Estimating phloem thickness in lodgepole pine stands using electrical resistance measurements[1]

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Correlations among measurements of electrical resistance of cambial zone tissue, phloem thickness, and tree diameter, reported earlier for other species, were also found for lodgepole pine (*Pinus contorta* Dougl.). Using these relationships, a model was developed for estimating phloem thickness in lodgepole pine, an important factor in assessing stand susceptibility to mountain pine beetle (*Dendroctonus ponderosae* Hopk.) epidemics. The predictive model and procedures for scaling estimates to specific time and location were tested with data from a lodgepole pine stand nearly 100 miles (161 km) away from the sample trees used in fitting the model. Results for stand data grouped into 3-in. (7.6 cm) diameter classes showed that class means of scaled model estimates were within ±4% of class means of phloem thickness for all diameter classes of the test stand. Model development and application procedures should be applicable to other species where estimates of phloem thickness and its distribution in stands is of interest.

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Les corrélations, déjà observées chez d'autres espèces, entre la résistance électrique du tissu cambial, l'épaisseur du phloème et le diamètre de l'arbre ont également été observés chez le pin à aiguilles tordues (*Pinus contorta* Dougl.). Grâce à ces relations, un modèle a pu être développé permettant l'estimation de l'épaisseur du phloème chez le pin à aiguilles tordues, facteur considéré important dans l'estimation de la sensibilité du peuplement aux épidémies de dendroctone du pin ponderosa (*Dendroctonus ponderosa* Kopk.). Le modèle de prédiction et les procédures utilisées pour graduer ces estimés en fonction d'un temps et d'un site donnés ont été mises à l'essai en utilisant des données provenant d'un peuplement de pin à aiguilles tordues situé à 100 milles (161 km) des arbres mesurés pour l'élaboration du modèle. Les résultats correspondant au peuplement ont été groupés en classes de diamètres de 3 po. (7.6 cm); ils montrent que les moyennes des classes des estimés gradués par le modèle sont situés à l'intérieur de la limite de ±4% des moyennes des classes d'épaisseur du phloème pour toutes les classes de diamètres du peuplement testé. Le développement du modèle et les procédures de son application devraient s'avérer utilisables pour d'autres espèces pour lesquelles il devient intéressant d'obtenir l'épaisseur du phloème et sa distribution dans les peuplements.

[Traduit par le journal]

Introduction

Phloem thickness of lodgepole pine (*Pinus contorta* Dougl.) trees is an important factor in the susceptibility of unmanaged stands to infestation by the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) (Amman 1976). To assess susceptibility of lodgepole pine stands by direct sampling of phloem thickness on large management units such as the National Forests is very time consuming and expensive. The senior author developed several alternative regression equations for estimating phloem thickness from measurements of recent periodic radial increment, diameter at breast height (dbh), and height, or from dbh, height, and age (Cole 1973). However, height measurements, increment borings, and age and radial growth measurements are still too time consuming; therefore, an improved method of estimating phloem thickness is needed. Our objective in this paper is to illustrate that the strong relationships between electrical resistance (ER) of cambial zone tissue and phloem (Carter and Blanchard 1978), and dbh and phloem (Cole 1973), can be developed into a single more sensitive and more useful model for estimating phloem thickness.

Electrical resistance measurements of trees are receiving much attention as useful indicators of the physiological status of the trees and as diagnostic aids for detecting effects of diseases, insects, and other damaging agents. Discolored and decayed wood of diseased, living hardwoods was found to have markedly lower resistance to low intensity, pulsed direct current (dc) voltage than did surrounding clear wood (Skutt *et al.* 1972). Also, the degree of resistance was shown to be related to the progressive stages of discoloration and

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[1] This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain.

decay in the wood (Tattar *et al.* 1972). Prototype circuitry and accessories were refined into a commercially available pulsed dc resistance meter, the Shigometer,[2] and guidelines were developed for using the Shigometer for detecting discoloration and decay in live trees and utility poles (Shigo and Shigo 1974).

ER in the overall cambial region of trees has been found to be related to tree vigor and degree of defoliation stress (Wargo and Skutt 1975), the amount of response to thinning release and fertilization (Smith *et al.* 1976), rates of growth and wound closure (Shortle *et al.* 1977), and levels and patterns of water potential (Dixon *et al.* 1978).

