ASSESSMENT OF DENDROCHRONOLOGICAL YEAR-OF-DEATH ESTIMATES USING PERMANENT SAMPLE PLOT DATA

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ABSTRACT

We combined crossdating with permanent sample plot (PSP) data to assess the precision and accuracy of year-of-death (YOD) estimates obtained by crossdating white spruce and lodgepole pine snags and logs. Crossdating indicated trees died between 1833 and 2006. Comparison of crossdated YOD dates for pairs of samples ($n = 121$) showed that 90% of YOD estimates were within 10 years of each other. Of 100 trees that died after PSP establishment, 59 YOD dates were within the documented interval of death (IOD). Of the 41 inaccurate dates, 77% of YOD dates preceded the IOD midpoints and error increased with time since death. Regression models increased the accuracy of spruce YOD estimates for trees that had been dead ≥ 17 years, but the corrections were modest (e.g. +5 at 50 years). For pine, the correction models increased accuracy regardless of time since death and corrections were greater than those for spruce (e.g. +4 and +11 at 5 and 50 years, respectively). Precision and accuracy errors resulted from many factors including loss of bark, wood decay, lack of ring formation prior to tree death, and human error. Our results reinforce the need for multiple lines of evidence when reconstructing tree deaths using tree rings. We urge others with access to PSP data to assess the quality of crossdated YOD estimates. Ideally, PSP re-measurements intervals would be short and consistent, facilitating comparisons through time and among genera and locations.

Keywords: crossdating, year of death, accuracy, precision, permanent sample plots, interval of death, *Pinus contorta*, *Picea glauca*, snags, logs.

INTRODUCTION

Coarsewood, including snags (standing dead trees) and logs (uprooted trees, snapped trees, snapped tops, and large branches on the ground), serves myriad ecological functions, but its dynamics are not thoroughly understood (Harmon *et al.* 1986). In order to effectively incorporate coarsewood into stand dynamics models, we require species- and ecosystem-specific understandings of mortality and coarsewood decay rates and processes. Understanding coarsewood decay dynamics requires knowledge of snag and log persistence (*i.e.* time since tree death) and thus year of tree death. Year of death (YOD) can be estimated directly using re-measurements of permanent sample plots and indirectly using dendrochronological analysis.

Permanent sample plot (PSP) studies provide direct observations of dead trees during plot re-measurements; however, the precision of YOD dates is restricted by the length of the re-measurement interval. YOD dates from PSP studies are either reported as an interval (e.g. Vanderwel *et al.* 2006) or assumed to be the midpoint of the re-measurement interval in which a tree died (e.g. Newberry *et al.* 2004). In many PSP networks, the target re-measurement interval is every five years (Lewis *et al.* 2004), but because of resource constraints, re-measurement intervals can vary considerably in length among both plots in a network and within individual plots. For example, mortality studies of permanent sample plots in Denmark revealed variation in re-measurement intervals of 1 to 35 years (Nord-Larsen 2006).

In contrast, dendrochronological analysis provides year-of-death estimates at an annual resolution. YOD estimates are obtained by cross-

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dating the ring-width series of an individual snag or log against a master chronology, which allows the assignment of a calendar year to the outermost ring on the sample. This technique assumes that the outermost ring indeed reflects the year of tree death, which may not be the case when samples are decayed or missing bark (Mast and Veblen 1994; Daniels *et al.* 1997). In addition, the outermost ring may not reflect the year of tree death if a tree is suppressed or declining prior to death (Takaoka 1993; Cherubini *et al.* 2002) or if it exhibits asymmetrical cambial mortality (Amoroso and Daniels 2010).

Dendrochronological methods have been widely used in studies of coarsewood dynamics to determine YOD dates for snags and logs (*e.g.* Daniels *et al.* 1997; Storaunet and Rolstad 2004; DeLong *et al.* 2005, 2008), but dendroecologists rarely have the opportunity to assess the quality of these estimates through comparisons with PSP inventory data. Many studies acknowledge the potential sources of error inherent in working with decayed wood but, to our knowledge, the magnitude of error associated with crossdating decayed wood has never been quantified.

In this study, we use a combination of crossdating and independent PSP data to assess the precision and accuracy of YOD estimates of white spruce (*Picea glauca* [Moench] Voss) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) snags and logs. We addressed two groups of research questions:

1. How precise are YOD estimates? Within a single tree (snag or log), how similar are YOD dates from pairs of cores (snags) or pairs of radii (logs)? When there is a mismatch in YOD dates, what factors contribute to this discrepancy?
2. How accurate are the YOD estimates? How do YOD estimates compare to the reported interval of death dates from the permanent sample plot data? What percent of YOD dates occur within the reported interval of death? What is the magnitude of error of YOD estimates?

