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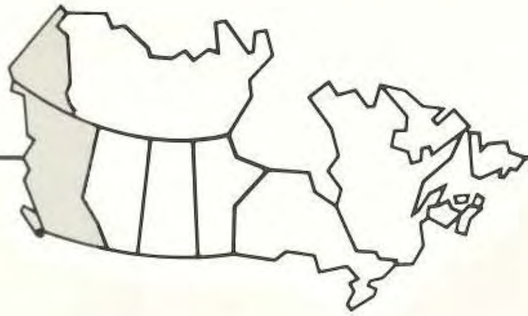

Line intersect sampling for the density and bark area of logging residue susceptible to the spruce beetle, *Dendroctonus rufipennis* (Kirby)

L. Safranyik and D.A. Linton

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Abstract

Twenty-two clearcut areas were sampled in central British Columbia using the line intersect method to: (a) determine the density and bark area of stumps and logs susceptible to attack by the spruce beetle, *Dendroctonus rufipennis* (Kirby), (b) calculate sample sizes for a predetermined degree of precision, and (c) develop new estimating procedures based on counts of intersected pieces. Estimates based on line intersect sampling were compared with estimates based on fixed plot sampling. The mean density (173.6) and mean bark area (161.6 m^2) per hectare of stumps was 12.2 and 3.9 times greater than the corresponding means for logs and tops. There were no statistically significant differences between the line intersect and fixed plot samples in estimates of either mean density or mean bark area per hectare of stumps, and variances were strongly related to means. Using line transects, less sampling time was required to estimate mean stump density and mean stump bark area per hectare with a half confidence belt equal to 0.2 (mean) than using fixed plots. Equations to estimate piece density and bark area per hectare based on counts of intersected pieces are presented.

Résumé

Vingt-deux parterres de coupe rase ont été echantillonnés dans le centre de la Colombie-Britannique par échantillonnage linéaire afin a) de déterminer la densité et la surface avec écorce des souches et des grumes vulnérables aux attaques du dendroctone de l'épinette (*Dendroctonus rufipennis* [Kirby]), b) de calculer la taille des échantillons permettant d'obtenir un degré de précision pré-déterminé et c) de mettre au point de nouvelles méthodes d'estimation basées sur le nombre de morceaux ou de souches de l'échantillon linéaire. Les estimations effectuées à partir de l'échantillonnage linéaire ont été comparées à celles obtenues par échantillonnage en bandes (placettes alignées). La densité moyenne (173,6) et la surface moyenne avec écorce (161,6 m^2) par hectare des souches étaient 12,2 et de 3,9 fois plus élevées que les moyennes correspondantes obtenues pour les grumes et les cimes. Il n'y avait aucune differences statistiquement significatives de la densité moyenne ou de la surface avec écorce par hectare des souches, entre les échantillons linéaires et les échantillons en bandes et les variances étaient fortement corrélées aux moyennes. Les transects linéaires ont permis de réduire le temps d'echantillonnage nécessaire pour estimer la densité moyenne et la surface moyenne avec écorce par hectare des souches, avec un demi-intervalle de confiance de 0,2 (moyenne); les placettes alignees (en bandes) n'offraient pas un tel avantage. Le rapport présente également des équations pour estimer la densité et la surface avec écorce par hectare d'après les chiffres obtenus dans chaque transect linéaire.

Introduction

The spruce beetle, *Dendroctonus rufipennis* (Kirby), is a highly destructive pest of mature spruce (*Picea* sp.) in North America. Normally, the beetles infest injured or otherwise weakened trees, windfalls and fresh logs and logging residue. Populations in such host materials can, under favorable conditions, infest and kill apparently healthy trees over large areas. Characteristically, the large-diameter spruce component of stands suffers greatest mortality during these outbreaks (Werner and Holsten 1983).

Fresh logging residue (stumps, cut logs, tops) is readily infested by spruce beetles (Dyer and Taylor 1971; Schmid 1977). Broods emerging from such host material may form a significant portion of the total beetle population in a timber harvesting area (Safranyik et al. 1983).

