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Physical properties of dead and downed round-wood fuels in the boreal forests of Alberta and Northwest Territories

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Abstract: Dead and downed woody fuels in forests are commonly estimated using the line intersect method, which requires appropriate values for specific gravity, piece tilt angle, and piece diameter. We present data for these variables for six commercially important tree species based on extensive surveys of slash and naturally fallen dead wood in four regions of the western Canadian boreal forest. The considerable variation by diameter size class, species, cover type, and, to a lesser extent, region suggests that specific values will improve fuel load estimates. We combine the three variables into a single factor so that fuel load (megagrams per hectare) can be simply calculated by multiplying this factor by the number of intersects per metre of sample transect.

Résumé : Les combustibles morts gisant sur le sol sont habituellement estimés à l'aide de la méthode d'échantillonnage linéaire. Son utilisation suppose que l'on dispose des valeurs appropriées de densité, d'angle d'inclinaison et de diamètre des pièces. Nous présentons ici des données sur ces variables pour six importantes espèces forestières commerciales, obtenues lors d'inventaires détaillés dans des rémanents et sur des arbres tombés naturellement au sol, dans quatre régions de l'Ouest de la forêt boréale canadienne. La très grande variation observée selon la classe de diamètre, l'espèce et le type forestier et, dans une moindre mesure, la région laisse supposer que des valeurs spécifiques amélioreraient les estimations de la charge des combustibles. Nous avons combiné ces trois variables dans un seul facteur de manière à ce que la charge des combustibles (mégagrammes par hectare) puisse être facilement calculée en multipliant ce facteur par le nombre d'intersections par mètre de la ligne d'échantillonnage.

[Traduit par la Rédaction]

Introduction

Dead and downed wood biomass in forests is important as fuel for forest fires, for wildlife habitat, for carbon storage, and as a potential source of energy for heating or electricity production. Inventories of dead and downed wood commonly utilize the line intersect method of sampling (Warren and Olsen 1964; Van Wagner 1968; Brown 1971; Brown and Roussopoulos 1974). For fire-fuel load surveys in Canada, small pieces 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 eq. 1 (after Van Wagner 1982):

$$[1] \quad W = \frac{\pi^2 G \sec(h) n QMD^2}{8L}$$

where W is mass per unit area (megagrams per hectare or tonnes per hectare), G is specific gravity (megagrams per cubic metre), h is piece tilt angle (degrees), n is the number of intercepts over the length of transect, QMD is the quadratic mean diameter (centimetres), and L is the length of transect (metres). Appropriate values for specific gravity, tilt angle, and diameter for each size class are required to calculate fuel loads, and locally derived data are important (Ryan and Pickford 1978; Sackett 1980; van Wagtenonk et al. 1996). Data for western Canada, however, are limited to montane and subalpine regions (Delisle and Woodard 1988; Bessie and Johnson 1995). This study focuses on the major commercial tree species across regions of the western Canadian boreal forest. The 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 hypothesized that diameter, tilt, and specific gravity were significantly affected by size class, species, cover type (forest stand or harvested site), and region.

Methods

We sampled six tree species, *Picea glauca* (Moench) Voss, *Picea mariana* (Mill.) BSP, *Pinus banksiana* Lamb., *Pinus contorta* Dougl. ex Loud., *Populus tremuloides* Michx., and *Populus balsamifera* L., and four regions (Fig. 1). Most stands and harvested sites were close to roads for ease of access, but within this constraint, we selected

