

Improving Tree Age Estimates Derived from Increment Cores: A Case Study of Red Pine

Shawn Fraver, John B. Bradford, and Brian J. Palik

Abstract: Accurate tree ages are critical to a range of forestry and ecological studies. However, ring counts from increment cores, if not corrected for the years between the root collar and coring height, can produce sizeable age errors. The magnitude of errors is influenced by both the height at which the core is extracted and the growth rate. We destructively sampled saplings and small trees of red pine (*Pinus resinosa* Ait.) and combined within- and between-tree cross-dating to determine accurate rings counts and radial growth rates for 11 stem sections of each sample. We developed regression models to estimate age adjustment as a function of coring height and radial growth rate. We compared candidate models using corrected Akaike's information criterion scores, and we evaluated model performance by jackknife permutations. Application of our best-fit equations clearly improved age estimates: compared with unadjusted ring counts, our adjusted age estimates had normally distributed errors centered near 0, lower standard deviations, and a narrower range of values. Thus, these equations can be used to adjust ages of cored, mature trees occurring in these same settings. The methods used here may be applied to other shade-intolerant or mid-tolerant species where improved tree establishment dates are needed. FOR. SCI. 57(2):164–170.

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TREE AGE IS A CRITICAL FACTOR in a wide range of ecological and forestry studies. In the absence of historically documented planting or establishment dates, researchers often rely on increment coring to estimate tree age. However, numerous factors confound the determination of tree age, even from increment cores that strike the pith. In combination, they can result in age inaccuracies of a few years up to several decades. For example, if not corrected by cross-dating, errors resulting from locally absent rings (producing underestimates) and to a lesser extent double rings (overestimates) can be substantial (Bormann 1965, Lorimer et al. 1999). Slow radial growth further confounds these factors, because locally absent rings are much more likely to occur during periods of slow growth (Swetnam and Lynch 1989, Lorimer et al. 1999). In addition, coring height above the point of germination clearly influences inferred ages (Palik and Pregitzer 1995, Wong and Lertzman 2001, Gutsell and Johnson 2002, Niklasson 2002).

Errors in tree age estimates are especially problematic in studies in which tree establishment dates are used as proxies for past disturbances (Heinselman 1973) or in cases in which the link between tree establishment and high-frequency climate variation is being tested (Savage et al. 1996, Brown and Wu 2005, League and Veblen 2006). Understanding how climate fluctuations drive tree establishment is increasingly important in the context of changing climatic conditions, including increased weather variability. Such

studies may require accurate tree establishment dates that are difficult or impossible to obtain from simple ring counts on increment cores.

Previous work has highlighted the magnitude of errors resulting from unadjusted ring counts, as well as the difficulties in correcting these errors. Gutsell and Johnson (2002) excavated all plot seedlings, saplings, and trees, followed by precise dating of fine cross-sections of each, to determine accurate establishment dates for trees classified according to successional status. Their results nicely demonstrated that all tree species, once properly dated and regardless of their successional status, established shortly after fire. Wong and Lertzman (2001) developed regression equations describing the relationship between the number of years to reach breast height and the radial growth rate of mature trees. Simulations based on these relationships showed that even these improved age estimates cannot be expected to produce precision greater than 10–20 years when trees are cored at breast height. Villalba and Veblen (1997) destructively sampled a large number of seedlings of *Austrocedrus chilensis*, determined their height-growth rates, and used those rates to estimate number of rings that must be added to increment cores from mature trees growing under similar conditions. Their work highlights the necessity of considering the seedling-to-seedling variability in growth rates when such data are used to adjust ages of mature trees.

Although coring at the root collar may in theory provide

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accurate age estimates for shade-intolerant species (see Results and Discussion), this too has its attendant challenges. First, owing to stem fluting near the base, the extracted core would contain a distorted ring-width pattern, which may be suitable for simple ring counts but would be inadequate for virtually all other purposes (e.g., growth patterns, productivity studies, and statistical cross-dating). Second, coring near the root collar requires excavation at the tree base, particularly for mature trees, to gain access to the root-shoot interface. Third, heartrot, if present, is likely to be located low on the stem, thereby precluding the extraction of a sound core. For these and other reasons, cores are typically extracted at some distance above the base, and when needed, a number of rings may be added to estimate germination date. Although seldom addressed (but see above), this adjustment is a function of both the coring height and the early growth rate.

