Accuracy and precision of measuring cross-sectional area in stem disks of Douglas-fir infected by *Armillaria* root disease

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Abstract: Stem cross-sectional areas were checked for accuracy and precision of area measurements in healthy and *Armillaria ostoyae* (Romagn.) Herink infected 18-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Ten trees were randomly selected in each combination of two size classes and four infection classes, and stem disks were taken at the soil line (0 m) and at 1.3 m. Disks were marked at the longest radius, 90° to the longest radius, the shortest radius, and at radii determined by the sum of the largest diameter and the diameter at 90° divided by four. These radii were used to calculate cross-sectional area, then these calculated areas were compared with the corresponding digitized areas. Cross-sectional areas calculated from radial measurements were generally not within 5% of digitized areas. Radii were also drawn on the disks corresponding to the positions at which healthy and infected roots arose from the root collar below. For 0-m disks, the stem radii over healthy roots averaged 7 mm longer than over infected roots. At 1.3 m, the stem radii over healthy roots were 4 mm longer, but this was reduced with increasing infection of the root system. Offset piths and irregular shapes formed because of radial reduction over infected roots, and corresponding radial expansion over healthy roots affected the accuracy of disk area estimation.

Résumé : L'exactitude et la précision des mesures de surface ont été vérifiées sur des sections radiales de tiges de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) sains ou infectés par *Armillaria ostoyae* (Romagn.) Herink et âgés de 18 ans. Dix arbres ont été sélectionnés au hasard pour chacune des combinaisons formées par deux classes de dimension et quatre classes d'infection. Des disques ont été prélevés au niveau du sol (0 m) et à 1,3 m. Le plus long rayon, le rayon faisant un angle de 90° avec le plus long rayon, le plus court rayon et le rayon résultant de la somme du plus grand diamètre et du diamètre faisant un angle de 90° avec ce dernier divisée par quatre ont été tracés sur les disques. Ces rayons ont été utilisés pour calculer la surface radiale qui a ensuite été comparée à la surface numérisée correspondante. Les valeurs de la surface radiale calculées à partir des mesures de rayon différaient généralement d'au moins 5 % de celles de la surface numérisée. Des rayons dont l'emplacement correspond à la position où les racines saines ou infectées émergeaient du collet ont également été tracés sur les disques. Sur les disques prélevés à 0 m, les rayons correspondant aux racines saines étaient en moyenne 7 mm plus longs que dans le cas des racines infectées. À 1,3 m, les rayons correspondant aux racines saines étaient 4 mm plus longs mais cette valeur diminuait avec la sévérité de l'infection du système racinaire. L'excentricité de la moelle et les formes irrégulières dus à la réduction de la croissance radiale au-dessus des racines infectées ainsi que l'expansion radiale correspondante au-dessus des racines saines affectent l'exactitude des mesures de la surface des disques.

[Traduit par la Rédaction]

Introduction

The prediction of timber supply is based on periodic mensuration of standing timber volume and projecting growth estimates over time. These measurements are used to calculate stand productivity, which is an important factor in decisions about harvest time and future cut allocations. Traditionally timber volume has been estimated by remeasurement of permanent sample plots and by stem sectioning and measurement of annual growth along several radii to obtain radial increment, basal area increment, or annual increment. Instruments used to measure annual tree ring width do so with a high degree of precision. However, does the radius thus measured reflect the true area of the stem cross section? Stems are rarely perfect circles; this leads to errors in the estimation of the true radius associated with the stem cross-sectional area. The errors are then squared and multiplied by π in the calculation of area.

The shape of the stem cross section affects the area estimated from radial measurements. Root disease is known to affect stem radial growth, but no information is available concerning the effect of root disease on cross-sectional stem shape and how that shape affects the accuracy and precision of stem area measurements derived from estimated radii. Despite this fact, several studies have estimated the volume losses for infected trees using cross-sectional area estimates derived from radial measurements (Bloomberg and Hall 1986; Bloomberg and Morrison 1989; Bloomberg and