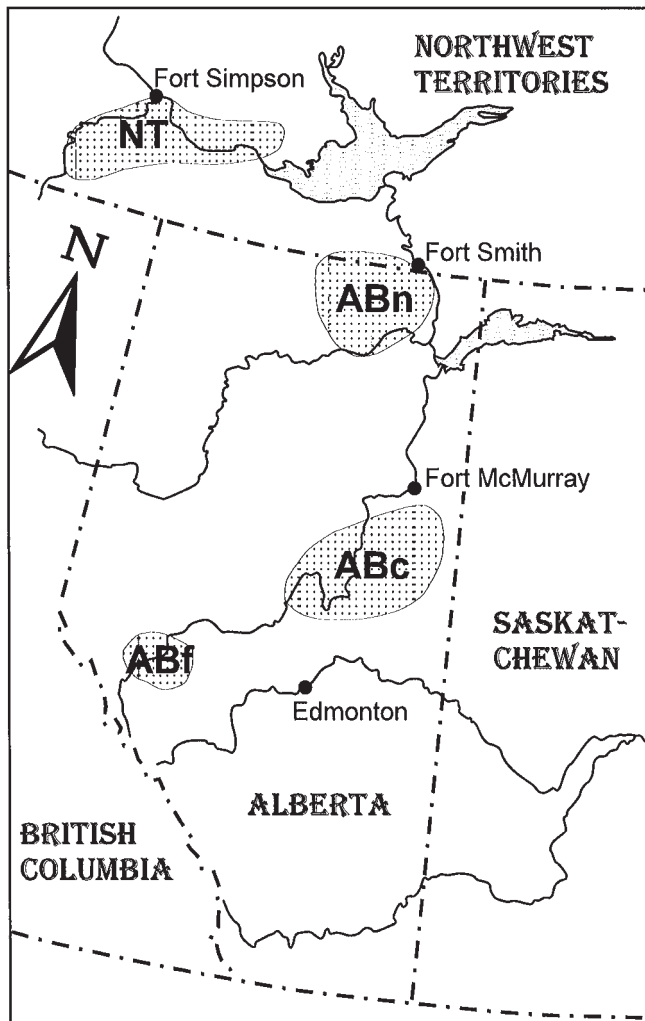
Received November 7, 1996. Accepted April 1, 1997.

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Fig. 1. Location of regions sampled. NT, Northwest Territories; ABn, northern Alberta; ABc, central Alberta; ABf, central Alberta foothills.



relatively pure stands with a range of stand ages and densities and a wide geographic dispersion.

Dead and downed wood was sampled using procedures similar to Delisle (1986). In each stand or site, we sampled along randomly oriented transects until we measured 20–25 pieces in each round-wood diameter size class (0–0.5, 0.5–1, 1–3, 3–5, and 5–7 cm, referred to as classes I–V, respectively). We measured the diameter of each piece with digital calipers to ± 0.01 mm and its tilt angle with a carpenter's slope gauge to the nearest 5°. From every third piece in each size class, we cut a segment, oven-dried it to constant weight at 105°C, and then measured specific gravity using the mass of water displaced method in accordance with ASTM D2395-93 method B-II (Anonymous 1994). We obtained at least 100 diameter and tilt measurements in each size class for each combination of species, cover type, and region that we sampled. We also recorded general site characteristics and, in forest stands, measured tree cover using three fixed-area plots.²

² A copy of the data for each stand/site is available, at a nominal charge, from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, ON K1A 0S2, Canada.

Table 1. ANOVA table for specific gravity (transformed to $\log(1 + G)$), tilt, and MSD (transformed by $\log(1 + \text{MSD}/(\text{ACC})^2)$).

Source	df	MSE	F-ratio	Pr > F
Specific gravity				
Class	4	0.0213	21.37	0.0001
Species	5	0.0343	34.43	0.0001
Cover type	1	0.0289	29.04	0.0001
Class × species	20	0.0064	6.46	0.0001
Class × region	12	0.0021	2.12	0.0145
Species × region	8	0.0036	3.69	0.0003
Tilt				
Class	4	1947	100.31	0.0001
Species	5	196	10.13	0.0001
Cover type	1	395	20.38	0.0001
Region	3	192	9.93	0.0001
Species × region	8	45	2.37	0.0166
MSD				
Class	4	0.7998	141.11	0.0001
Species	5	0.1051	18.56	0.0001
Cover type	1	0.0211	3.72	0.0542
Region	3	0.0167	2.96	0.0320
Class × species	20	0.0973	17.18	0.0001

The stand/site means for specific gravity, tilt, and mean squared diameter (MSD) were used as observations for ANOVA, with size class, species, cover type, and region as factors. We followed Sackett (1980) in calculating MSD rather than QMD because it is a direct measure of cross-sectional area and therefore directly related to fuel load. We divided MSD by the square of the arithmetic class centre (ACC), since we were interested not in the absolute effect of size class but in the effect relative to class midpoint. Because of unequal replication and missing cells, we used a general linear model type IV analysis (SAS Institute Inc. 1988). Where the ANOVA showed significant differences within factors, we tested for differences among means with multiple comparison tests using a 5% significance level. Scheffé tests were utilized to give a conservative result (Boardman and Moffit 1971).