Thus, our objective in this study was to develop a method for improving estimates of tree establishment dates that takes into account both coring height and early radial growth rates. Our method builds on that of Villalba and Veblen (1997), using empirical growth-rate data from saplings and small trees to adjust ages of mature trees in the same study area. To this end, we first combined within- and between-tree cross-dating (to correct for double or locally absent rings) to determine accurate ring counts and radial growth rates for 273 radial cross-sections from 26 saplings and small trees of red pine (*Pinus resinosa* Ait.). From these results, we developed several nonlinear multiple regression equations that adjust age estimates simultaneously for both coring height and radial growth rate. These regressions can then be applied to increment cores from mature red pines in similar settings to improve age estimates. Although labor intensive, this method may be applied to other mid-tolerant to shade intolerant species where knowledge of tree establishment dates is critical. Further, in the absence of species-specific adjustments as presented here, the use of our equations for other pine species of similar shade tolerance would probably result in an improvement in age estimations over no adjustment at all.

Materials and Methods

Field and Laboratory Methods

Twenty-six red pine saplings were destructively sampled by harvesting at the root collar, taken to be the widest diameter flare that apparently separated stem from root (Fritts 1976, but see Results and Discussion). Samples were collected from various locations in the Superior and Chippewa National Forests, Minnesota, USA, and were selected to span a range of canopy cover conditions, from near full shade to near full sun, assuming that growth rates varied accordingly. Samples ranged in diameter from 1 to 9 cm at breast height. Stem disks 1 cm thick were cut every 20 cm from the root collar to 200 cm along the stem, using 11 disks per sample, for a total of 273 disks (several unusable rotten sections excluded). We chose a height of 200 cm because this is the maximum height at which we collect cores from dead and down wood for dendrochronological analyses. Disks were dried and sanded to a fine polish or shaved with

a scalpel and treated with zinc-oxide paste to enhance latewood boundaries. Two perpendicular radii were measured on each disk. Annual rings were properly dated and corrected by within-tree cross-dating using narrow rings, false rings, and compression wood as marker years (Niklasson 2002). A number of within-site marker years also aided in cross-dating (Yamaguchi 1991). Ring widths were measured to the nearest 0.01 mm using a Velmex sliding-stage stereomicroscope. In cases in which radii contained a sufficient number of rings, dating was verified statistically by COFECHA (Holmes 1983). For analyses of growth rates, two radii per disk were averaged.

Data Analyses

Each disk yielded number of years of growth (after cross-dating corrections) and a growth rate. We define the growth rate as the mean of the innermost ring widths for each disk, testing three rates: that of the innermost 5, 10, and 15 rings (as per Wong and Lertzman 2001). We assume the date of the innermost ring at the root collar to represent the tree's establishment date (but see Results and Discussion). The number of rings that must be added to ring counts from successively higher disks to achieve the root collar age generally increases with both increasing height and with decreasing growth rates; we refer to this number as the *age correction*.

We developed regression equations (predicting age correction from coring height and early growth rate) with the practitioner in mind, reasoning that most would need to make adjustments for cores extracted either near the tree base or at breast height (defined here as 140 cm). "Basal" cores are typically taken approximately 30 cm above the base (Gutsell and Johnson 2002) to avoid the butt swell and basal fluting that cause distorted ring-width patterns and to allow space for rotating the borer handle. We thus developed two height-specific equations, one at 30 cm (assumed to be the midpoints of data from 20 and 40 cm heights) and one at 140 cm. We also developed a regression surface allowing for age corrections across a range of growth rates and coring heights (0–200 cm). Thus, by knowing the height from which a given core was extracted, coupled with a growth rate determined from its innermost rings, the practitioner could apply one of these equations to estimate an establishment date for that sample.