Measures of the density and bark area of infested logging residue are required for several reasons: (a) assessment of spruce beetle hazard, (b) planning operational treatments, and (c) estimating brood and attack totals in studies of population dynamics. Previous work in assessing the density and bark area of infested spruce slash involved sampling with fixed plots (e.g., Dyer and Taylor 1971). Sampling with fixed-size plots is time-consuming and expensive and requires high intensity to achieve acceptable levels of precision (Warren and Olsen 1964; Bailey 1970). Line intersect sampling in forestry was introduced by Warren and Olsen (1964) in response to a need for a practical method of assessing the volume of wood residue on areas that had been clearcut. Subsequently, Bailey (1969, 1970) concluded that reliable estimates of volumes of logging slash could be made up to 70% faster using this technique rather than fixed plot sampling. De Vries (1973, 1974) and De Vries and Van Einsbergen (1973) have provided a rigorous general treatment of the underlying theory of line intersect sampling; the technique is now in common use (Van Wagner 1982).

As part of a study of population dynamics of the spruce beetle carried out in central British Columbia from 1972 to 1980, yearly estimates of the density and bark surface area of logging residues were needed. The objectives of this paper are to: (a) compare estimates of the density and bark area of stumps based on fixed plots and line intersects, (b) determine sample sizes required for a predetermined degree of precision, and (c) develop a method of estimating densities and bark areas of stumps based on counts only of the intersected pieces.

Material and methods

The experimental area was in a mature, predominantly spruce (*P. glauca* × *P. engelmannii* hybrid population) — subalpine fir (*Abies lasiocarpa*) stand in the Naver Forest about 50 km southeast of Prince George, British Columbia (53°55′N, 122°45′W).

Each spring from 1972 to 1979 maps (scale = 6336:1 (1 inch = 8 chains)) of recently logged areas were obtained from the British Columbia Ministry of Forests. Depending on the size of the cut blocks, 5 to 20 randomly selected points were located on each map, each point being the center of a 120.7-m (6-chain) transect line randomly oriented by 10° intervals (Figure 1). The distance and direction of travel from the end of one line transect to the beginning of the next were also noted on each map. The primary consideration in developing the network of lines connecting the transects was to reduce, as much as possible, the total distances of travel.

At the end of the flight period of the beetle, the line transects were established on the ground for each mapped area using a hand compass and topographic chain. All lines were measured horizontally using slope correction where necessary.

The following information was recorded separately for each line transect: a) infestation status, height (h) and mid-diameter (dm) of each intersected stump larger than 20 cm in diameter; and the infestation status, length (l) and end diameters (d_1 and d_2) of each intersected log and top with small-end diameter greater than 20 cm and length more than 91 cm. All measurements of d and h were made to the nearest 2.5 mm and l was measured to the nearest 3.0 cm. For logs and tops, the intersections of the tallied pieces were determined by the rules given in De Vries (1973). For stumps, intersection of dm with the line transect was the basis for inclusion in the tallies.

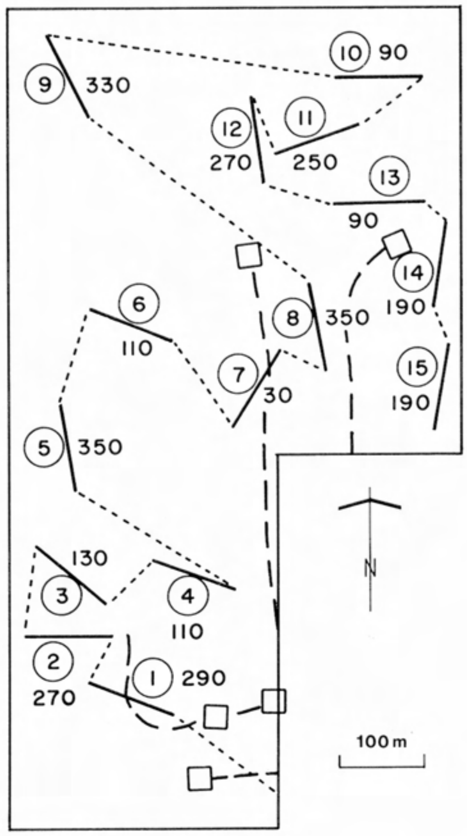

Figure 1. A typical clearcut area showing the distribution of sample lines (solid lines), their orientation angles, and lines of travel connecting them (broken lines).