We applied the outcomes of the accuracy assessment to develop regression models for

improving crossdated estimates of the YOD of spruce and pine coarsewood for our study area. Ultimately, our intent is to understand the magnitude of different sources of error in YOD, providing a more precise and accurate understanding of coarsewood dynamics.

METHODS

Study Area

This study was conducted in the Hinton Wood Products Forest Management Area of the Foothills Research Institute near Hinton, Alberta (53°24'09"N, 117°34'33"W), east of the Rocky Mountains. In this region, upland forests are characterized by closed-canopy coniferous stands, dominated by lodgepole pine, white spruce, and black spruce (*Picea mariana* (Mill.) BSP). The landscape is a mosaic of mixed-successional pine, pine-white spruce, and white spruce-black spruce stands, created by stand-initiating fires with a historical return interval of 100 years (Beckingham *et al.* 1996).

Between 1956 and 1961, North Western Pulp and Paper (now Hinton Wood Products) established a network of *ca.* 3,000 permanent sample plots (PSPs) that included a range of forest types and stages of stand development (Hinton Wood Products 2006). At plot establishment, all live trees were tagged and tree status (live, snag, log, or missing) was recorded at each re-measurement. The target re-measurement interval for old-growth coniferous PSPs is every five years; however, as many as 34 years have lapsed between successive measurements.

This study focused on five old-growth white spruce (hereinafter "spruce") and five old-growth lodgepole pine (hereinafter "pine") PSPs (Table 1). In the Alberta foothills, old-growth characteristics develop *ca.* 160 years after a stand-replacing disturbance (Morgantini and Kansas 2003). To be included in this study, the PSPs had to meet three criteria:

1. The last stand-replacing disturbance was at least 160 years prior to program establishment in 1956.
2. No stand-level biotic or abiotic disturbances had been noted in the PSP records.

Table 1. Attributes of old-growth white spruce (SA–SE) and lodgepole pine (PA–PE) sites. All data except location were provided by Hinton Wood Products.

Site	Site Cluster	Location	Stand Origin	Plot Establishment	Measurement Dates
SA	S1	53°39'26"N, 118°26'28"W	1741	1958	1958, 1966, 1999, 2008
SB	S2	53°20'14"N, 117°36'29"W	1770	1956	1956, 1962, 1996, 2002, 2008
SC	S3	53°39'31"N, 118°23'33"W	1741	1959	1959, 1966, 1999, 2008
SD	S3	53°39'36"N, 118°23'33"W	1741	1959	1959, 1966, 1999, 2008
SE	S3	53°39'31"N, 118°23'41"W	1741	1959	1959, 1966, 1999, 2008
PA	P1	53°47'35"N, 118°12'03"W	1768	1959	1959, 1966, 1999, 2008
PB	P1	53°46'30"N, 118°12'03"W	1768	1959	1959, 1966, 1999, 2008
PC	P2	53°46'26"N, 117°51'57"W	1741	1961	1961, 1966, 1996, 2002, 2008
PD	P2	53°46'27"N, 117°52'04"W	1741	1961	1961, 1966, 1996, 2002, 2008
PE	P3	53°44'41"N, 118°23'48"W	1710	1958	1958, 1966, 1983, 1996, 2002, 2008

3. At the last re-measurement, PSPs were at least 65% spruce or pine by both basal area and stem density.

We randomly selected 10 study plots (five spruce, five pine) that were accessible and met our criteria (Figure 1, Table 1). All plots have stand origin dates of 1710 to 1770, based on interpretation of fire and forest cover maps. Six of the plots (SA, SC–SE, PA, PB) were re-measured four times (including the initial measurement and 2008),

three were re-measured five times (SB, PC, PD), and one was re-measured six times (PE). Re-measurement intervals ranged from 5 to 34 years with an average of 14.0 ± 3.7 (mean $\pm$ standard deviation) years.

Field Sampling

To build species- and site-specific tree-ring chronologies, we extracted increment cores from living canopy-dominant trees at all six PSP clusters. Trees were sampled outside the boundaries of the PSPs to ensure the integrity of these long-term monitoring plots and, when there was more than one study plot in a PSP cluster (e.g. CS3; see Table 1), we sampled trees between the plots when possible. We extracted a single core per tree, ≤ 30 cm above the ground. We cored *ca.* 30 trees per PSP cluster, depending on core quality.

We located all trees in each plot and identified each as living or dead, and subsequently as a snag or log. For each piece of coarsewood, we identified species and assessed decay class, using a nine-stage decay classification for snags (Table 2; Thomas *et al.* 1979) and a five-stage decay classification system for logs (Table 2; Maser *et al.* 1979). We restricted this study to spruce coarsewood in spruce sites and pine coarsewood in pine sites.