For the height-specific data, we evaluated linear and nonlinear regression models (negative exponential, power functions, and hyperbolic forms) with and without natural logarithmic transformations of the predictor variable. These model forms were suggested by preliminary plots of age corrections versus growth rates at given coring heights. Similarly, for the full data set (i.e., including heights 0–200 cm), we evaluated a number of linear and nonlinear regression models (plane, parabolic, multiplicative, and additive forms), with and without natural logarithmic transformations of predictor variables. For the full data set, several candidate models included a random term to account for within-stem data dependence. For these data, we also evaluated partial null models that included height only and growth rate only. Finally, all models were evaluated using

each of the three growth rates (innermost 5, 10, and 15 rings). The various models were fit using PROC REG, PROC NLIN, and PROC NLMIXED (to include the random term) in SAS/STAT software (SAS Institute, Inc., Cary, NC). Data from one sapling were deleted as an outlier, owing to a dramatic growth increase that began at 100-cm height.

We evaluated candidate models using corrected Akaike's information criterion (AICc) scores, which allowed us to determine which models were best supported by the data (Burnham and Anderson 2002). We also calculated Akaike model weights to gauge the probability of a given model being the best in the model set (Burnham and Anderson (2002). In all three model-selection routines (heights of 30, 140, and the full data set including 0–200 cm), the model with the lowest AICc score was selected as the best. Finally, for the selected models, we ensured that the spread of residuals versus predicted values, as well as the normality of the residuals, were acceptable.

Once a model had been selected for each height situation (30, 140, and 0–200 cm), we used a leave-one-out jackknife procedure to further evaluate model performance. In brief, this method excludes one stem from the entire data set, uses the remaining data to fit the model parameters, and then uses the fitted model to predict the age adjustment for the excluded stem. The process is repeated 25 times, excluding a different stem each time. The generalized error rate for a given model was taken as the mean error (known age adjustment minus predicted adjustment) of all jackknife runs (Conover 1999). Finally, selected models were evaluated by their ability to predict known age correction using the entire data set. We thus determined bias and precision for these predictions, where bias was taken to be the mean of the residuals and precision to be the model root mean square error (Cochran 1977).

Results and Discussion

Once properly cross-dated, these data allowed us to determine the range of aging errors that could result if adjustments for coring height and growth rate are not made. We thus found that samples extracted at 30 cm contained from 2 to 13 (mean = 6, median = 5) fewer rings than did the root collar disk, whereas samples extracted at breast height (140 cm) contained from 7 to 36 (mean = 15, median = 14) fewer rings. This latter range generally brackets previous estimates of the number of years needed to achieve breast height for this species. For example, Palik and Pregitzer (1995) found this number to be 16 years on average, Rudolf (1957) reported 15–16 years, and Horton and Bedell (1960) and Benzie (1977) reported 8–10 years.

The best-fit model for predicting age correction from growth rate at the height of 30 cm was a linear form (Figure 1; Table 1) using the natural logarithmic transformation of growth rate based on the innermost five rings. The model was highly significant ($P < 0.003$) and produced results with very low bias of 0.00 (years) and precision of 2.72 (years). This precision means that at 30 cm height, 84% of the adjusted estimates fell within ± 3 years of the actual age, and 100% fell within ± 5 years. In comparison, values for