Results

We sampled a total of 80 forest stands and 20 harvested sites. Forest stands ranged from 34 to 294 years in age and from 8 to 65 $\text{m}^2\text{-ha}^{-1}$ in basal area. Stand purity on a live biomass basis averaged 94%, with only seven stands being less than 80% pure. Harvested sites ranged in time since harvest from 6 months to 4.5 years. The full set of data for this project is available at the Depository of Unpublished Data, CISTI, NRC.

Size class, species, and cover type all had a significant effect on specific gravity. Region was only significant within an interaction term (Table 1). Scheffé pairwise comparison tests showed that (1) all classes were different apart from II and III, (2) harvested sites were different from forest stands, and (3) species of different genera were different but not species of the same genus.

All independent factors had a significant effect on tilt. Scheffé pairwise comparison tests showed that (1) all size classes were different, (2) forest stands were different from harvested sites, (3) the central Alberta foothills region was different from the other regions, but the others were not

Table 2. Specific gravity ($\text{Mg}\cdot\text{m}^{-3}$) summarized by size class, genus, and cover type (-h indicates harvested site).

Genus/cover	Class I	Class II	Class III	Class IV	Class V
<i>Picea</i>	0.518	0.596	0.584	0.493	0.471
<i>Picea</i> -h	0.493	0.620	0.607	0.562	0.465
<i>Pinus</i>	0.468	0.506	0.485	0.475	0.442
<i>Pinus</i> -h	0.497	0.517	0.521	0.508	0.483
<i>Populus</i>	0.478	0.440	0.406	0.391	0.382
<i>Populus</i> -h	0.462	0.484	0.426	0.433	0.427

Table 3. Tilt angles (degrees) summarized by size class, genus, cover type, and region (-h indicates harvested site).

Genus/cover	Class I	Class II	Class III	Class IV	Class V
Northwest Territories/northern Alberta/central Alberta					
<i>Populus</i> -h	15.9	14.6	12.2	8.4	8.0
<i>Populus</i>	16.6	18.5	15.1	10.5	8.2
<i>Pinus</i> -h	11.7	18.5	10.3	9.6	6.5
<i>Pinus</i>	14.1	16.0	10.0	10.7	8.9
<i>Picea</i> -h	16.6	17.9	13.9	10.4	7.6
<i>Picea</i>	19.3	21.3	17.3	12.5	8.6
Central Alberta foothills					
<i>Populus</i>	17.6	17.1	15.2	12.8	11.2
<i>Pinus</i>	16.9	22.4	14.7	8.2	7.7
<i>Picea</i>	20.2	30.8	21.2	14.9	13.3

significantly different from each other, and (4) *P. tremuloides* and *P. banksiana* were different from *P. mariana* and *P. glauca*.

For MSD, size class, species, and region had a significant effect, but cover type did not quite meet the 5% criterion for significance. Scheffé pairwise comparison tests showed that (1) size classes were different except II and IV and IV and V, (2) there were no differences between species within the same genus, but *Picea* differed from *Pinus* and *Populus*, and (3) there were no differences between regions.

Based on these analyses, we grouped species within each genus, grouped regions (except for tilt), and additionally grouped cover types for MSD to provide tables showing the major patterns of variation for each of the factors specific gravity (Table 2), tilt (Table 3), and MSD (Table 4).

Discussion

Specific gravity

Specific gravity varied strongly across size classes (Table 2), generally being highest in class II and declining to a minimum in class V. A similar trend was reported by Roussopoulos and Johnson (1973). There was also considerable variation among genera, with *Picea* having the highest values, followed by *Pinus* and then *Populus*. It might be expected that this would be a reflection of the specific gravity of tree stemwood, but this is only partially true. From data reported by Singh (1984, 1986) for the Prairie Provinces and Northwest Territories, the average stemwood specific gravity values for *Picea*, *Pinus*, and *Populus* were 0.459, 0.448, and 0.425 $\text{Mg}\cdot\text{m}^{-3}$, respectively. This is the same ranking as our dead and downed wood data in Table 2, but shows much less difference among genera,

Table 4. MSD (cm^2) summarized by size class and genus (ACC^2 is shown for comparison).