All snags included in this study were ≥ 7.0 cm in diameter at breast height (dbh) and either had their original tag or their identity could be established using the PSP data. We collected two increment cores per tree from a stratified random

Figure 1. Old-growth white spruce (SA–SE) and lodgepole pine (PA–PE) study plots in the Hinton Wood Products Forest Management Area of the Foothills Research Institute.

Table 2. Snag and log decay classes based morphology and structural integrity of the bole (after Thomas *et al.* 1979, Maser *et al.* 1979).

Coarsewood Type	Decay Class	Characteristics
Snag	1	Live; in good health
	2	Live; declining
	3	Dead; bark intact, sound wood, fine branches present, needles may be present
	4	Dead; bark sloughing, sound wood, fine branches absent, sapwood beginning to soften
	5	Dead; bark mostly absent, heartwood sound, sapwood rotting
	6	Dead; bark absent, heartwood beginning to rot, sapwood rotting, broken top
	7	Dead; decomposing, heartwood and sapwood rotting, still standing
	8	Dead; decomposing, mostly downed material, heartwood and sapwood rotting
	9	Dead; decomposing stump
Log	1	Solid log, sapwood and heartwood sound; branches present; needles may be present; bark fully intact
	2	Structurally-sound log, sapwood beginning to decompose; bark has begun to fall off
	3	Sections of sapwood in advanced stages of decay; log round and supports own weight; little bark remaining
	4	Heartwood decay; log resting on ground and cannot support its own weight; pieces easily slough off; moss often present on outer surface
	5	Advanced decay; log incorporating into the forest floor; powdery texture

subsample of snags. Up to four snags per decay class were sampled at each site, limited by the number of snags in each represented decay class. Where possible, cores included the bark and avoided basal scars and other anomalies. We collected increment core samples from a total of 75 snags.

Logs included uprooted trees, snapped trees, snapped tops, and large branches. Tags were found on only 31% of the logs, and the study was restricted to these tagged logs. To be included, a log had to be ≥ 7 cm in diameter at mid-length, ≥ 1 m in length, and at least 50% of the log had to be within the plot boundaries. Using a chainsaw, we collected a single cross-sectional disc from each of a stratified random subsample of logs. Up to four logs per decay class were sampled at each site, limited by the number of tagged logs in each represented decay class. Samples were taken from the most structurally sound section of the log and included bark and solid sapwood where possible. Cross-sections were reinforced with duct tape before sampling to ensure integrity of the sample. We collected cross-sectional discs from a total of 57 logs.

Dendrochronological Analyses

We mounted all cores on wooden supports and reinforced discs from logs with hot glue as

needed. All samples were sanded using progressively finer sandpaper to 600 grit before viewing the rings with a microscope (Stokes and Smiley 1996). To develop master chronologies, each core was visually crossdated and ring-width series were measured to the nearest 0.001 mm using a Velmex bench interfaced with MeasureJ2X V3.2.1 measuring software (VoorTech Consulting, Holderness, NH). The ring-width series were statistically crossdated using the program COFECHA (Holmes 1983; Grissino-Mayer 2001) and accurately dated and highly correlated cores were combined in site- and species-specific master chronologies. The chronologies were standardized using the horizontal standardization option in the program ARSTAN (Cook 1985).

All cores from snags were measured to the nearest 0.001 mm and two radii were measured per disc from logs. Radii were selected based on series length and the presence of bark and intact sapwood. To estimate year of tree death for both snags and logs, we used COFECHA (Holmes 1983; Grissino-Mayer 2001) and the Time Series Analysis Programme (TSAP-Win, Rinn 2003) to statistically crossdate the ring-width series and assigned a calendar year to the outermost ring of each sample. To verify crossdating, we used the Math Graph function of TSAP-Win to visually compare the ring-width series of the individual

cores against the standardized ring-width series of the appropriate chronologies.

Precision: YOD Estimates from Pairs of Cores and Pairs of Radii

We compared the outermost ring date from pairs of cores and radii to identify discrepancies in crossdated YOD dates related to sample quality and decay, missing bark, narrow outer rings, and asymmetrical cambial death. We labeled each outermost ring date in a pair; the more recent of the two dates became year₁ (core₁ or radius₁) and the other date became year₂ (core₂ or radius₂). Precision error was the difference between year₁ and year₂. By definition, it was always a positive value.

