TREE-RING RESEARCH, *Vol. 64(1), 2008, pp. 55–60*

RESEARCH REPORT

WHEN IS ONE CORE PER TREE SUFFICIENT TO CHARACTERIZE STAND ATTRIBUTES? RESULTS OF A *PINUS PONDEROSA* CASE STUDY

C. W. WOODALL*

USDA Forest Service, Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108, USA

ABSTRACT

Increment cores are invaluable for assessing tree attributes such as inside bark diameter, radial growth, and sapwood area. However, because trees accrue growth and sapwood unevenly around their pith, tree attributes derived from one increment core may not provide sufficient precision for forest management/research activities. To assess the variability in a tree's inside bark radius, sapwood radius, and 10-year radial growth estimated by tree cores, two increment cores at 90 degree angles were collected from ponderosa pine (*Pinus ponderosa*) trees in eastern Montana (n = 2,156). Paired core measurements varied substantially with 13% mean difference for inside bark radius, 19% mean difference for sapwood radius, and 23% mean difference for estimates of radial increment. Furthermore, decreasing crown ratio, decreasing diameter, and increasing site slope were all found to increase differences in estimates derived from paired cores. Whether for management or research purposes, the number of cores that should collected per tree depend on a stand's susceptibility to reaction wood, required measurement precision, and budgetary constraints.

Keywords: ponderosa pine, increment cores, sapwood, growth, *Pinus ponderosa*.

INTRODUCTION

Sampling of fundamental tree attributes such as diameter and height has been standard procedure in forestry since the advent of the field. In particular, estimates of a tree's growth and age provide temporal insights that guide many ecological investigations and forest management activities (for example, see Johnson and Fryer 1989; Telewski and Lynch 1991; Veblen *et al.* 1991; Abrams *et al.* 1995). Extracting cores from a tree's bole via increment borers has become standard practice for acquiring tree growth and age data. Numerous scientific disciplines (*e.g.* dendrochronology and dendroclimatology) have been based on data from tree cores (for examples see Cook and Kairiukstis 1990; Graumlich 1993). Much of this research has been focused on observing long-term patterns in tree-ring width variations and relating these variations to climatic or disturbance events. In contemporary forestry, tree cores covering relatively short time periods are used to assess numerous forest attributes. For example, with the increase in focus on uneven-aged forestry in the past few decades, trees cores have been used to estimate sapwood area for use in leaf area models (Shinozaki *et al.* 1964; Waring *et al.* 1982; O'Hara 1995; Mainwaring and Maguire 2004).

It is a widely held belief that collecting more than one tree core per tree will reduce estimate variability (for example, see McDowell *et al.* 2002; Mainwaring and Maguire 2004); however, little research has been conducted to assess intra-tree core variability for assessment of tree attributes. Fritts (1976) suggests a relationship between the number of trees that need to be sampled on a site *versus* the number of cores collected per tree to reduce crossdating uncertainty. For assessing climate through tree rings, Fritts (1976) suggests collecting two cores per tree if 14 trees are sampled in a stand but, only one core per tree if 17 or more trees are sampled in a stand. Schweingruber (1988)