On 13 of the 22 sampled clearcuts, in addition to the stumps on the line transects, stumps within 1.82 m wide by 120.7 m (6 chain) long plots the long axes of which were centered on the line transects were also measured as described above.

The numbers ($\hat{Ns}$) and bark area ($\hat{Ss}$) per hectare of stumps based on line intersect sampling were estimated as in equations (1) and (2), respectively (see De Vries (1979), equations 8a, 35 and 36, for general estimators of totals of any quantity per unit area of circular objects).

$$\hat{Ns} = \frac{10^4}{L} \sum^{n} \frac{1}{dm_i} \quad (1)$$

$$\hat{Ss} = \frac{10^4 \pi}{L} \sum^{n} h_i \quad (2)$$

Where L = length of line, n = number of intersected pieces, and the other symbols are as defined earlier; L, dm and h are in metres. In deriving equation (2), stump bark area (a) was defined as $a_i = \pi (dm_i) h_i$. The estimates for numbers of logs and tops per hectare (Nl) and bark area per hectare (Sl) are given in equations (3) and (4), respectively (see De Vries (1979), equation 8).

$$\hat{Nl} = \frac{5000\pi}{L} \sum^{n} \frac{1}{l_i} \quad (3)$$

$$\hat{Sl} = \frac{2500\pi^2}{L} \sum^{n} (d_{1i} + d_{2i}) \quad (4)$$

where l_i, d_1 and d_2 are in metres. In deriving equation (4), bark surface area for logs (S_i) was defined as $S_i = \pi (d_{1i} + d_{2i})\, l_i / 2$.

Estimates of $\hat{Ns}$ and $\hat{Ss}$ based on line transect sampling and corresponding estimates based on fixed plot sampling were compared by paired t-test. The model $y = ax^b$ was selected to describe the relationship between the variance (y) and mean (x) for both numbers and surface areas per hectare of stumps and logs based on line intersect sampling. This model was fitted to the data in its linearized form by the method of least squares and was used for estimating sample size. Sample size, q, was calculated assuming simple random sampling and setting the half-width of the confidence interval, $ts_{\bar{x}}$, where t is Student's t corresponding to the desired confidence probability and $s_{\bar{x}}$ is the standard error of the mean, to a certain proportion, p, of the mean, $\bar{x}$. Hence for q we have

$$q = \frac{t^2}{p^2}\, ax^{(b-2)}. \quad (5)$$

To develop estimates for the number and bark area per ha of stumps and logs based only on the number of intersected pieces, the sums on the right sides of equation (1) to (4) for each clearcut area were plotted on the corresponding n, and weighted least squares linear regressions were fitted to the data.

Results

Statistics for stump density and bark area on the sampled clearcuts are given in Table 1. On average, a transect line intersected about 1 stump and 0.4 logs (ratios of means for columns 3 and 13, to the mean for column 2, Table 1). Based on line intersect sampling, the mean density per hectare (173.6) and mean bark area per hectare (161.6 m^2) of stumps was 12.2 and 3.9 times greater than the corresponding means for logs and tops. Only in one clearcut (number 5) out of the 22 did the piece count and corresponding bark area per hectare ($n = 15$, bark area $= 152.1\ m^2$) of logs and tops exceed the count and surface area for stumps ($n = 6$, bark area $= 90.0\ m^2$).

The mean difference in the estimated numbers of stumps per hectare (17.9) and bark area per hectare (9.7 m^2) based on line intersect sampling and fixed plot sampling was not statistically significant ($t_{12df} = 1.69$, $p = 0.12$ for stumps per hectare; $t_{12df} = 0.62$, $p = 0.55$ for bark area per hectare). Although centered on the sampling lines, the fixed plots sampled a greater portion of the stump population than the line intersect sample lines. On average, 2.7 times as many stumps were tallied on a fixed plot than on a sample line.