Genus	Class I	Class II	Class III	Class IV	Class V
<i>Picea</i>	0.062	0.503	3.09	15.3	35.2
<i>Pinus</i>	0.092	0.489	3.16	15.0	34.8
<i>Populus</i>	0.108	0.517	3.19	15.0	35.1
ACC^2	0.063	0.563	4.00	16.0	36.0

and it is clear that use of stemwood specific gravity values for dead and downed wood fuel load studies would be inappropriate. Specific gravity was higher for slash than for naturally fallen material, which is to be expected because the slash was less than 5 years old and would therefore be less subject to decomposition.

The patterns of variation across size class and genera were very similar to those obtained from montane and subalpine regions in Alberta (Delisle and Woodard 1988; Bessie and Johnson 1995). However, absolute mean differences were 4 and 9% and ranged up to 10 and 26%, respectively, perhaps indicating an effect of region. Results from the United States tend to give even greater differences (Roussopoulos and Johnson 1973; Ryan and Pickford 1978; Sackett 1980), although the use of different round-wood diameter size classes makes these comparisons difficult.

We must emphasise, however, that measurement of dead and downed wood specific gravity is not a precise science. First, our values will be slightly higher than true field values, as some pieces had to be rejected because they were too rotten to obtain an accurate specific gravity measurement. Second, the process of coating pieces in paraffin for waterproofing can overestimate the volume due to the finite thickness of paraffin. Third, uptake of moisture between removal of the pieces from the drying oven and the measurement of their volume can result in a slight increase in volume. Considering all these 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 boreal forest of Canada to date. The large variation, from a high of 0.652 $\text{Mg}\cdot\text{m}^{-3}$ for class II *P. mariana* in the central Alberta foothills to a low of 0.335 $\text{Mg}\cdot\text{m}^{-3}$ for class V *P. tremuloides* in central Alberta, represents a significant potential source of bias if not incorporated into calculations of fuel loads.

Tilt

In contrast with specific gravity, the effect of region was significant for tilt, mainly because of higher tilt angles in the central Alberta foothills region; the mean tilt angle here was 17° compared with 14° for the other three regions. This regional difference is probably due to the greater relief rather than differences in the way dead and downed wood lay on the ground: the mean slope across transects in the central Alberta foothills was 9% compared with 4% in the other regions. Tilt angles were highest for *Picea* and lowest for *Pinus*, with harvested sites having slightly lower angles, as would be expected with slash (Table 3). By far the greatest variation was with size class as shown by the mean square error in Table 1. This pattern of variation by class was consistent, with classes I and II

Table 5. Recommended multiplier values (*M*) for calculating fuel loads from the line intersect method of sampling by size class, region, species, and cover type (-h indicates a harvested site).

Species/cover	Class I	Class II	Class III	Class IV	Class V
Northwest Territories					
<i>P. tremuloides</i>	0.0716	0.303	1.70	7.87	18.2
<i>P. banksiana</i>	0.0558	0.300	2.18	8.47	19.2
<i>P. mariana</i>	0.0484	0.394	2.68	10.45	22.3
<i>P. glauca</i>	0.0404	0.371	2.30	9.52	20.7
<i>P. glauca</i> -h	0.0439	0.453	2.10	10.24	22.5
Northern Alberta					
<i>P. tremuloides</i>	0.0629	0.299	1.82	8.00	17.5
<i>P. balsamifera</i>	0.0760	0.287	1.47	6.86	15.5
<i>P. banksiana</i>	0.0525	0.346	1.87	8.89	18.6
<i>P. mariana</i>	0.0332	0.370	2.55	9.53	21.1
<i>P. glauca</i>	0.0484	0.406	2.28	9.36	20.4
<i>P. glauca</i> -h	0.0534	0.429	2.25	9.68	20.1
Central Alberta					
<i>P. tremuloides</i>	0.0563	0.256	1.65	6.43	14.6
<i>P. tremuloides</i> -h	0.0695	0.334	1.65	7.59	19.5
<i>P. banksiana</i>	0.0419	0.292	1.69	9.46	20.3
<i>P. banksiana</i> -h	0.0577	0.352	2.00	9.05	20.7
<i>P. mariana</i>	0.0322	0.326	2.57	10.41	20.7
<i>P. glauca</i>	0.0468	0.403	1.97	9.98	19.3
<i>P. glauca</i> -h	0.0390	0.423	2.49	9.64	19.3
Central Alberta foothills					
<i>P. tremuloides</i>	0.0598	0.320	1.63	7.51	16.4
<i>P. contorta</i>	0.0730	0.319	1.98	9.48	19.5
<i>P. mariana</i>	0.0406	0.475	2.27	10.41	21.7
<i>P. glauca</i>	0.0381	0.451	2.31	9.60	19.9