Accuracy: YOD Dates *versus* PSP Data

When there was a discrepancy in YOD dates from pairs of cores or pairs of radii, we used the more recent YOD date to estimate the year of tree death. Time since death was calculated as 2008 minus the YOD, and is equivalent to snag and log age (the number of years a tree had been dead). For trees that died after plot establishment (1956–1961, Table 1), we verified YOD dates by comparing them to the recorded interval of death (IOD) from the PSP data. We restricted further analyses to trees that died after plot establishment as we could not calculate the magnitude of error of YOD estimates for trees that died prior to plot establishment. The IOD was defined as follows: the upper limit was the re-measurement year in which the tree was recorded as dead and the lower limit was the preceding re-measurement year. We compared the estimated YOD date with the recorded IOD dates for each snag and log and calculated the number of YOD dates that occurred within, before, and after the observed IOD dates.

The magnitude of error for accuracy was also assessed. Because exact years of death were not recorded in the PSP data and census intervals varied in length, we defined accuracy error in two ways. First, the IOD midpoint minus the YOD estimate yielded positive/negative error values for

YOD estimates that preceded/followed the IOD midpoint. This was a “conservative” estimate of accuracy error as it assumed the midpoint of the IOD was the actual YOD and that all departures from that year represent an error. Second, the crossdated YOD estimates that were within the IOD were classified as accurate, and YOD estimates that were before or after the IOD were classified as inaccurate. Accuracy error (IOD midpoint minus the YOD estimate) was calculated only for inaccurate YOD estimates. This was a “liberal” estimate of error as it was calculated using only the subset of observations outside the IODs.

Corrections of Accuracy Error

We used linear regression to quantify the degree to which accuracy error increased with time since death, then developed models to correct the crossdated YOD estimates and improve accuracy. These analyses were conducted for the two genera using the snag and log data combined to maximize the sample size. Four correction models were tested for each genus:

$$YOD_1 = YOD + (b_0 + b_1(YOD)) \quad (1)$$

where, YOD₁ is the corrected YOD; YOD is estimated by crossdating; and, b₀ and b₁ are the coefficients from the genera-specific linear regression of accuracy error on year of death using the “conservative” error estimates (e.g. IOD midpoint minus YOD, for all YOD estimates).

$$YOD_2 = YOD + (b_0 + b_1(YOD)) \quad (2)$$

where, YOD₂ is the corrected YOD; and, the coefficients b₀ and b₁ are from the genera-specific linear regression of accuracy error on year of death using the “liberal” error estimates (e.g. IOD midpoint minus YOD, for inaccurate YOD estimates only).

$$YOD_3 = p_{\text{accurate}}(YOD) + p_{\text{inaccurate}}(YOD_1) \quad (3)$$

where, YOD₃ is the corrected YOD; p_{accurate} is the proportion of YOD estimates determined by crossdating (YOD) that were within the

Table 3. Summary statistics for site-specific white spruce (CS1–CS3) and lodgepole pine (CP1–CP3) master ring-width chronologies.

Chronology	Number of Trees	Mean Series Length (years)	Chronology Start	Chronology End	Series Intercorrelation	Average Mean Sensitivity
S1	29	258	1695	2007	0.61	0.19
S2	30	96	1889	2007	0.60	0.21
S3	28	262	1709	2007	0.64	0.18
P1	26	171	1774	2007	0.50	0.17
P2	32	163	1730	2007	0.49	0.21
P3	26	111	1718	2007	0.52	0.18

IOD; $p_{\text{inaccurate}}$ is the proportion of crossdated YOD estimates that preceded or followed the IOD; and, YOD_1 is the corrected YOD derived from the linear regression of the “conservative” error estimates using equation (1).

$$\text{YOD}_4 = p_{\text{accurate}}(\text{YOD}) + p_{\text{inaccurate}}(\text{YOD}_2) \quad (4)$$

where, YOD_4 is the corrected YOD, and YOD_2 is the corrected YOD derived from the linear regression of the “liberal” error estimates using equation (2).

We used two criteria to evaluate the quality of the original crossdated YOD estimates and corrected YOD estimates derived from each model for each genus. First, we determined the percentage of corrected YOD estimates that were within the IOD and deemed accurate (large percentage values indicate high accuracy). Second, we conducted goodness of fit tests using a chi-squared (X^2) test statistic in which the YOD estimates were the observed values and the IOD midpoints were the expected values (low X^2 values indicate high accuracy).

RESULTS

Chronology Development

We developed six chronologies, three for spruce and three for pine. Summary statistics for the chronologies indicated that trees within a site responded similarly to variation in environmental factors (Table 3). Series intercorrelation values ranged from 0.49–0.64, suggesting that crossdating within each chronology was robust and suitable for estimating years of tree death.