*E-mail: cwoodall@fs.fed.us

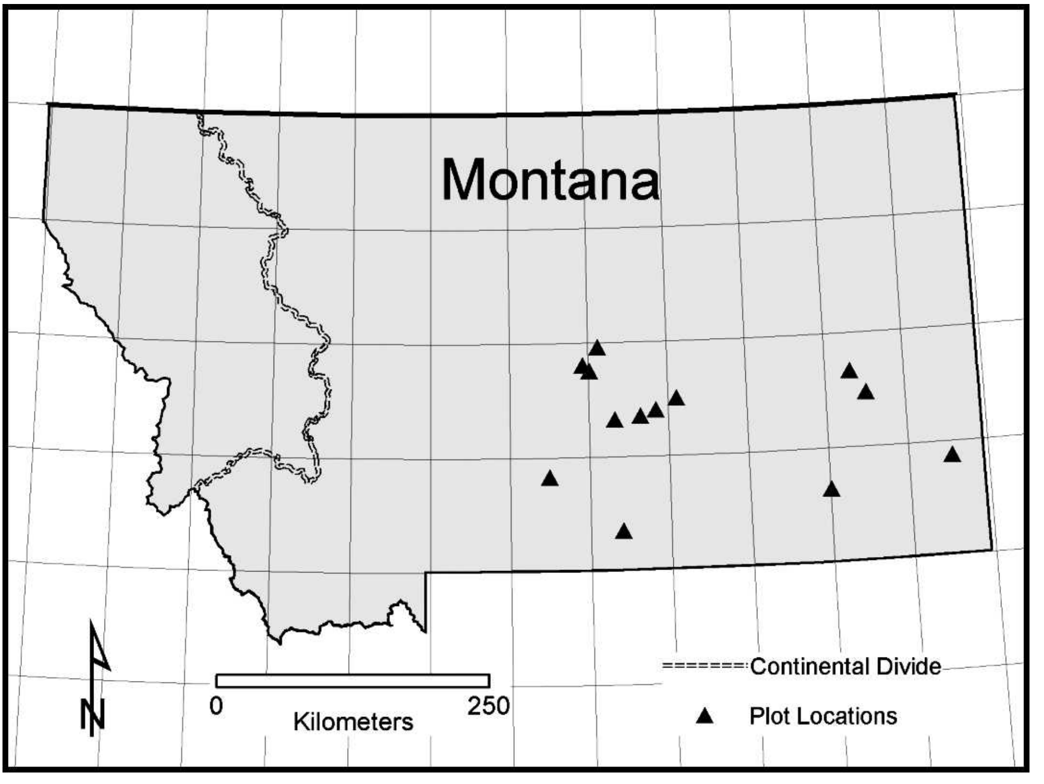

Figure 1. Study site locations in eastern Montana, U.S.A.

suggests single-coring 20–30 trees per site for short-term ecological assessments (*e.g.* stand growth declines), but stresses this process is simpler than the extensive work (*i.e.* crossdating) needed for assessment of long-term ecological analyses (*e.g.* climate change). Eccentricity in a tree's annual rings, caused by gravity/bending stresses resulting from wind and/or steep slopes (Gartner 1995; Schweingruber 1996), may further exacerbate differences between cores from the same tree.

The goal of this study is to measure the variability of individual-tree attributes derived from paired increment cores. Specific objectives are to 1) assess differences in measurements of inside bark radius (IBR), sapwood radius (SW), and most recent 10-year radial growth increment (RGI) for paired increment cores by classes of diameter at breast height (DBH, 1.3 m), 2) determine the effect of a tree's DBH, crown ratio and study-site slope on differences between paired increment measurements, and 3) develop suggestions for foresters/researchers based on these study results.

METHODS

This work is derived from a larger silvicultural study that examined the size/density relationships (Woodall *et al.* 2003a) and growth/competition characteristics (Woodall *et al.* 2003b) of uneven-aged ponderosa pine stands. As such, the methods are constrained to the field procedures originally undertaken by the broader study (*e.g.* no crossdating).

Study Sites

Fourteen study sites that exhibited negligible evidence of recent human or natural disturbances were located in pure ponderosa pine forests east of the Continental Divide in Montana (Woodall 2003a, 2003b) (Figure 1). Study site slopes ranged from gentle (0.3°) to relatively steep (18.3°).

Although most land in eastern Montana is dominated by agriculture or grazing, ponderosa pine monocultures still occupy nearly 0.9 million ha (O'Brien and Collins 1991; O'Brien and Conner 1991) on lowlands and hilly terrain (850 to 1,350 m a.s.l.) (Arno 1979), where soils are typically shallow and poorly developed with precipitation averaging 26–42 cm a year (Pfister *et al.* 1977). Because of the historic low-intensity fire regime, sporadic regeneration, and harsh environmental conditions (*e.g.* wind disturbances) of eastern Montana, these forests are often mosaics of tree sizes and stand densities constituting irregular multi-storied stands (Alexander 1986).

Field and Laboratory Methods

A 0.2- to 0.4-ha fixed-radius circular plot was established at each study site with an attempt to minimize within-plot physiographic and stand density variation. The slope of each study plot was determined as an average slope across the plot through plot center. All trees were measured for DBH (to the nearest 0.25 cm), total tree height, and crown-base height. An increment borer was used to extract two cores at right angles (bored to the pith) from all plot trees with a DBH greater than or equal to 12.7 cm. A random sample of approximately 1 out of every 12 trees from the highly populated class of trees with DBH less than 12.7 cm was also cored. Each sampled tree was cored once from an upslope position and then cored at a 90° angle to the upslope position on contour (perpendicular to slope) whenever possible. The presence of excessive branching, adjacent trees, or hollow/cavities occasionally precluded paired boring of trees with a DBH greater than or equal to 12.7 cm, thus eliminating approximately 6% of the sample trees from the study. Across all study sites, 2,156 trees were sampled resulting in over 4,300 tree cores.