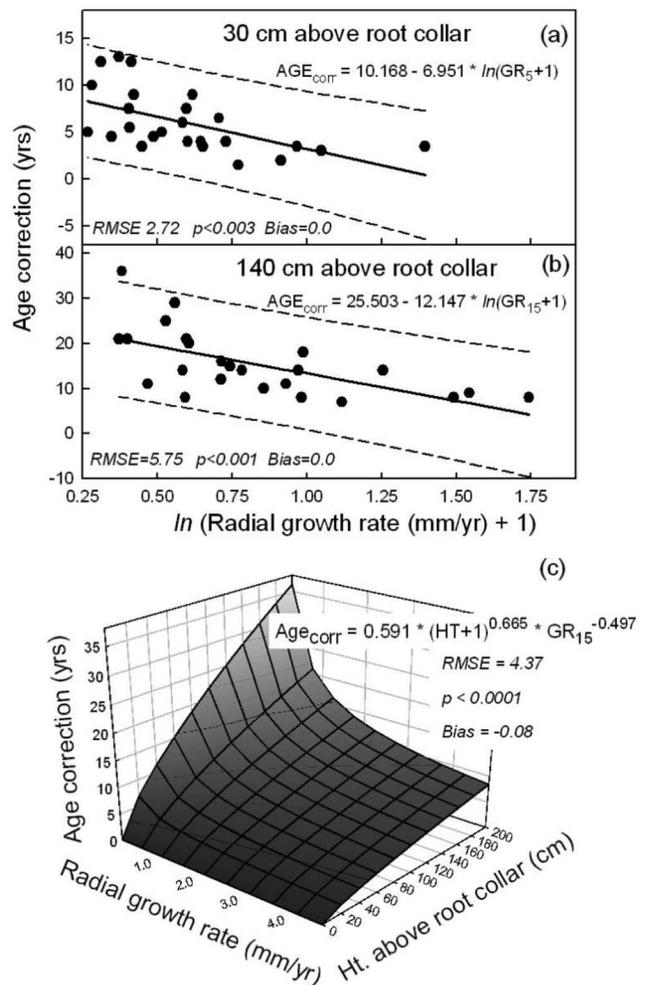


Figure 1. Age corrections needed to estimate tree establishment dates from increment cores, as a function of height above root collar and radial growth rate derived from the innermost rings. **a.** Best-fit regression equation and diagnostics (inset) using a common height above root collar of 30 cm. AGE_{corr} is the number of rings needed to achieve root collar age, and GR_5 is the mean ring width of the innermost 5 rings (mm/year). Solid lines show the predicted values, and broken lines indicate 95% confidence intervals for the predicted values. **b.** Best-fit equation using another common height above root collar of 140 cm. GR_{15} is the mean ring width of the innermost 15 rings (mm/year). **c.** Best-fit equation and fitted surface based on the full range of coring heights (HT, 20–200 cm) above the root collar. RMSE, root mean square error.

unadjusted ring counts were 12 and 56%, respectively. The generalized error rate produced by the jackknifed permutations was 0.080 (years); the mean intercept was 10.186 (95% jackknife confidence limits = 10.025–10.346), quite close to that of the best-fit model (10.168); and the mean slope was -6.985 (95% jackknife confidence limits = -7.232 to -6.738), also quite close to that of the best-fit model (-6.951).

The best-fit model for breast-height samples was also a linear form (Figure 1; Table 1), however, using the natural logarithmic transformation of growth rate based on the innermost 15 rings. The model was highly significant ($P < 0.001$) and produced results with bias of 0.00 (years) and precision of 5.747 (years). This precision means that at

Table 1. Model diagnostics for the top five models in each of the three height situations (30 cm, 140 cm, and the full data set)

Height	Model form (AGE _{corr} =) ^a	<i>b</i> ₀	<i>b</i> ₁	<i>b</i> ₂	Rings	AICc	DAICc	AICc wt	RMSE	Bias
30 cm	$b_0 + b_1 \cdot \lnGR$	10.168	-6.950	—	5	59.06	0.00	0.28	2.72	0.00
	$b_0 + b_1 \cdot SQRT_GR$	12.033	-6.667	—	5	59.21	0.15	0.26	2.73	0.00
	$b_0 + b_1 \cdot \lnGR$	9.562	-5.403	—	10	60.18	1.12	0.16	2.78	0.00
	$b_0 + b_1 \cdot SQRT_GR$	10.981	-5.154	—	10	60.27	1.21	0.15	2.79	0.00
	$(b_0 \cdot b_1)/(b_1 + GR)$	16.522	0.412	—	5	60.39	1.34	0.14	2.63	0.00
140 cm	$b_0 + b_1 \cdot \lnGR$	25.503	-12.147	—	15	95.35	0.00	0.26	5.75	0.00
	$(b_0 \cdot b_1)/(b_1 + GR)$	39.301	0.714	—	15	95.7	0.35	0.21	5.43	0.18
	$b_0 + b_1 \cdot SQRT_GR$	28.287	-11.208	—	15	95.79	0.44	0.20	5.80	0.00
	$b_0 + b_1 \cdot \lnGR$	26.807	-12.582	—	5	96.05	0.70	0.18	5.83	0.00
	$b_0 + b_1 \cdot SQRT_GR$	29.627	-11.598	—	5	96.44	1.09	0.15	5.87	0.00
All heights	$b_0 \cdot (HT + 1)^{b_1} \cdot GR^{b_2}$	0.591	0.665	-0.497	15	805.36	0.00	0.50	4.37	-0.08
	$b_0 \cdot SQRT_HT^{b_1} \cdot GR^{b_2}$	0.396	1.445	-0.497	15	805.37	0.01	0.50	4.37	-0.06
	$b_0 \cdot (HT + 1)^{b_1} \cdot GR^{b_2}$	0.517	0.699	-0.479	10	826.53	21.17	0.00	4.54	-0.09
	$b_0 \cdot SQRT_HT^{b_1} \cdot GR^{b_2}$	0.337	1.522	-0.478	10	826.71	21.35	0.00	4.54	-0.07
	$b_0 \cdot (HT + 1)^b \cdot GR^{b_2}$	0.393	0.763	-0.489	5	832.48	27.12	0.00	4.59	-0.09