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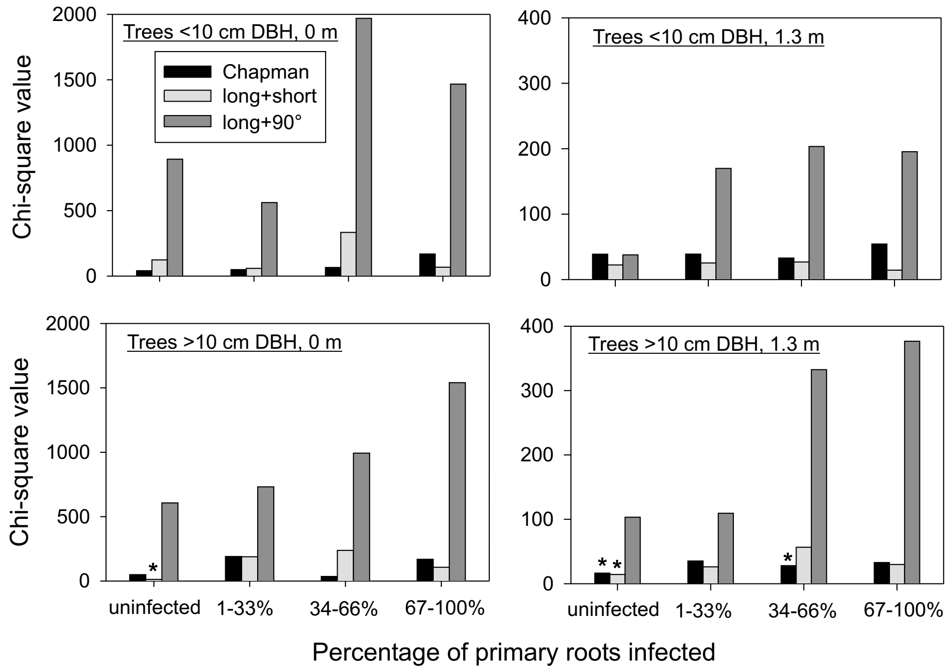
Fig. 1. Chi-square values for proportional errors of three different methods of estimating stem areas using radial measurements. The test compares the area calculated by two averaged radial measurements to the corresponding digitized disk areas at 0 and 1.3 m for juvenile Douglas-fir. There are 10 trees for each category, and the required accuracy for the test is 5% 19 of 20 times. Bars with asterisks are not significantly different.



Reynolds 1985; Bradford et al. 1978; Froelich et al. 1977; Lewis 1997; Thies 1983; Whitney and MacDonald 1985). The losses were estimated by the difference in growth between the healthy and infected trees. Estimates of cross-sectional area were calculated using the mean of two, three, four, or more radii. The positioning of these radii was a combination of the longest radius and one at 90° to the longest, the longest and shortest radii, or equally spaced radii. The averaged radii are assumed to reflect the area of the stem cross section. These methods have been borrowed from inventory techniques used to calculate annual increments.

This study examines the possibility that infected roots may have localized effects on radial growth of the stem and that the current techniques used to calculate cross-sectional area using estimated radii may have significant errors, especially in diseased stems. Precision is affected by random errors and concerns the repeated measurements of a quantity and their distribution; on the other hand, accuracy is affected by both random and systematic errors.