having the largest angles and higher classes having progressively lower angles.

Values from western Montana, northern Minnesota, and lower Michigan for *P. contorta* and *P. banksiana* (Brown and Roussopoulos 1974) reflect the same trend to lower tilt angles for larger size classes as our data, although their values are substantially higher than ours. In contrast, values for *P. contorta* from the Sierra Nevada are very close to ours (van Wageningen et al. 1996). Brown and Roussopoulos (1974) pointed out that failure to account for tilt angle can result in large underestimates of fuel loads, but from our data, the tilt correction factor ($\sec(h)$ in eq. 1) is not large, e.g., averaged across species, cover types, and regions, the correction factor is 1.05, 1.07, 1.04, 1.02, and 1.02 for classes I–V, respectively.

MSD

Some fuel load surveys have used ACC as an approximation of QMD. This is not always a good assumption (Table 4). MSD values were often very different from the square of ACC, particularly for classes I and III. Class III MSDs were on average 21% less than the midpoint assumption whereas class I MSDs were 40% higher, and up to 73% higher in the case of *Populus*. There was considerable variation among genera, but no consistent pattern across classes.

For comparison with other studies, we calculated QMD for each combination of species and size class. QMD values for

P. contorta, *P. glauca*, and *P. tremuloides* in montane Alberta (Delisle and Woodard 1988) were within 10% of ours, except for class I *P. glauca*, which differed by 21%. Values for *P. banksiana*, *P. mariana*, and *P. tremuloides* slash in Ontario (McRae 1982) were within 13% of ours, except for class I *P. mariana*, which differed by 29%.

Fuel load estimates

Values for specific gravity, tilt, and MSD (=QMD²) can be applied individually into eq. 1 or incorporated into one single multiplication factor that can be applied to the equation

$$[2] \quad W = \frac{n \times M}{L}$$

where $M = G \cdot \sec(h) \cdot \text{MSD} \cdot \pi^2 / 8 / 100$ (g·cm⁻¹). In Tables 2, 3, and 4, we grouped factors to focus on the major sources of variation, but this is not practical for *M*, since the groupings for each factor were different, i.e., different factors were responsible for most of the variation. Consequently, in Table 5, we present values for *M* specific to each size class, species, cover type, and region. Some of these means may not be significantly different, yet they still represent the best estimates available at this time.

In the absence of specific data, fuel load surveys by the Alberta Lands and Forest Service (ALFS) have used a fixed tilt correction factor of 1.13, specific gravities of 0.48, 0.46, 0.44, and 0.42 Mg·m⁻³ for size classes IA (0–1 cm), III, IV, and V, respectively, and MSD values of 0.3333, 4.3333, 16.3333, and 36.3333 for the same size classes (Anonymous 1984). Compared with our values for each size class, species, cover type, and region, the absolute mean discrepancy is 15%, but it ranges up to 47%. For 46 of the 88 comparisons, the ALFS values lie outside 2 standard errors of our means, indicating that use of *M* values from Table 5 should significantly improve fuel load estimates.