Recently, Carter and Blanchard (1978) found that the path of electrical current through bark and xylem tissue, when uninsulated electrodes are inserted radially into tree boles, is analogous to an electrical circuit having several different resistors in parallel. They found that ER was less in the phloem than in the xylem or phellem of red maple (*Acer rubrum* L.), and that total ER was highly correlated ($r = -0.92$) with the phloem thickness. They also confirmed the reported correlation of cambial electrical resistance with tree diameter (Wargo and Skutt 1975); however, through its strong correlation with phloem thickness (PT), diameter was concluded to be only transitively correlated with ER. We found similar relationships among ER, dbh, and PT for lodgepole pine and consider them sufficient for developing more useful phloem estimation procedures as described in the following sections.

Methods and materials

Electrical resistance of the cambium was measured with a Shigometer, model 7950, by inserting two uninsulated stainless steel needle electrodes through the bark and into the xylem of sample trees. Each sample tree was measured for ER and PT on the north and south sides of the bole at breast height (4.5 ft (1.37 m)). Electrodes were inserted in vertical orientation to the bole. Electrodes were spaced 0.550 in. (1.4 cm) apart and secured in pin chucks mounted in the end of a plastic (lucite) rod, thus an electrode could be quickly replaced if broken. Electrodes were steel needles used for sewing leather. The needles are cheap, readily available in 2–2.5 in. (5.0–6.4 cm) lengths, and are sturdy enough to penetrate lodgepole pine bark.

After recording ER, we obtained PT at the site of each ER measurement by excising a rectangular bark section having parallel sides running through the needle holes in the bark. On excision, the bark sections naturally separated at the inner boundary of the phloem adjacent to the xylem. Because phloem has an irregular boundary with the corky tissue (the phellem) external to it, average thickness of phloem on each side of the sample was measured and recorded, and an arithmetic average thickness calculated for the sample. Phloem was measured with a dial caliper. The dbh was measured with a steel diameter tape to the nearest 0.1 in. (0.25 cm).

Data were obtained from 53 randomly selected lodgepole pine trees in five stands near West Yellowstone, Montana, on July 20, 1976. Stands ranged in age from 19 to 86 years. Preliminary analysis of data revealed the same pattern of correlation among variables in each of the five stands and suggested that an improved predictive model for PT could be developed with nonlinear curve-fitting techniques. To allow greater sensitivity in model development and a more realistic range of eventual application, data were obtained from an additional 128 trees in two older and larger stands near West Yellowstone on July 14–15, 1977. The age range in those stands was from 80 to 135 years. Climatic conditions were nearly identical at the time of sampling in 1976 and 1977 (in both cases skies had been clear for several days and maximum temperatures were in the 80–85°F range (26–30°C) during the time of measurements). Because ER in living trees is known to vary with daily and seasonal temperature changes and seasonal physiological changes (Fensom 1966), the magnitude of these effects was considered.

Change in electrical resistance during the day was monitored on July 16, 1977, by measuring a tagged subsample of 16 trees at 9:00–9:30 a.m. and again at 4:00–4:30 p.m., to represent minimum and maximum temperatures likely to be encountered in a typical midsummer workday. At each time ER was measured on both the north and south sides of each tree at breast height, and the average ER calculated for the time of measurement. The mean change in ER was $-1.80\ \mathrm{k}\Omega$, or about a 12% reduction, apparently due to temperature-related effects during the day. This effect was represented in all diameter classes in the study data, and although it introduced additional variation in the ER variable, the effect was uniform and did not hinder model development.

Seasonal change in electrical resistance was monitored by tagging and measuring a sample of 11 lodgepole pines periodically throughout the period from April 15 to October 16, 1977. From these measurements, both the lowest (May) and the highest (October) levels of ER were identified. We believe ER data from these seasonal contrasts represent highly active versus relatively dormant growth periods; thus, these data were included in the analysis and the development of the model.