Precision: Comparison of YOD Estimates within Trees

We successfully crossdated and obtained YOD estimates for 71 of 75 snags, which ranged from 1840–2006 for spruce and 1866–2002 for pine. YOD estimates were obtained for both cores for 69 snags. The YOD dates from 13 pairs of cores from spruce snags were the same, while the remaining 19 pairs differed by 1–16 years, 90% of which differed by ≤ 5.9 years (mean = 2.3, median = 1.0 years; Figure 2). For pines, five pairs of cores had the same YOD dates and 32 pairs differed by 1–63 years (mean = 8.8, median = 3.0 years). Three pairs of cores from pine snags were outliers that differed by 52, 54, and 63 years. After re-evaluating these cores we confirmed the second core of each pair was missing its bark and/or sapwood and the structure and colour of the wood indicated decayed sapwood in two cores. The other pairs of cores from pine snags differed by less than 24 years, 90% of which differed by ≤ 8.7 years (mean = 4.6, median = 3.0 years), which was similar to the other coarsewood types.

We successfully crossdated and obtained YOD estimates for 54 of 57 logs, which ranged from 1833–2008 for spruce and 1906–2002 for pine. YOD estimates were obtained for both radii for 52 logs. The YOD dates from nine pairs of radii from spruce logs were the same, while the remaining 20 pairs differed by 1–32 years, 90% of which differed by ≤ 8.2 years (mean = 4.0, median = 1.0 years; Figure 2). For pines, four pairs of radii had the same YOD dates and 19 pairs differed by 1–18 years, 90% of which differed by ≤ 8.0 years (mean = 3.9, median = 3.0 years). Scatter plots of time since death vs. precision error

Figure 2. Precision and accuracy errors by genera and coarsewood type. Precision error is the difference in pairs of YOD dates from the same tree and is always positive. Accuracy error is the IOD midpoint minus the YOD estimate and includes positive (YOD precedes the IOD midpoint) or negative (YOD follows the IOD midpoint). In each panel, the mean and median values are indicated by the vertical dashed lines. In the accuracy error panels, the midpoint is indicated by the vertical solid line.

($\text{year}_1 - \text{year}_2$) did not reveal a trend between the magnitude of error and time since death for both genera and coarsewood types (data not shown).

Accuracy: Assessment YOD Dates *versus* PSP Data

For the subset of 58 snags that died after the establishment of the PSPs, YOD estimates for spruce snags (70% within the IOD) were more accurate than for pine snags (49% within the IOD) (Figure 3). On average, YOD estimates preceded the IOD midpoint by 4.2 years for spruce

(accuracy error = -13 to 41 years) and 11.9 years for pine (accuracy error = -3 to 39 years; Figure 2). Most YOD estimates occurred before the IOD midpoint (61 and 94% of spruce and pine, respectively), suggesting that the corresponding time-since-death values are overestimated.

Similar to the snags, for the subset of 42 logs that died after the establishment of the PSPs, YOD estimates for spruce logs (74%) were more accurate than pine logs (47%) (Figure 3). Spruce YOD estimates preceded the IOD midpoint by 3.3 years on average (accuracy error = -23 to +34 years), with 57% of YOD estimates preceding

Figure 3. Comparison of intervals of death (IOD) from permanent sample plots and year of death (YOD) determined by crossdating for pine (top, circles) and spruce (bottom, triangles). Genera-specific regression models (equations (1) and (4)) were used to derive corrected YOD estimates (middle and right panels). In each panel, the shaded boxes depict the re-measurement intervals for the permanent sample plots. White and black symbols are snags and logs, respectively. Symbols located in the shaded boxes represent accurate YOD estimates relative to the IOD. The X^2 goodness of fit statistic quantifies difference between each YOD estimate and the midpoint of the IOD.

the IOD midpoint. Most (90%) of the pine YOD estimates preceded the IOD midpoint and resulted in average overestimates of time since death of 10.0 years (accuracy error = -9 to +53 years). YOD determined by crossdating commonly preceded the recorded IOD for all re-measurement intervals, including recent intervals (1996–2002, 1999–2008, 2002–2008) and the early intervals (1958–1966, 1961–1966; Figure 3). Accuracy error increased significantly with time since death for pine and spruce (Figure 4). The regression models for pine met the assumptions of homogeneity of variance and normality; the models for spruce did not meet the assumption of normality even after transforming the data. For spruce, the normal

probability plots for the untransformed data approximated a linear relationship but included small departures, which limits predictive inferences from the coefficients and confidence limits but allows descriptive interpretation (Neter *et al.* 1996), as follows. For both genera, correction models 1 and 2 systematically underestimated YOD values from recent intervals and overestimated YOD values from the early intervals (Figure 3). The underestimates were particularly pronounced for spruce as the regression models included negative accuracy error values for $YOD \geq 1992$ (Figure 4), so that corrected YOD values preceded the crossdated YOD values, falsely indicating the trees died before the last ring was