In each case, we selected the model with the lowest AICc score. Height refers to the coring height above root collar; rings refers to the number of innermost rings used to determine growth rate. DAICc, Delta AICc; RMSE, model root mean square error; wt, weight.

^a AGE_{corr} is age correction, i.e., the difference in age between coring height and root collar, GR is growth, determined from some subset of innermost rings on each core (mm/year), SQRT_GR is the square root of GR, HT is height above root collar (cm), and SQRT_HT is the square root of HT.

breast height, 46% of the adjusted estimates fell within ±3 years of the actual age, 75% fell within ±5 years, and 96% fell within ±10 years. By comparison, values for unadjusted ring counts were 0, 0, and 29%, respectively. The generalized error rate produced by the jackknifed permutations was 0.123 (years); the mean intercept was 25.512 (95% jackknife confidence limits = 25.187–25.837), quite close to that of the best-fit model (25.503); and the mean slope was -12.163 (95% jackknife confidence limits = -12.464 to -11.863), also quite close to that of the best-fit model (-12.147).

The best-fit model using the full range of coring heights (0–200 cm) was a multiplicative form (Figure 1; Table 1), also using a growth rate based on the innermost 15 rings. The model was highly significant ($P < 0.0001$) and produced results with an overall bias of 0.0 (years) and overall precision of 4.370 (years). This precision means that across the full range of coring heights, 63% of the adjusted estimates fell within ±3 years of the actual age, 84% fell within ±5 years, and 95% fell within ±10 years. In comparison, values for unadjusted ring counts were 6, 14, and 47%, respectively. The strong dependence of age correction on both explanatory variables can be seen in the model’s fitted surface (Figure 1). Not surprisingly, the predictive ability of this equation generally decreased with decreasing growth rate and increasing height. The generalized error rate produced by the jackknifed permutations was -0.04 (years); the mean *b*₀ term was 0.590 (95% jackknife confidence limits = 0.587–0.594), quite close to that from the best-fit model (0.591); the mean *b*₁ term was 0.665 (95% jackknife confidence limits = 0.664–0.666), essentially the same as that from the best-fit model (0.665); and the mean *b*₂ term was -0.497 (95% jackknife confidence limits = -0.501 to -0.494), also essentially the same as that of the best-fit model (-0.497).

All three model-selection routines (30, 140, and 0–200 cm) included model uncertainty, meaning that no single model clearly outperformed the others, based on Akaike information criterion weights (Table 1). This finding high-

lights the importance of considering a variety of model forms in the event that this method is applied to other species or environmental settings. However, any of the top two or three models in each height category produced results that we deem as acceptable. In addition, all jackknifed permutations produced error rates and parameter estimates very close to those derived from the full data set, suggesting acceptable model performance. However, we point out that the general applicability of the models to other species or settings remains unknown, as this would require independent data of comparable detail, which are not available.