The relationship between the estimated variance for numbers of stumps and logs per hectare ($\bar{V}ns$ and $\bar{V}nl$) and the corresponding means ($\bar{X}ns$ and $\bar{X}nl$) is given in equations (6) and (7).

$$\log \hat{V}ns = 1.234 + 1.470 (\log \bar{X}ns) \qquad (6)$$

$$r^2 = 0.677,\ F_{1,2}\text{df} = 39.905,\ p<0.001$$

$$\log \hat{V}nl = 1.125 + 1.336 (\log \bar{X}nl) \qquad (7)$$

$$r^2 = 0.968,\ F_{1,17}\text{df} = 505.040,\ p<0.001$$

The regressions corresponding to equations (6) and (7) for bark area per hectare are given in equations (8) and (9), respectively.

$$\log \hat{V}as = 1.462 + 1.368 (\log \bar{X}as) \qquad (8)$$

$$r^2 = 0.427,\ F_{1,2}\text{df} = 14.931,\ p<0.01$$

$$\log \hat{V}al = 2.097 + 0.863 (\log \bar{X}al) \qquad (9)$$

$$r^2 = 0.822,\ F_{1,17}\text{df} = 78.,532,\ p<0.001$$

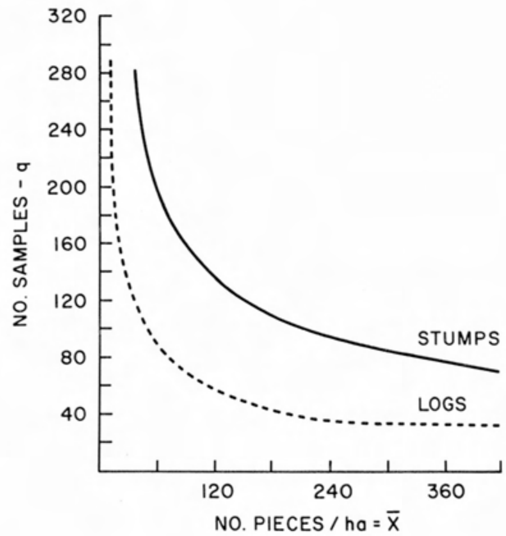

Figure 2. Required sample sizes for a 95% half confidence belt of 0.2 (mean) for different densities of spruce stumps and logs susceptible to the spruce beetle in clearcut areas. Data for the Naver Forest, British Columbia, 1972-79.

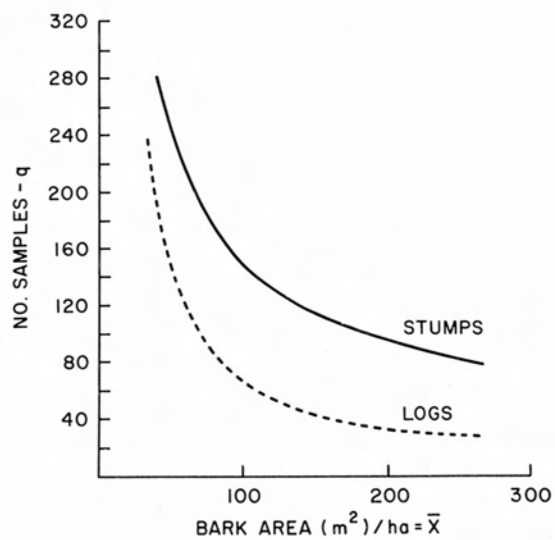

Figure 3. Required sample sizes for a 95% half confidence belt of 0.2 (mean) for different mean bark areas per hectare of spruce stumps and logs susceptible to the spruce beetle in clearcut areas. Data from the Naver Forest, British Columbia, 1972-79.

The regression coefficients of equations (6) to (9) were not significantly different from unity ($p > 0.05$). Sample size, q, required for a 95% half confidence of 0.2 (mean) was calculated for various densities of stumps and logs (Figure 2) and bark areas per hectare of stumps and logs (Figure 3) using equation (5). Logs and tops required smaller sample sizes than stumps to estimate either factor within a specified half confidence belt. In general, the required sample sizes for piece density and bark area per hectare were comparable for both stumps and logs within the ranges of the data.