Materials and methods

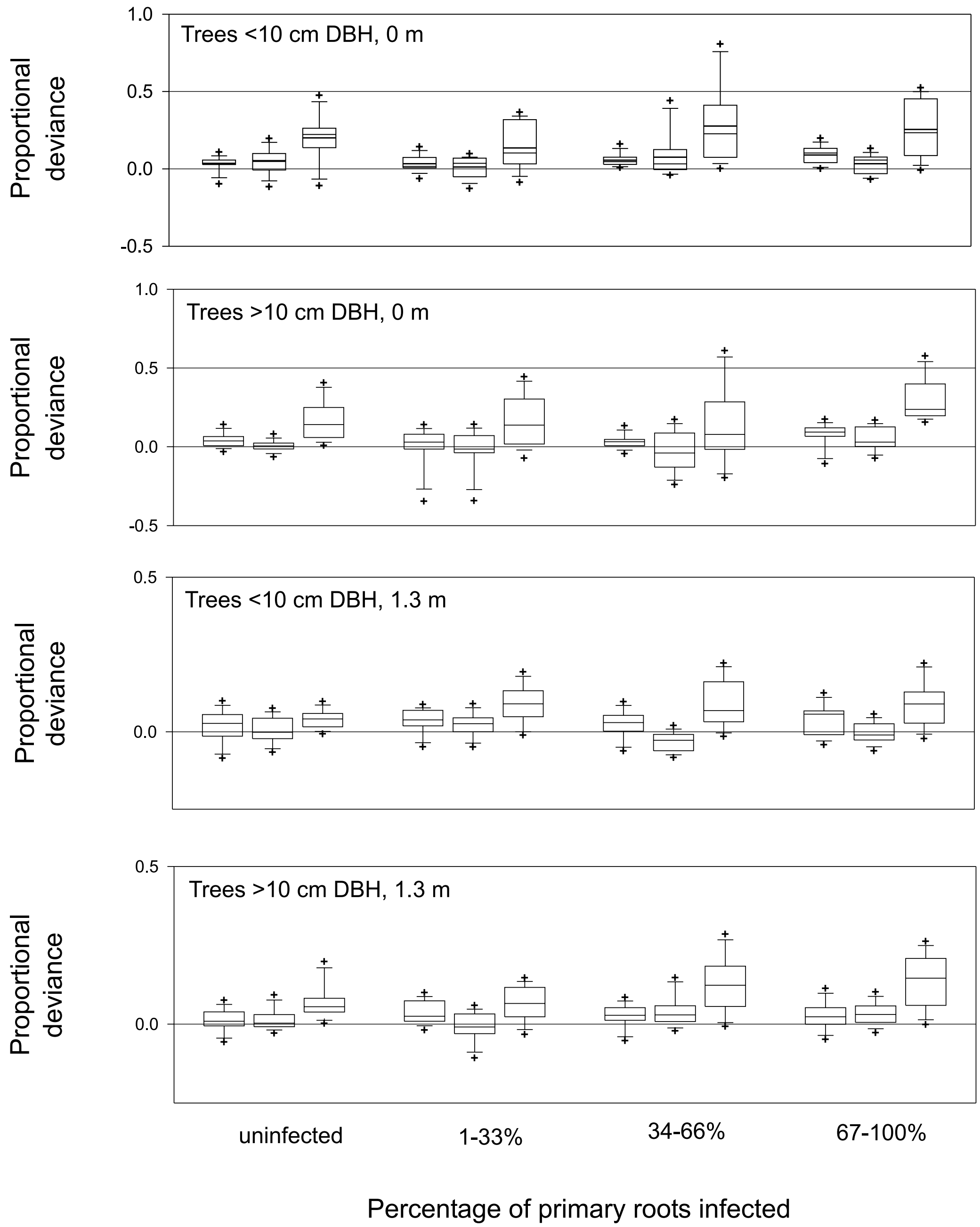
One hundred fifty Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees in an 18-year-old plantation near Kaslo, B.C. (50°18′N, 117°00′W), were removed from the soil using an excavator so that the roots were intact with the stem. Stem cross-sectional disks were taken at 0 and 1.3 m from the base and marked so that alignment of the roots and stem could be determined. The root systems were examined for lesions caused by *Armillaria ostoyae* (Romagn.) Herink. Roots greater than 10 mm in diameter arising from the root collar were called primary roots

Trees were assigned to one of two size classes on either side of the median diameter at breast height (median 10.0 cm, range 16.9–5.5 cm) and four infection classes (0, 1–33, 34–66, and 67–100% infected primary roots). Ten trees were selected randomly for each combination of size and infection class, totaling 80 trees with disks at 0 and 1.3 m for each tree (160 disks). The stem disks were air-dried and sanded, and the areas were determined using a digitizing tablet (GTCO Corp., Columbia, Md.). This was done by photocopying the disks and then integrating the photocopied areas. To determine the accuracy of this method, a 500-cm^2 area of graph paper was integrated 10 times on the tablet. The mean area obtained was 499.24 ± 0.59 cm^2 (mean ± SD) for an overall accuracy of 99.85%. After photocopying the same area and digitizing the area 10 times, the mean area was 495.9 ± 0.43 cm^2 for an overall accuracy of 99.16%. To determine the effect of size on bias of the photocopy method, areas of 5, 25, 100, 500, and 1000 cm^2 were photocopied and then 10 measurements were made on each area. A regression equation between the known and digitized area was fit which showed a slight negative bias of about 1% of the area (R^2 = 0.96). The regression equation was

$$\text{Bias} = 0.008\,83 - 0.011\,53 \times \text{measured area}$$

The area of each disk was corrected for bias using this equation, and the corrected area was used as the control area from which to investigate the accuracy and precision of the radially developed areas. The methods of developing cross-sectional area were (*i*) Chapman's method (Chapman and Meyer 1949), which consists of summing the largest diameter and the diameter at 90° to this and dividing by four to get