Thus, all three best-fit models produced estimates with extremely low bias, yet they had less than ideal precision. Nevertheless, these equations clearly improve age estimates. Our adjusted estimates have a range of errors that are normally distributed and centered near 0 and compared with unadjusted ages, they have less variability and exhibit a more narrow range (Figure 2). Previous studies have illus-

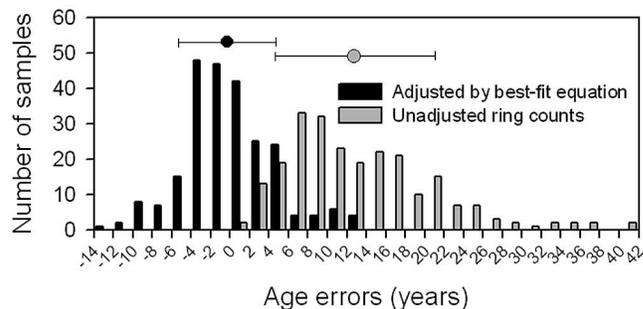


Figure 2. Distribution of age errors from unadjusted ring counts compared with samples adjusted using our best-fit regression equation that accounts for both height above root collar and radial growth rate (using all heights 20–200 cm). These adjustments clearly improved age estimates: compared with unadjusted ring counts, the adjusted estimates have normally distributed errors centered near 0, have lower variability, and exhibit a more narrow range. Mean age errors (circles) and standard deviations (bars) are shown above histograms.

trated the simultaneous influence of coring height and radial growth rate on the corrections needed to estimate tree establishment dates (Villalba and Veblen 1997, Wong and Lertzman 2001). Their results have also shown sizeable imprecision, even when using best-fit regression models (Wong and Lertzman 2001). Collectively, these results attest to the difficulty in achieving exact establishment dates from increment cores, owing to tree-to-tree variability in growth, as well as nonconstant within-tree growth (Villalba and Veblen 1997, above). Yet, in the absence of fully excavating mature trees or stumps and locating the root-shoot interface by tangential sectioning (Sirén 1950) or by numerous consecutive adjacent stem sections (Gutsell and Johnson 2002), adjustments that take into account coring height and radial growth rate remain the best nondestructive alternatives currently available for improving tree age estimates.

When adjusted establishment dates (as above) for individual trees, each still containing uncertainty, are compiled at the plot or stand level, the resulting age-class distribution necessarily incorporates this uncertainty. The near-zero bias of estimates (above) does not mean that under- and overestimates are cancelled out once samples are combined. However, this concept points to an application of these equations that we had not originally intended. For tree species that become established en masse immediately after disturbance, the date of disturbance may be best estimated by the mean of the adjusted ages, which has quite high population-level accuracy (bias ~ 0 , SE = 0.27, using entire data set). This concept can perhaps be best appreciated in Figure 2, which shows the distribution of adjusted and unadjusted age estimates.

The development and application of these models involves a number of assumptions. First, our models assume that growth rates do not vary by height within a stem (i.e., the growth rate determined from a core needing adjustment represents the growth rate at points below the core height), which was not true for numerous samples. The most common form of inconsistent within-stem growth was that of generally increasing growth rate with height; however, several samples also showed parabolic forms (slow-rapid-slow) or simply variable growth. This inconsistent, height-variant growth represents a source of variation that was not addressed in our analyses. Although our models could potentially be improved by adding a parameter characterizing the shape of the nonconstant growth, we did not do so, because our intent was to develop predictive equations for real-world situations in which within-stem, height-variant growth rates would not be known.

Second, application of these adjustments assumes that the saplings used to develop the equations represent the juvenile growth rates of the trees to which the adjustments are being applied (Villalba and Veblen 1997, Wong and Lertzman 2001). By selecting saplings from a range of light and competitive conditions, we successfully captured a wide range of growth rates: mean rates (per disk) ranged from 0.09 to 4.76 mm/year, providing an adequate range for analyses. This range probably represents much of the variability in growth for this species under natural conditions in this region and thus mitigates the potential errors resulting

from failure to meet this assumption. Indeed, this range is quite similar to that of an independent data set of mature trees to which these equations were ultimately applied (0.26–4.92 mm/year, $n = 166$ trees).