Results and discussion

The initial data sets were subjected to regression screens of linear effects in additive models, which indicated that PT of lodgepole pine was well related to both electrical resistance and to tree dbh ($P < 0.05$). But these simple model alternatives do not have the capacity to represent the strongly interactive relations theorized and that the data support. As earlier noted, lodgepole pine PT is functionally related to other growth expressions that are commonly interpreted as indicators of tree vigor (Cole 1973). And for other tree species, high ER levels in cambial zone tissue were found to be related to measures of lowered tree vitality, such as degree of defoliation (Wargo and Skutt 1975). On this basis we postulated that ER would be exceptionally high where thin phloem predominates and, conversely, would be very low when phloem is much thicker. More complex effects were expected at low than at high ER, because at low ER a broader range in both dbh and PT was noted.

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[2] Northeast Electronics Corporation, Concord, New Hampshire. Mention of a particular product should not be taken as an endorsement by the Forest Service or the United States Department of Agriculture.

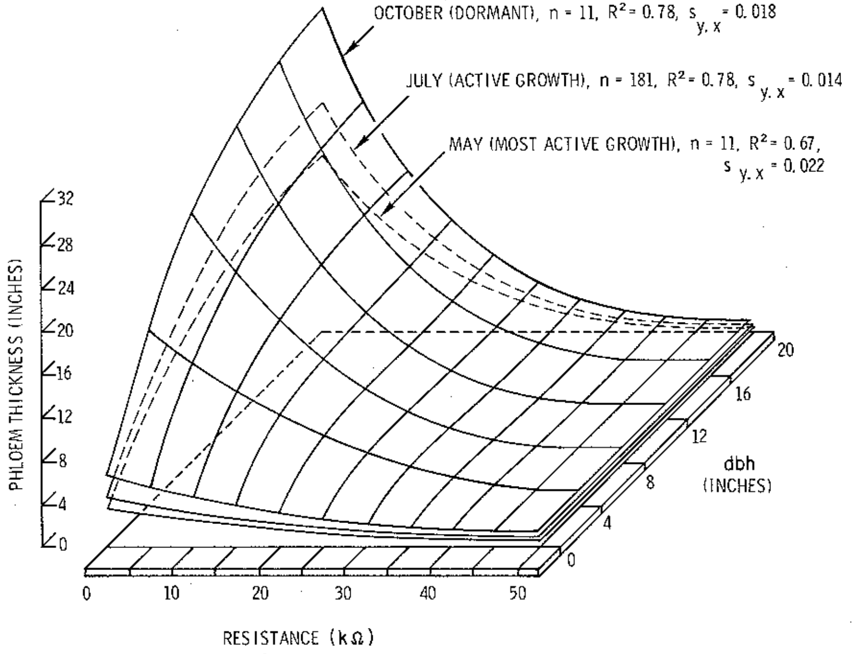

FIG. 1. Phloem thickness of lodgepole pine in relation to dbh and electrical resistance of cambium.

Here, as with tree growth in general, phloem thickness should tend to become asymptotic at some relatively high level, over the upper range of dbh. Noting the negative correlation between PT and ER, and assuming an asymptotic approach to zero PT in the upper range of ER, we finally postulated that a concave-upward form would describe PT at medium and low levels of ER. These expectations prompted inclusion of additional data for a more exacting estimate of the shape and scale of the relation.

Using the methods of Jensen and Homeyer (1970, 1971) and Jensen (1973, 1976), the combined data from 181 trees clearly support the expected form. Without suggesting causality in any sense, it appears that PT rises exponentially with *decreasing* resistance and ranges from a low, constant linear effect over dbh when resistance is high to a convex-upward effect over dbh when resistance is low, as shown by the surfaces in Fig. 1. The mathematical form of the basic model is

$$[1] \quad X = 0.01 + [YP/(45)^n]\,[(50-R)^n]$$

where

X = estimated phloem thickness in inches

$$YP = 0.148 - [(2.2687 \times 10^{-5})\,(22-D)^{2.72}] - [(1.2694 \times 10^{-14})\,(22-D)^{9}]$$

$$n = 1.9 + 1.3 \exp\left[- \left| \frac{(D/22 - 1)^7}{0.7} \right| \right]$$

R = ER in thousands of ohms (kΩ)

D = dbh in inches

The *limits* are $0 \leqslant D < 22$; for $D > 22$, $n = 3.2$ an $< R \leqslant 50$ kΩ; for $R > 50$, $X = 0.01$.

Refitting of this form to most active (May), acti (July), and dormant (October) growth period data sho the change in general scale of the relation that can expected between growth activity extremes during t year, for lodgepole pine stands in the sample area (F 1, and Table 1).