Fig. 2. Box plots of proportional errors among three different methods of estimating stem areas using radii. The graph compares the errors between the calculated areas using averaged radii and the corresponding digitized disk areas at 0 and 1.3 m from the base. Within each infection category, the methods of estimating radii are arranged from left to right as follows: (*i*) Chapman's; (*ii*) long plus short; (*iii*) long plus 90°. The box plot shows the 75th percentile; lines inside the box are the mean and median. The whisker bars above and below the plots show the 90th percentile; outliers are shown by +.



the mean radius; (*ii*) the mean of the longest and shortest radii; and (*iii*) the mean of the longest radius and one at 90° to the longest radius. These measurements were done on the actual disks using a dendrochronometer (digitial positiometer manufactured by L. Kutschenreiter, Austria) whose precision was ±0.01 mm. On stem disks, radii were also drawn at positions corresponding to the primary roots below and measured using the dendrochronometer.

All statistical analyses were performed using the SAS statistical package (version 8.0, SAS Institute Inc., Cary, N.C.). A chi-square test was used to statistically compare the accuracy of radial development of cross-sectional stem areas to their digitized equivalents (Freese 1960). Radii over roots were analyzed by ANOVA. Independence of the radii over roots is not totally assured, because multiple roots occur on one stem.

Results

The chi-square analyses (Fig. 1) determined the accuracy of each method within the desired tolerance (5 or 10%) of the digitized area. Only one infected category and three un-

Table 1. Results from an ANOVA performed on stem radii drawn corresponding to root position below for infected trees only for (A) disks at 1.3 m and (B) disks at soil line (0 m).

Parameter	df	SS	*P*	Coefficient
(A) Radii over roots at 1.3 m.				
Overall ANOVA				
Model	3	903	0.0079	
Error	551	41 577		
Total	554	42 480		
Factors				
Infection class (C)	1	386	0.0200	
Healthy				3.9476
Infected				0.0000
Proportion of infected roots (P)	1	432	0.0169	–0.0086
C × P interaction	1	287	0.0516	
Healthy				–0.0760
Infected				0.0000
(B) Radii over roots at soil line (0 m).				
Overall ANOVA				
Model	3	7 773	0.0001	
Error	551	146 589		
Total	554	154 362		
Factors				
Infection class (C)	1	1 019	0.0508	
Healthy				6.4129
Infected				0.0000
Proportion of infected roots (P)	1	31	0.7304	–0.0191
C × P interaction	1	8	0.8599	
Healthy				0.0129
Infected				0.0000

Note: Radii over healthy roots are larger than those over infected roots at the soil line. At 1.3 m the effect is similar, except there is an interaction with the proportion of infected roots (interaction C × P). When most of the tree roots are infected, radial stem growth over the remaining healthy roots is also reduced.

infected categories had stem areas that were within 5% of the digitized area at both stem positions 19 of 20 times (critical value at 18.31 with 10 df). When the desired accuracy required was raised to 10%, about one-half of the 0-m disk areas were within 10% (19 of 20 times) for Chapman's and long-plus-short methods only, while accuracy for all disks in the long-plus-90° method was outside this range. For disks at 1.3 m, all estimated disk areas were within the 10% tolerance except for the long-plus-90° method, in which all were outside this range. In general, the chi-square values were affected most by stem position, positioning of radii on stem disks, and infection status.

Chi-square values indicate departures in accuracy and precision but do not indicate the sign of the departure. To show the departures, the proportional errors were plotted for the same infection, size, and position classes (Fig. 2). In almost all cases the residuals were positively biased, indicating that the methods tended to overestimate the true area. The long-plus-90° method had the largest positively biased errors, ranging up to 60%. Chapman's and the long-plus-short methods were less positively biased but showed some negatively biased estimates of area, especially on larger trees and lower disks. Again, stem position, positioning of radii, and infection status had the largest effect on the magnitude of the errors.