Figure 4. Genera-specific regressions of accuracy error relative to year of death (YOD). Regression model 1 (top) was based on the “conservative” errors for all snags and logs of pine (circles, solid line) and spruce (triangles, dashed line). Regression model 2 (bottom) was based on “liberal” errors for the subset of snags and logs for which crossdated YOD was outside the interval of death.

formed. We addressed this bias by applying correction models 3 and 4 only to spruce with $\text{YOD} \leq 1991$ (e.g. time since death ≥ 17 years). Model 4, the model derived using the “liberal” estimates of error and weighted to account for accurate crossdated YOD estimates, yielded the highest accuracy and lowest X^2 values, indicating it provided the best corrections for YOD for both genera (Figure 3, Table 4). The improvements for spruce that had been dead ≥ 17 years were modest, with corrections of +2 and +5 years (based on model 4) for coarsewood that had been dead 25 and 50 years, respectively. For pine, the improvements applied to all coarsewood and were more substantive. Corrections were +4, +7 and +11 for pine coarsewood that had been dead 5, 25 and 50 years, respectively.

DISCUSSION

Precision of YOD Estimates

By combining our crossdating outcomes with the independent data from permanent sample plots, we assessed the precision and accuracy of estimated years of death for white spruce and lodgepole pine trees. In our study, the variation in outer-ring dates of different radii within a single snag or log represents the precision of year of death estimates. Overall, 31 of 121 pairs of samples were precise, meaning the YOD estimates matched for pairs of cores from snags and radii within logs. The differences between cores and radii measured the magnitude of error in precision within individuals. These differences were generally small, with 90% within 10 years of each other,

Table 4. Comparison of models to improve accuracy of year-of-death (YOD) estimates. A high percent accuracy and low X^2 value indicated the best model for accurately estimating YOD.

Genus	Model	Accuracy (%)	Fit (X^2)
Pine	YOD = determined by crossdating (no correction)	48	7.0
	$YOD_1 = YOD + (796.3 - 0.4(YOD))$	55	2.7
	$YOD_2 = YOD + (608.8 - 0.3(YOD))$	57	3.0
	$YOD_3 = (0.48)(YOD) + (0.52)(YOD + (796.3 - 0.4(YOD)))$	61	4.1
	$YOD_4 = (0.48)(YOD) + (0.52)(YOD + (608.8 - 0.3(YOD)))$	72	2.8
Spruce	YOD = determined by crossdating (no correction)	72	4.1
	$YOD_1 = YOD + (997.1 - 0.5(YOD))$	63	1.9
	$YOD_2 = YOD + (1183.4 - 0.6(YOD))$	58	4.4
	$YOD_3 = (0.72)(YOD) + (0.28)(YOD + (997.1 - 0.5(YOD)))$	78	3.0
	$YOD_4 = (0.72)(YOD) + (0.28)(YOD + (1183.4 - 0.6(YOD)))$	78	2.9

indicating a relatively high degree of precision for most snags and logs. The small differences within pairs of YOD estimates were expected because we were primarily working with trees that had retained their tags, and we aimed to collect samples that included the bark or sound sapwood, meaning that at least part of the tree was not substantially decayed. As illustrated by the three pine snags with precision errors exceeding 50 years, snags and logs in more advanced stages of decay can have a larger mismatch in YOD dates. Consequently, we would not expect to see such a high correlation in paired YOD dates for all snags and logs at our study sites, particularly those missing their tags or those that were in advanced stages of decay having died before the PSPs were established. Nevertheless, the outcome of this analysis indicates that most YOD dates we obtained from crossdating closely represent the calendar year of a tree’s outermost ring, making these samples suitable for comparison to the PSP IOD dates.

Accuracy of YOD Estimates

Comparison between the best YOD estimate and the IOD derived from repeated measures of permanent plots allowed us to assess the accuracy of our crossdating results in two ways: (1) by classifying each YOD date as accurate *versus* inaccurate and (2) by comparing the YOD date relative to the midpoint of its IOD. Overall, 59 of 100 YOD dates were classified as accurate, meaning the YOD estimate occurred within the

documented IOD. Of the 41 inaccurate results, 39 YOD estimates preceded the observed IOD. Similarly, most (77%) YOD dates preceded the IOD midpoints yielding positive accuracy errors. These skewed outcomes were unexpected. We had expected tree deaths would occur randomly through time so that accuracy errors would be evenly distributed around the IOD midpoints. Underlying this expectation, we assumed that tree deaths were caused by background mortality in absence of stand-level disturbances and the crossdated YOD dates had no systematic errors. Field records for the PSPs indicated windstorms and fires affected some PSPs, but not those included in our study. Therefore, we sought to understand the systematic underestimates of the YOD dates.