When a core was extracted, its sapwood/heartwood boundary was marked with a pen and the core was inserted into a labeled plastic straw for subsequent drying, mounting, and sanding. Once cores were prepared, SW and IBR were measured to the nearest mm. RGI (most recent 10 years' growth) was measured to the nearest 0.03 mm using an ACU-GAGE Coordinate Measuring Machine and Javelin Smart Cam video system. For each core pair a relative difference was determined by:

$$Reldiff = |att_a - att_b| / att_{\bar{x}} \quad (1)$$

where *Reldiff* is the relative difference, att_a is the attribute measured on core a, att_b is the attribute measured on core b, and $att_{\bar{x}}$ is the mean of the two core measurements.

Analysis

The mean and associated standard errors of *Reldiff* were determined for IBR, RGI, and SW using all observations. The research hypotheses of slope, DBH, and crown ratio affecting *Reldiff* were tested using beta regression because the distribution of *Reldiff* is bounded by 0 and 1. Beta regression analysis was conducted using the SAS Glimmix procedure with IBR, RGI, and SW as response variables, DBH, crown ratio, and slope as independent variables, and study sites as a random effect.

RESULTS AND DISCUSSION

The mean *Reldiff* for SW was 18.8%, with the largest *Reldiff* (23.8%) for the smallest diameter class, 4.1–14.0 cm (Table 1). The mean *Reldiff* for IBR was 12.5% for all DBH classes, while the smallest and largest DBH classes had the largest differences, in excess of 15%. The mean *Reldiff* for RGI was the largest among tree attributes at 22.8%; the smallest and largest diameter classes had *Reldiffs* over 25%. For all DBH classes and tree attributes, mean *Reldiffs* varied in excess of 10% demonstrating an inherent variability in how trees accrue woody tissue within their boles. The distribution of individual tree *Reldiffs* by DBH was highly variable for SW, IBR, and RGI with a skewing towards higher *Reldiffs* in smaller trees (Figure 2).

For all study beta regression models, the regression fit statistics (Pearson chi-square/DF) were close to 1, indicating an adequate fit. Beta regression odds ratio estimates indicate the effect that independent variables have on the response variable for every one measurement unit increase

Table 1. Mean relative differences for tree attributes (sapwood radius, inside bark radius, and 10-year radial growth) based on paired increment cores by DBH class.

		Relative difference					
		Sapwood radius		Inside bark radius		10-year radial growth	
DBH class (cm)	n (trees)	Mean	Std. err.	Mean	Std. err.	Mean	Std. err.
4.1–14.0	518	0.238	0.008	0.150	0.006	0.267	0.009
14.1–24.0	880	0.187	0.005	0.123	0.003	0.218	0.005
24.1–34.0	467	0.151	0.005	0.102	0.003	0.204	0.007
34.1–44.0	205	0.151	0.009	0.115	0.007	0.215	0.011
44.1–54.0	81	0.182	0.015	0.153	0.015	0.253	0.018
Total	2,151	0.188	0.003	0.125	0.002	0.228	0.004

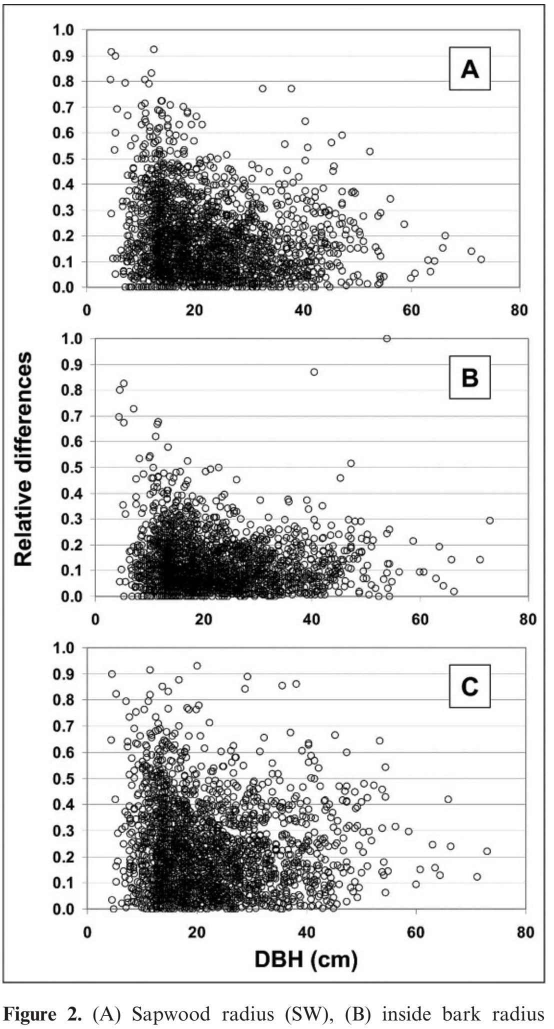

Figure 2. (A) Sapwood radius (SW), (B) inside bark radius (IBR), and (C) 10-year radial growth (RGI) relative differences by DBH class for paired core measurements.