Stem radial length measured over roots at 0 and 1.3 m was analyzed by an ANOVA (Table 1) for infected trees only. At the soil line (0 m), the stem radii over healthy roots were about 7 mm larger (least squares means) than infected roots regardless of infection status of the tree (Table 1B). At 1.3 m, the healthy roots interacted with the infection status. At low infection levels, the radii in stems over healthy roots were about 4 mm larger than over infected roots, but this difference decreased with increasing infection in the tree (Table 1A, interaction C × P), indicating that reduction in ring width spreads to the entire circumference.

Discussion

Root and butt rots are widely distributed. In addition, the incidence of belowground infection can be quite high as the stand ages (Kallio and Tamminen 1974; Morrison et al. 2000; Whitney 1989), and symptoms are difficult to detect aboveground (Morrison et al. 2000). Because forest-management practices can exacerbate the disease, it is important to accurately determine the impacts of disease on stand yields. A 10% difference is significant for forest management. If a 10% difference needs to be detected, then the errors associated with the accuracy of the measurement need to be less than 10%. An accuracy of 5% is probably more

Fig. 3. Healthy (left) and infected (right) stem disks of juvenile Douglas-fir at 1.3 m. The lines on the infected disk denote the positions that primary roots arose from the root collar below. Root five was initially infected 8 years ago. Radial growth is reduced above that root, while on the opposite side, radial stem growth increases initially over roots one and two at the same time. This results in off-centered piths and irregularly shaped stems.

suitable for this; furthermore, even a 5% difference has a considerable impact on the volume of timber in any one area.

In this study, the accuracy of estimated areas obtained by three traditional methods of stem analysis was not consistently within 5% of digitized areas. Only Chapman's method and the long-plus-short method were within 10% at 1.3 m stem height. Positioning of the radii affects the area estimation of disks (Siostrzonek 1958; Biging 1983), as was clear in the long-plus-90° method. A 10% error in estimation of disk area can be common, and at least four radii or cores were needed to reduce most errors to less than 5%, if the stems are not off-centered or irregularly shaped (Matérn 1961; Siostrzonek 1958). For irregularly shaped stems, eight or more radii may be needed to reduce the error to within 6% (Siostrzonek 1958; Smaltschinski 1986), but the error may not be consistent within this tolerance for some irregularly shaped stems. The process of accurately using radii to calculate stem areas on irregularly shaped stems can become very time consuming with no guarantee of accurate results.

The analysis of stem radii over healthy and infected roots on diseased trees showed localized effects on stem shape. The radii are not completely independent of each other, because several radii belong to one stem, and infection intensity can be negatively correlated with radial length for all radii on that stem (average seven primary roots per stem). To attempt to account for differences in infection intensity between trees, the percentage of infected roots per tree was used as a covariate for each stem radius on that tree. While the results must be viewed with caution, they suggest that diseased roots affect stem shape in columns over these roots. At the soil line, the stem (and probably the root) can increase growth locally over healthy roots in response to infection (Ehrlich 1939) even as the proportion of infected roots on the tree increases. The same effect occurs higher up the stem, except when most of the roots on a tree are infected; in this case, the infected roots interfere with localized radial expansion over the remaining healthy roots. The localized reductions and expansions caused by infected roots create off-centered piths and irregularly shaped stem cross sections (Fig. 3). The reduced radial growth of stems over infected roots occurs up the stem for some distance and may go as high as 3 m in 40-year-old Douglas-fir (Bloomberg and Hall 1986). The results from this study were generated using juvenile Douglas-fir, but stem shape is likely to become more irregular in trees and extend higher up the bole as the tree ages (Matérn 1961; Siostrzonek 1958).

Digital area estimation is time and cost effective, requires no specialized or expensive equipment, and has acceptable accuracy and precision. This method can alleviate problems associated with area estimation using radial development of irregular and off-centered stems (Ishibashi and Nishiyama 1995). Digital measurement is especially effective, and may be preferred, in studies of stem analyses of trees with root and butt rot because of the effects of disease on stem shape and cross-sectional area estimation.

The accurate estimation of cross-sectional area of stems that are not round has implications not only for forest productivity, but also for carbon sequestration, biomass, and economic analyses. The implications to each one of these areas are not as straightforward as might first appear. For example, the effects on carbon sequestration and biomass are not completely clear because of the suggestion from this study that healthy roots may grow as the tree reallocates resources from the stem to the healthy roots. Overestimation of stem volume should also take into account the economic consequences of disease on wood quality due to uneven growth rings. Since root and butt rots are common worldwide, these issues are important and need to be dealt with more completely in future studies.

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