Consistent with the skewed frequency distributions, the regressions showed that accuracy error increased significantly with TSD, with subtle differences between genera. The general trend of decreased accuracy with time is consistent with well-documented processes of coarsewood decomposition. For the pine and spruce coarsewood that we studied, decay progresses from loss of needles, branches and bark to decay of the sapwood and heartwood (Newberry *et al.* 2004; DeLong *et al.* 2005, 2008; Powell *et al.* 2009). Different parts of the bole can decay at different rates, so even snags and logs in advanced stages of decay may have solid sections that can be dated accurately. However, as wood decomposes and outer rings are lost through time, the accuracy of crossdated YOD estimates decreases (Dynesius and Jonsson

1991; Daniels *et al.* 1997). For spruce in our study area, there appears to be *ca.* 17-year lag after death before ring loss causes predictable errors in YOD estimates and corrections were modest (*e.g.* +2 and +5 years after 25 and 50 years, respectively). In contrast, corrections improved accuracy for pine YOD dates regardless of time since death and the corrections were more substantive (*e.g.* +4, +7 and +11 after 5, 25 and 50 years, respectively). These results may indicate more rapid onset of decay and loss of the outer rings of pine relative to spruce, although our previous research did not detect differences in decay rates between genera for logs that had been dead <50 years (Jones 2009; Powell *et al.* 2009). Alternatively, this difference may relate to the unexpected, high frequency of accuracy errors for trees that died during the 1990–2000s. Most pines (12 of 18), but only some spruces (3 of 16), had YOD estimates that preceded the 1999, 2004 and 2005 IOD midpoints by up to 30 years. Because these snags and logs were not in advanced stages of decay, these inaccuracies suggest that some trees in our study had not formed rings in the years prior to death.

Sources of Error in YOD Estimates

The observed imprecision and inaccuracy in the YOD dates were attributed to combinations of several potential factors: (1) missing bark, (2) decayed sapwood, (3) highly suppressed outer rings, (4) asymmetrical cambial mortality, (5) lags between cessation of ring formation and tree death, (6) crossdating errors, and (7) errors in PSP data. The first two factors relate to sample quality caused by the stage of decomposition of the coarsewood. Although we attempted to sample all snags and logs using only radii that included bark and sound sapwood, poor sample quality caused by decomposition explains some discrepancies in pairs of YOD dates and crossdating inaccuracies. Consistent with our sampling protocols, only 6% of spruce and 15% of pine snags were missing bark or showed signs of decayed sapwood when processed in the lab. Low sample quality may be a more significant cause of error for logs, as 33% of spruce and 54% of pine logs were in advanced stages of decay and identifying

two high-quality radii with bark and sound sapwood was difficult or not possible. For the latter logs, we compromised and assessed radii from the least decayed and most intact part of the bole, but it contributed to imprecision within individuals. These outcomes illustrate the importance of supplementary assessments of sample quality, such as the presence of the bark or evidence of sapwood decay, when estimating YOD dates from tree rings.

Tree growth prior to death can influence YOD estimates reconstructed using dendrochronology. Prolonged and severe radial growth suppression prior to death may result from competition and self-thinning in forests (Kozlowski *et al.* 1991; Takaoka 1993), senescence of old trees (Kelly *et al.* 1992; Larson *et al.* 1993), climatic variation causing stress (Villalba and Veblen 1998; Bigler *et al.* 2007; Drobyshev *et al.* 2007), damage caused by biotic disturbance (Cherubini *et al.* 2002), or combinations of these factors (Pederson 1998; Bigler *et al.* 2004). Highly suppressed outer rings are difficult to visually crossdate and measure (Mast and Veblen 1994). In extreme conditions, it is possible that trees do not allocate carbon to radial growth; thus, the calendar year of the outermost ring does not accurately indicate the year of tree death (Marchand 1984; Cherubini *et al.* 2002; Parent *et al.* 2002; Amoroso and Daniels 2010). Alternatively, stressed or declining trees may exhibit locally absent rings during periods of suppression (Mast and Veblen 1994; Cherubini *et al.* 2002) or asymmetrical cambial mortality (Kelly *et al.* 1992; Daniels *et al.* 1997; Amoroso and Daniels 2010) so that rings are incomplete around the circumference of the bole, resulting in imprecise or inaccurate YOD estimates.