The sums (s) over all sample lines in each clearcut area of d_m^{-1} (equation 1), h (equation 2), l^{-1} (equation 3), and ($d_1 + d_2$) appeared to be linearly related through the origin to the number of intercepted pieces (n) (Figure 4). The model of best fit with no abnormalities in the residuals was $s = bn$, using weighted least squares with weights proportional to $1/n$. Hence, the slopes (b) of the regressions in Figure 4 were estimated as ratios of the mean number of intersections ($\bar{n}$) to the mean of each of the four variables ($\bar{s}$) ($b = \bar{s}/\bar{n}$). Substituting the right sides of equations S_a through S_d (Figure 4), respectively, for the sums in equations (1) through (4), we obtain estimates of piece density and bark area per hectare based only on tallies of the total numbers of intersected pieces:

$$\hat{Ns} = \frac{85\,250}{L}\, n \qquad (10)$$

$$\hat{Ss} = \frac{80\,480\pi}{L}\, n \qquad (11)$$

$$\hat{Nl} = \frac{1\,400\pi}{L}\, n \qquad (12)$$

$$\hat{Sl} = \frac{1\,230\pi^2}{L}\, n \qquad (13)$$

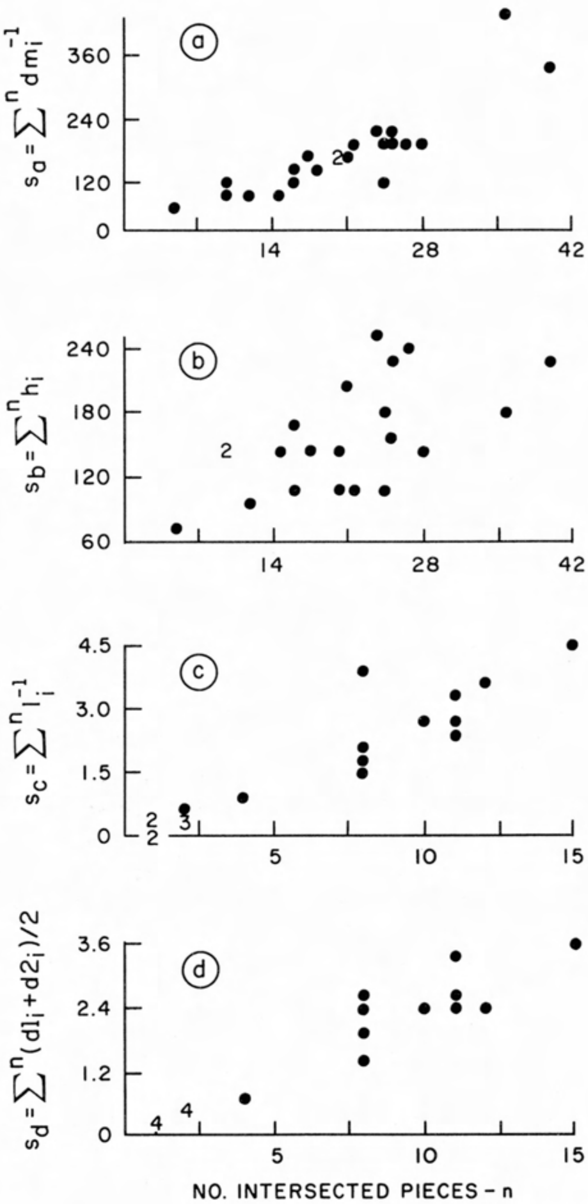

Figure 4. Regressions on the number of intersected pieces on all sample lines in a clearcut area (n) of: (a) the sums of the inverse of stump mid-diameter (S_a = 8.525 n, $F_{(1,\,21df)}$ = 441.42, $p<0.001$); (b) stump height (S_b = 8.048 n, $F_{(1,\,21df)}$ = 200.51, $p<0.001$); (c) inverse log length (S_c = 0.280 n, $F_{(1,\,18df)}$ = 330.15, $p<0.01$): (d) average end diameter (S_d = 0.246 n, $F_{(1,\,18df)}$ = 766.55, $p<0.001$).

Discussion

Although a general estimator based on line intersect sampling of totals per unit area of circular objects has been derived (DeVries and Van Einsbergen 1973), this sampling technique has not been used previously for estimating attributes of stump populations on clearcut areas. As piece orientation is not a problem with circular objects, line intersect sampling of stumps in clearcut areas could be done using any convenient grid. The 22 areas we sampled were located on reasonably flat terrain and we had no difficulty establishing the sample lines or ascertaining the intersection of stumps.