in the independent variable. A significant independent variable ($p < 0.0001$) for the SW model was DBH with an odds ratio estimate of 0.985 indicating that for every 1-cm increase in DBH the *Reldiff* of SW decreased by approximately 1.5% (Table 2, Figure 2). Additionally, odds ratio estimates indicated that as crown ratio increased the *Reldiff* of SW decreased (p-value = 0.0385). For the response variable of IBR, as DBH increased the *Reldiff* was reduced ($p < 0.0001$) and as slopes increased the *Reldiff* also increased ($p = 0.0719$). For RGI, as DBH increased the *Reldiff* was reduced ($p = 0.0721$) (Figure 2) and as crown ratio increased the *Reldiff* was reduced ($p = 0.0003$).

The results of this study demonstrate the effect of wind and gravity (slope) on the precision of tree core measurements. Smaller trees are more susceptible to tree-ring eccentricity caused by more bending stresses during high winds (Mattheck 1995; Gartner 1995). These trees that suffer from wind stresses may also have smaller/misshapen crowns (Schweingruber 1996). Additionally, trees on steep slopes can have compression wood form in many different directions over long periods of time as the tree overcompensates for gravity (Schweingruber 1996). The result of this study supports many of these assertions. Differences in paired core measurements were most evident in small trees, trees with small crowns, and in trees on steep slopes. In a field context, a 1-cm difference in SW for a tree with a 5-cm DBH is tremendous on a relative scale, whereas the same difference for a tree with a 50-cm DBH may be inconsequential. Therefore, double-coring benefits will be reduced as trees increase in size (except for

Table 2. Beta regression model results for individual tree response variables (sapwood radius, inside bark radius, and 10-year radial growth relative differences) and independent variables (DBH, slope, and crown ratio) with study site as a random effect.

Response variable	Pearson Chi-square / DF	Independent variables	Parameter estimate	P significance	Odds ratio estimate*
Sapwood radius	1.05	DBH	−0.0156	< 0.0001	0.985
		Slope	0.0024	0.4681	1.002
		Crown ratio	−0.2205	0.0385	0.802
Inside bark radius	1.09	DBH	−0.0089	< 0.0001	0.991
		Slope	0.0056	0.0719	1.006
		Crown ratio	−0.0064	0.9523	0.994
10-year radial growth	0.99	DBH	−0.0035	0.0721	0.997
		Slope	0.0052	0.1437	1.005
		Crown ratio	−0.4646	0.0003	0.628

*Odds ratio estimates indicate the effect that independent variables have on the response variable for every one measurement unit increase in the independent variable.

the largest trees: DBH $>$ 44.1 cm). Slope only affected IBR *Reldiff*, most likely because of the long-term effects of compression wood growth on bole form (Schweingruber 1996); however, coring trees for IBR is a rare forest management activity. Increasing crown ratio reduced the *Reldiff* for the RGI variable to the greatest degree of all beta regression models. It can be assumed that trees with high crown ratios (healthy trees in low-density and/or less wind prone stands) may have less tree-ring eccentricity. Thus, double coring may be unnecessary in stands with vigorous crown forms/lengths. Overall, forest managers should only consider double coring trees when a stand is subject to extensive reaction wood formation. A single core parallel to elevation contours may be adequate in mature forests where wind- or slope-induced reaction wood is minimal. In contrast, researchers requiring high levels of precision may need to always consider double coring trees because of the implicit effect of reaction wood in all stands, especially in wind disturbed forest ecosystems.

CONCLUSIONS

If a high level of tree attribute estimate precision ($<$ 25% *Reldiff*) is required for management or research efforts, then the practice of double-coring trees appears warranted based on this study's results. If budgets preclude the double-coring of all subject trees, then focusing double-coring efforts to trees subject to wind disturbance (*e.g.* small trees on steep slopes) is recommended. Ultimately, decisions regarding the number of cores to be extracted from a tree depend on a stand's susceptibility to reaction wood, required measurement precision, and budgetary constraints.