Conclusions

This paper has presented data for the first time on specific gravity, tilt angle, and MSD of dead and downed wood for a wide range of forest stands and harvested sites in the western Canadian boreal forest. We have combined the three factors into a single multiplier, *M*, which can be used to calculate fuel load (megagrams per hectare) for each size class, species, cover type, and region by applying it to the number of piece intersections per metre of transect.

Acknowledgements

Our summer students Q. Bottorf, S. Dedio, and L. Wood did excellent work and we are particularly grateful to volunteers S. Nalder, M. Liston, B. Sander, D. Wein, and S. Yueno. Logistical support was provided by Wood Buffalo National Park, Government of Northwest Territories Department of Renewable Resources, Alberta Lands and Forest Service, and Alberta Pacific Forest Industries. Funding came from the Canadian Forest Service under the ENFOR program, from the Natural Sciences and Engineering Research Council of Canada to R.W. Wein and I.A. Nalder, and from the STEP program to L. Wood. Comments by S.S. Sackett and two anonymous reviewers are appreciated.

References

- Anonymous. 1984. Measurement and description of fuels in natural stands in Alberta. (Booklet available from Alberta Forest Service, Edmonton, Alta.)
- Anonymous. 1994. Standard test methods for specific gravity of wood and wood-base materials, D2395-93. *In* 1994 annual book of ASTM standards. Vol. 04.10. Wood. American Society for Testing and Materials, Philadelphia, Pa. pp. 384–391.
- Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behaviour in subalpine forests. *Ecology*, **76**: 747–762.
- Boardman, T.J., and Moffit, D.R. 1971. Graphical Monte Carlo Type I error rates for multiple comparison methods. *Biometrics*, **27**: 738–743.
- Brown, J.K. 1971. A planar intersect method for sampling fuel volume and surface area. *For. Sci.* **17**: 96–102.
- Brown, J.K., and Roussopoulos, P.J. 1974. Eliminating biases in the planar intersect method for estimating volumes of small fuels. *For. Sci.* **20**: 350–356.
- Delisle, G.P. 1986. Physical components and biomass regression equations required for fuel quantification of forest stands in Jasper National Park, Alberta. M.Sc. thesis, University of Alberta, Edmonton, Alta.
- Delisle, G.P., and Woodard, P.M. 1988. Constants for calculating fuel loads in Alberta. *Can. For. Serv. North. For. Cent. Manage. Note* No. 45.
- McRae, D.J. 1982. Physical properties of some Ontario slash fuels. *Can. For. Serv. Res. Notes* **2**: 21–22.
- McRae, D.J., Alexander, M.E., and Stocks, B.J. 1979. Measurement and description of fuels and fire behaviour on prescribed burns: a handbook. *Can. For. Serv. Rep.* 0-X-287.
- Roussopoulos, P.J., and Johnson, V.J. 1973. Estimating slash fuel loading for several Lake States' tree species. *USDA For. Serv. Res. Pap.* NC-88.
- Ryan, K.C., and Pickford, S.G. 1978. Physical properties of woody fuels in the Blue Mountains of Oregon and Washington. *USDA For. Serv. Res. Note* PNW-315.
- Sackett, S.S. 1980. Woody fuel particle size and specific gravity of southwestern tree species. *USDA For. Serv. Res. Note* RM-389.
- SAS Institute Inc. 1988. SAS/STAT® user's guide, release 6.03 edition. SAS Institute Inc., Cary, N.C.
- Singh, T. 1984. Variation in the oven-dry wood density of ten prairie tree species. *For. Chron.* **60**: 217–221.
- Singh, T. 1986. Wood density variation of six major tree species of the Northwest Territories. *Can. J. For. Res.* **16**: 127–129.
- Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. *For. Sci.* **14**: 20–26.
- Van Wagner, C.E. 1982. Practical aspects of the line intersect method. *Can. For. Serv. Inf. Rep.* PI-X-12.
- van Wagtendonk, J.W., Benedict, J.M., and Sydoriak, W.M. 1996. Physical properties of woody fuel particles of Sierra Nevada conifers. *Int. J. Wildland Fire*, **6**: 117–123.
- Warren, W.G., and Olsen, P.F. 1964. A line intersect technique for assessing logging waste. *For. Sci.* **10**: 267–276.