Random orientation and distribution of line transects of fixed length over the sample area were used to ensure statistically sound estimates of piece density and bark area for both stumps and logs. Howard and Ward (1972) state that on tractor-logged, flat terrain the orientation angles of logs tend to be uniformly distributed. In these types of clearcuts, unidirectional orientation and systematic spacing of sample lines is quite satisfactory. Although the clearcuts sampled in this study were logged by tractor and feller-bunchers, some tendency toward nonuniform distribution of piece orientation angles occurred due to irregularities in terrain and the radiating pattern of skid trails from landings.

The range in the bark area per hectare of stumps and logs combined (73.6 — 305.0 m^2) for the 22 clearcuts is approximately equivalent to the bark areas of 2.5 to 10 average-sized trees. Considering that, on average, the density per hectare of windfalls in stands in the experimental area was about 2 (Safranyik et al. 1983), the logging residue on a unit area basis contained up to five times as much bark area suitable for attack by the spruce beetle as the bark area of windfalls.

Precision in line intersect sampling is related to the number of intersections per unit length of sample line (Van Wagner 1982), the variability of piece dimensions (Pickford and Hazard 1978), and the variability in the number of intersections among sample lines. Intersections of logs tended to be more uniformly distributed among sample lines than intersections of stumps. For both stumps and logs, the variance tended to increase geometrically with increasing mean (equations (6) to (9)) indicating that both types of host materials tended to have clumped distributions. Although for these four regressions the slopes were not significantly different from unity, the sample sizes were small for testing whether variances tended to increase in direct proportion to mean values.

The estimates of stump density and bark area based on line intersect sampling and fixed plot sampling agreed closely considering the difference in the numbers of stumps tallied using the two methods. The time required to complete tallies on fixed plots relative to line transects was usually greater than would be indicated by the ratio of the respective number of tallied pieces, due to the need to establish plot boundaries and to check greater numbers of borderline trees. The averaged coefficients of variation (*cv*) for density and bark area per hectare based on line intersect samples (130.1% and 125.1%, respectively) was approximately proportional to the product of the square root of the ratio of the average number of tallied pieces ($\sqrt{36.1/11.4}$) and the corresponding averaged *cv* for fixed plots (68.2% and 75.2%). Therefore, considering the last two statements and that in unrestricted random sampling required sample size for a predetermined degree of precision is proportional to cv^2, sampling with the fixed plots used in our study would require greater total sampling time than line intersect sampling.

Line intersect sampling required considerable sampling effort to establish mean densities and bark areas per hectare with moderate levels of precision (Figures 2 and 3). This finding agrees with earlier work based on both field sampling and simulation studies (Pickford and Hazard 1978). As a two-man crew could sample 20 sample lines of 120.7 m length per day, over 5 days of sampling time would be required to estimate mean stump density and bark area per hectare ($\bar{x}$) with a 95% half confidence belt of 0.2 $\bar{x}$ near the lower range of the means observed in our study. For logs, the sampling effort required for the same precision would normally be prohibitive. A solution to this problem would be to reduce the required precision at low piece concentrations or to hold sampling effort constant below a predetermined threshold level of piece concentration.

The slopes of regression equations in Figure 4 define the average contribution of an intersected piece to the density and bark area per hectare of stumps and logs and depend on the dimensional characteristics of the total piece population (Warren and Olsen 1964). Figure 4 indicates that this slope remained reasonably constant over all sampled areas. Major changes are expected to occur only when utilization standards, forest types, or logging techniques change.

Equations (10) through (13) can be used when speedy assessments of the density and bark area per hectare of logging residue is required, such as in surveys for assessing hazard of increases in spruce beetle population in such materials. In such surveys, there is no need to provide separate estimates for logs and stumps, and a system of parallel lines or a rectangular grid of lines traversing the clearcut area could be used. Whatever system is used, care must be taken in determining the intersection of pieces by the sample lines. Because major changes in the dimensional characterisics of the intersected pieces are likely to affect the reliability of estimates based on equations (10) through (13), new equations should be developed for situations where utilization standards, forest types or logging techniques differ significantly from those reported in this study.