Changes in scale can also occur with changes in ge graphic area. Thus, a unique scaling factor (S) is re ommended for each season and geographical area use. Since we are unable to discern any systematic va iance pattern within the ranges of ER and dbh encou tered, we believe that a simple multiplier is adequate scaling the basic model to a new area or time of app cation. To accomplish this, the basic form (Eq. 1) be fitted to a data set of perhaps 50 well-distributed terms of dbh) trees from the intended general area time of application. Then, the scaling multiplier (S) be calculated according to the following equation:

$$[2] \quad S = \Sigma XY/\Sigma X^2$$

where X = estimated phloem thickness according general derived form of Eq. 1; and Y = measured PT inches.

The multiplier, thus calibrated for the area and ti of application, is then used to scale estimates from

TABLE 1. Phloem thickness (in inches) by dbh and resistance value

Month	dbh, in.	Resistance (kΩ)					
		0	10	20	30	40	50
May	4	0.09	0.06	0.04	0.02	0.01	0.01
	8	0.13	0.07	0.04	0.02	0.01	0.01
	12	0.15	0.08	0.04	0.02	0.01	0.01
	16	0.16	0.08	0.04	0.02	0.01	0.01
	20	0.17	0.09	0.04	0.02	0.01	0.01
July	4	0.12	0.08	0.05	0.03	0.01	0.01
	8	0.16	0.10	0.05	0.02	0.01	0.01
	12	0.20	0.10	0.05	0.02	0.01	0.01
	16	0.21	0.11	0.05	0.02	0.01	0.01
	20	0.22	0.11	0.05	0.02	0.01	0.01
October	4	0.16	0.11	0.07	0.04	0.02	0.01
	8	0.23	0.13	0.07	0.03	0.02	0.01
	12	0.28	0.14	0.07	0.03	0.02	0.01
	16	0.29	0.15	0.07	0.03	0.02	0.01
	20	0.30	0.15	0.07	0.03	0.02	0.01

general derived model according to the relationship:

[3] $PT = S(X)$

where PT = location and time specific estimate of phloem thickness.

The model and procedure for scaling to other geographical areas and seasons were tested with an independent set of data obtained the year following model development. Data were obtained from 70 lodgepole pine trees in Hyalite Canyon, approximately 95 miles (153 km) north of the area where model-development data were obtained. Estimated PT was calculated for each tree by programming solutions to Eqs. 1, 2, and 3 into a programmable hand calculator. Trees were then arranged into 3-in. (7.62 cm) diameter classes and class means computed for both observed PT and estimated PT. Results of the test are summarized in Table 2.

It is shown in Table 2 that the mean estimates without the scaling factor were consistently low; however, with the inclusion of the scaling factor the final mean estimates were within ± 4% of observed means.

These results indicate that the derived model form and scaling procedure provides an effective means for obtaining estimates of PT distributions in lodgepole pine stands. By programming the solutions of Eqs. 1, 2, and 3 into a programmable calculator, computational speed and accuracy are added to the recognized field advantages of using electrical resistance to measure PT. Because programmable calculators and computers are commonly available, the procedures presented here pro-

TABLE 2. Independent test of phloem estimation model and scaling procedure for estimating phloem distributions in lodgepole pine stands

dbh class, in.	No. of trees	Mean observed PT, in. (mm)	Mean estimated PT (without scaling factor)		Mean estimated PT (with scaling factor)	
			in. (mm)	% actual	in. (mm)	% actual
0–3	7	0.068 (1.73)	0.061 (1.55)	90	0.065 (1.65)	96
3–6	18	0.071 (1.80)	0.070 (1.78)	99	0.073 (1.85)	103
6–9	17	0.097 (2.46)	0.096 (2.44)	99	0.100 (2.54)	103
9–12	11	0.112 (2.84)	0.102 (2.59)	91	0.107 (2.72)	96
12–15	10	0.126 (3.20)	0.118 (3.00)	94	0.124 (3.15)	98
15–18	7	0.109 (2.77)	0.107 (2.72)	98	0.113 (2.87)	104

vide foresters and pest management specialists an efficient and effective means for estimating PT distributions of stands, for all lodgepole pine forests in their jurisdictions. This technique should prove adaptable to other species where PT estimation is of interest.

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