Third, our analyses assume that the age determined at the apparent root collar represents the date of establishment. This assumption would clearly not hold for slow-growing, shade-tolerant species, in which the root-shoot interface representing the point of germination (Telewski 1993) may lie well below the apparent root collar. Such situations arise during extremely slow juvenile growth, where overgrowth of the lower stem by moss or other vegetation allows the formation of adventitious roots, which displace the apparent root collar away (upward) from the true root-shoot interface. This situation is further exacerbated by locally absent rings common in this situation, the result of slow growth. For example, samples extracted from lower stems or root collars of slow-growing, shade-tolerant species can yield underestimates of 13 years (Peters et al. 2002), 19 years (DesRochers and Gagnon 1997), 26 years (Niklasson 2002, Parisien et al. 2005), and 35 years (Parent et al. 2002). Although we recognize that the root collar age used in the present study is a potential source of uncertainty, we do not believe this has led to significant errors, owing to the shade tolerance rating of red pine as intermediate (Horton and Brown 1960) to intolerant (Baker 1949), which suggests adequate growth at the juvenile stage. Indeed, seedlings of this species cannot persist for more than a few years under suppressed and competitively stressful conditions (Cook et al. 1952, Van Wagner 1971, Ahlgren 1976). Our analyses would also be inappropriate for species such as oaks (*Quercus*) that repeatedly root- or stump-sprout after crown damage (Larsen and Johnson 1998), thereby obscuring both the determination and the concept of stem age.

Fourth, the application of our equations assumes that the increment core needing adjustment passed through the pith. Cores passing near but not through the pith would require additional adjustment following one of several methods (e.g., Applequist 1958, Duncan 1989, Villalba and Veblen 1997). These methods introduce an additional source of error because they necessarily assume that the absent rings grew at the same rate as some subset of the innermost rings present. Likewise, the application of these equations assumes that the core receiving age adjustment has already been correctly dated by means of cross-dating against a known chronology. Finally, for tree species, such as giant sequoia (*Sequoiadendron giganteum*) whose bole diameter greatly exceeds that of increment borer length, ages can be approximated by regression equations that include tree diameter and the growth rate of the outermost bole segment (Stephenson and Demetry 1995).

Further, when establishment dates are used as proxies for past disturbances, equations such as those developed here are appropriate only for studies involving mid-tolerant or intolerant tree species. When working with shade-tolerant species, abrupt and sustained increases in growth (Lorimer 1985, Fraver and White 2005), not establishment dates, are the appropriate proxies for past disturbances. That is, the

ages of shade-tolerant species, even if they could be correctly determined, are often poorly linked to past disturbances (Lorimer 1985, Veblen et al. 1990, Groven et al. 2002).

Could these equations developed for red pine be used for other species? Because our equations were developed for this one species in a particular setting in Minnesota, their applicability to other species and other settings remains unknown, as this would require independent data of comparable detail. Further, for reasons enumerated above, neither these equations nor any simple adjustment could be used for species that repeatedly root- or stump-sprout after crown damage or for slow-growing, shade-tolerant species. Both Wong and Lertzman (2001) and Gutsell and Johnson (2002) have demonstrated the strong dependence of shade tolerance on the magnitude of age adjustments needed. However, within other shade-intolerant or mid-tolerant pine species, errors resulting from within-stem growth variability (not addressed in these equations) probably overshadow those attributable to species, meaning that in the absence of species-specific data, the use of these equations probably represents an improvement over no age adjustment at all.

In summary, both the height at which an increment core is extracted and the early growth rate of a tree determine the age adjustments needed to estimate the tree's establishment date. Our regression equations, derived from red pine samples growing under a wide range of competitive conditions, thus incorporate both coring height and early growth rate. We developed these equations for the common coring heights of 30 and 140 cm above root collar, and we developed a third equation to cover a continuous range of heights up to 200 cm. Use of the equations clearly improved age estimates: compared with unadjusted ring counts, our adjusted age estimates had normally distributed errors centered near 0, lower standard deviations, and a narrower range of values. These equations can be used to adjust ages of cored, mature red pines occurring in these same settings. Acknowledging a few caveats (above), the method used here may be applied to other shade-intolerant or mid-tolerant species for which improved tree establishment dates are needed. The method is probably best applied to shade-intolerant species for which the root collar age can be assumed to closely approximate the establishment date.

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