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Table 1. Statistics for stumps and logs infested by spruce beetle on clearcut areas sampled from 1972 to 1979 on the Naver Forest using line intersect and fixed plot sampling. Line intersects were 120.7 m long and fixed plots measured 1.82 m × 120.7 m. Long axes of fixed plots were centered on line intersects.

	Stumps											Logs				
	Line intersects						Fixed plots					Line intersects				
Area	Number lines	Number stumps	No./ha	S^2	Bark area m^2/ha	S^2	Number stumps	No./ha	S^2	Bark area m^2/ha	S^2	Number pieces	No./ha	S^2	Bark area m^2/ha	S^2
1	16	16	158.9	29 860.0	104.5	13 639.4	*	*	*	*	*	10	24.5	919.2	63.0	3951.4
2	12	15	187.5	33 787.5	157.5	32 482.7	*	*	*	*	*	11	30.4	1035.4	80.9	4519.0
3	14	15	199.7	54 976.3	111.1	8895.6	*	*	*	*	*	11	32.0	1190.5	96.8	11 421.8
4	20	40	346.0	81 850.0	232.3	37 436.9	*	*	*	*	*	12	23.9	730.6	50.3	1921.4
5	10	6	104.3	14 581.2	90.0	12 724.2	*	*	*	*	*	15	58.7	3185.9	152.1	15 909.5
6	5	8	441.2	203 593.7	180.6	65 381.2	*	*	*	*	*	1	7.8	301.6	17.9	1596.5
7	16	19	225.3	36 730.0	254.2	29 876.9	*	*	*	*	*	8	14.9	456.7	50.8	2329.8
8	14	17	188.8	27 238.7	178.5	24 961.2	*	*	*	*	*	11	21.7	571.4	77.9	4070.8
9	14	17	111.5	6877.5	106.5	7525.7	*	*	*	*	*	8	35.9	1682.1	45.2	1725.2
10	20	18	135.2	51 175.0	268.4	148 143.1	43	97.3	5235.7	189.1	26 198.7	4	6.0	158.7	16.8	1262.6
11	11	9	121.6	25 080.0	104.1	15 222.6	20	121.9	9358.9	77.0	9143.4	1	2.8	84.5	6.8	514.6
12	10	5	110.0	26 406.1	140.5	36 694.6	17	77.0	3212.5	149.3	16 317.5	2	3.2	45.9	23.1	2373.9
13	10	5	86.0	15 631.2	147.7	35 492.7	26	117.7	3280.9	260.4	30 565.5	0	0	0	0	0
14	12	12	160.5	29 827.5	139.1	15 183.6	51	192.5	13 096.5	148.9	6827.5	1	0.4	1.9	9.1	1000.8
15	17	4	60.2	32 731.4	73.6	39 563.9	38	101.2	7569.0	118.8	10 782.7	0	0	0	0	0
16	15	13	169.8	21 046.9	139.7	25 316.0	52	157.0	10 506.3	141.6	9405.3	0	0	0	0	0
17	15	20	195.5	43 790.6	245.2	130 196.9	49	141.9	9041.9	153.9	18 900.8	2	2.2	50.5	12.5	1135.3
18	5	7	189.5	30 262.5	142.6	19 615.5	13	108.7	9842.6	137.8	9128.7	2	12.9	484.9	39.4	2920.3
19	15	12	145.2	19 725.0	162.1	24 076.4	49	147.9	5409.6	202.9	11 233.9	1	1.1	19.5	9.7	1404.9
20	15	16	174.7	18 675.0	201.9	28 434.5	40	123.7	4529.0	146.0	9601.1	8	13.3	278.3	69.3	5963.2
21	15	19	102.7	19 820.6	149.6	41 003.1	21	86.4	4287.5	122.4	7489.9	2	4.1	136.3	21.4	2284.3
22	15	19	205.8	39 937.5	224.6	34 745.1	50	150.9	8690.3	165.2	10 062.1	8	17.5	872.4	67.8	6393.0
Means	13.3	13.7	173.6	39 254.7	161.6	37 573.3	36.1	124.9	7235.4	154.9	13 512.1	5.4	14.2	554.8	41.4	3304.5

* = No data were taken