In our study, most tree deaths seemed to result from stand-development processes including competition, self-thinning and senescence, because there was no record of stand-level biotic or abiotic disturbances affecting our study sites. In absence of specific disturbance agents (*e.g.* pathogens or insects), pine appeared to be more susceptible than spruce to stress that resulted in a cessation of ring formation prior to death and which led to the systematic underestimates of YOD by crossdating.

Given these findings, we concur with recommendations that analysis of multiple increment cores or full cross-sections will increase the probability of determining the actual year of tree death using dendrochronology (Amoroso and Daniels 2010). For our study area, application of the genera-specific correction models can improve accuracy of crossdated YOD estimates, although additional work is needed to improve the spruce models to meet all statistical assumptions.

Lastly, human error also may have contributed to imprecision and inaccuracies. Although we used a combination of crossdating techniques and assigned outer-ring dates independently to each core, we cannot eliminate the possibility that some crossdating outcomes were incorrect. For some ring-width series, more than one potential outer-ring date was identified using COFECHA. We differentiated among possible outcomes using TSAP-Win statistics and graphics and by assessing the alignment of narrow and wide marker rings by visual crossdating (Cherubini *et al.* 2002). Nevertheless, incorrect YOD dates may have been assigned to some samples. Alternatively, mistakes while recording data in the field or entering the data in the lab would cause errors in the PSP records.

Limitations of the PSP Data for Assessing Accuracy

Although comparison of crossdated YOD dates with the PSP was insightful, it did have limitations that could be overcome in future research. Ideally, PSP re-measurements would be conducted consistently at short intervals (*e.g.* every 5 years) for results to be directly comparable through time. In this study, however, the PSP intervals varied from 5–34 years, with short intervals in the 1950–1960s and 1990–2000s (<10 years) but long intervals from the 1960–1990s (13–34 years). Given the large variation in interval lengths, we expected that accuracy would vary through time. Consistent with this expectation, accuracy of pine YOD dates was greater during the long intervals (19 of 27, 70%) than the short intervals (1 of 9, 11% in the 1950–1960s and 6 of 18, 33% in the 1990–2000s). In contrast, for

spruce, accuracy was greatest during the short intervals in the 1990–2000s (13 of 16, 81%), followed by long intervals in the 1960–1990s (17 of 22, 73%), and least accurate during the short intervals in the 1950–1960s (4 of 8, 50%). This difference between genera is consistent with our interpretation that pine was more susceptible than spruce to cessation of ring formation prior to death.

CONCLUSIONS AND RECOMMENDATIONS

Crossdating provides annually-resolved estimates of YOD for snags and logs, but these outcomes are not always precise (consistent between samples from a single tree) and accurate (crossdated YOD is the actual year of death). Comparison of crossdated YOD dates for pairs of cores from snags or radii from logs showed that 90% of YOD estimates were within 10 years of each other, indicating a relatively high degree of precision for spruce and pine that had been dead ≤ 50 years in our study area. For future studies based on a single radius from coarsewood, we recommend grouping YOD dates into classes that are at least 10-years wide to account for precision error.

Comparison of crossdated YOD dates with the IOD recorded in PSP records showed that accuracy was greater for spruce than pine in our study area. Correction models improved the accuracy of spruce YOD estimates only for trees that had been dead ≥ 17 years and the resulting corrections were modest (*e.g.* +5 years after 50 years); however, these models have limited application beyond comparative analysis with pine because they did not meet the assumption of normality. Cessation of ring formation prior to death, likely caused by competition and senescence, was more prevalent in pine, resulting in correction models that improved accuracy of YOD dates regardless of when trees died and more substantive corrections through time (*e.g.* +4 and +11 years after 5 and 50 years, respectively). We recommend using the error correction model for pine coarsewood in similar environments and urge others to develop genus- and environment-specific corrections when possible.

Precision and accuracy errors resulted from many factors including loss of bark, wood decay, lack of ring formation around the bole caused by stress prior to death, and human error. Our results reinforce the need for multiple lines of evidence when reconstructing tree deaths using tree rings. In general, precision and accuracy of crossdated YOD estimates can be improved by (1) assessing only radii that include bark and sapwood, (2) assessing multiple radii around the bole of coarsewood, (3) verifying crossdating outcomes with supplemental field notes on snag or log morphology, such as decay class or presence of bark and sapwood, (4) considering the cause of tree death and its potential impacts on ring formation prior to death, and (5) using multiple crossdating techniques. Ideally, when comparing crossdating outcomes to data from PSPs, the re-measurement intervals would be short and consistent, maximizing comparability through time. This would also facilitate comparisons among genera and locations.

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