ACKNOWLEDGMENTS

The study was funded by a grant from the McIntire-Stennis program at the University of Montana under the dedicated supervision of Carl Fiedler. The author would like to thank Todd Morgan, Henri Grissino-Mayer, and Thomas Swetnam for insights and comments regarding this manuscript. Additionally, the author would like to thank Todd Morgan and Michael Heaney for their tireless work coring thousands of trees.

REFERENCES CITED

Abrams, M. D., D. A. Orwig, and T. E. Demeo, 1995. Dendroecological analysis of successional dynamics for a presettlement-origin white-pine-mixed-oak forest in the southern Appalachians, USA. *Journal of Ecology* 83:123–133.

Alexander, R. R., 1986. *Silvicultural Systems and Cutting Methods for Ponderosa Pine Forests in the Front Range of the Central Rocky Mountains*. USDA Forest Service Gen. Tech. Rep. RM-128.

Arno, S. A., 1979. *Forest Regions of Montana*. USDA Forest Service Res. Pap. INT-218.

Cook, E. R., and L. A. Kairiukstis, 1990. *Methods of Dendrochronology – Applications in the Environmental Sciences*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Fritts, H. C., 1976. *Tree Rings and Climate*. Academic Press, New York.

Gartner, B. C., 1995. Patterns of xylem variation within a tree. In *Plant Stems: Physiology and Functional Morphology*, Ch. 6, edited by B. C. Gartner, pp. 125–149. Academic Press; 440 pp.

Graumlich, L. J., 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Research* 39: 249–255.

Johnson, E. A., and G. I. Fryer, 1989. Population dynamics in lodgepole pine-Engelmann spruce forests. *Ecology* 70:1335–1345.

Mainwaring, D. B., and D. A. Maguire, 2004. The effects of local stand structure on growth and growth efficiency in heterogenous stands of ponderosa pine and lodgepole pine in central Oregon. *Canadian Journal of Forest Research* 34: 2217–2229.

Mattheck, C., 1995. Biomechanical optimum in wood stems. In *Plant Stems: Physiology and Functional Morphology*, Ch. 3, edited by B. C. Gartner, pp. 27–90. Academic Press; 440 pp.

McDowell, N., H. Barnard, B. J. Bond, T. Hinckley, R. M. Hubbard, H. Ishii, B. Kostner, F. Magnani, J. D. Marshall, F. C. Meinzer, N. Phillips, M. G. Ryan, and D. Whitehead, 2002. The relationship between tree height and leaf area: Sapwood area ratio. *Oecologia* 132:12–20.

O'Brien, R. A., and D. C. Collins, 1991. *Forest Statistics for Land Outside National Forests in west-central Montana*. USDA For. Ser. Resour. Bull. INT-72.

O'Brien, R. A., and R. C. Conner, 1991. *Forest Statistics for Land Outside National Forests in Eastern Montana*. USDA For. Ser. Resour. Bull. INT-71.

O'Hara, K. L., 1995. Dynamics and stocking-level relationships of multi-aged ponderosa pine stands. *Forest Science* 42:1–34.

Pfister, R. D., B. L. Kovalchik, S. F. Arno, and R. C. Presby, 1977. *Forest Habitat Types of Montana*. USDA For. Ser.Gen. Tech. Rep. INT-34.

Schweingruber, F. H., 1988. *Tree Rings: Basics and Applications of Dendrochronology*. Kluwer Academic Publishing Group, Boston.

———, 1996. *Tree Rings and Environment: Dendroecology*. Paul Haupt Publishers; 609 pp.

Shinozaki, K., K. Yoda, K. Hozumi, and T. Kira, 1964. A quantitative analysis of plant form – the pipe model theory. *Japanese Journal of Ecology* 14:97–104.

Telewski, F. W., and A. M. Lynch, 1991. Measuring growth and development of stems. In *Techniques and Approaches in Forest Tree Ecophysiology*, edited by J. P. Lassoie, and T. M. Hinckley, pp. 503–555. RCR Press, Boca Raton, FL.

Veblen, T. T., K. S. Hadley, and M. S. Reid, 1991. Disturbance and stand development of a Colorado subalpine forest. *Journal of Biogeography* 18:707–716.

Waring, R. H., P. E. Schroeder, and R. Oren, 1982. Application of the pipe model theory to predict canopy leaf area. *Canadian Journal of Forest Research* 12:556–560.

Woodall, C. W., C. E. Fiedler, and K. S. Milner, 2003a. Stand density index in uneven-aged ponderosa pine stands. *Canadian Journal of Forest Research* 33:96–100.

———, 2003b. Inter-tree competition in uneven-aged ponderosa pine stands. *Canadian Journal of Forest Research* 33: 1719–1726.

Received 17 July 2007; accepted 11 January 2008.