

ORIGINAL ARTICLE

Assessing bias in diameter at breast height estimated from tree rings and its effects on basal area increment and biomass



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ARTICLE INFO

Keywords:

Forest ecology
Dendrochronology
Dendroecology
Basal area increment
Biomass
Tree growth

ABSTRACT

Above-ground forest productivity can be reliably estimated from tree-ring width measurements. In doing so, annual growth is linked to the tree's basal area increment (BAI), which is the change in cross-sectional area associated with each annual ring. When BAI is estimated from ring-width series, a value for the diameter of the tree is required. This diameter is ideally measured in the field, but can also be estimated as the sum of the annual ring widths. Tree biomass can also be estimated directly from the diameter estimates derived from tree-rings. Summing the ring widths, however, typically underestimates the tree's true diameter. To evaluate this potential bias in diameter, we compared field-measured diameter and diameter estimated from the sum of the ring widths using tree-ring chronologies for seven common species in the eastern United States. We then evaluated the impacts of using the biased diameter estimates on derived BAI and biomass values. To simulate field-sampling error (i.e., failure to reach the pith when obtaining a core sample), we re-calculated BAI and biomass after removing a portion of the innermost rings from each tree. Comparisons of these various methods quantify the substantial and consistent underestimations in forest productivity estimates. To reduce the bias in diameter when using ring widths, we developed a regression model to adjust the diameter using core samples. This model is predicated on having some field-measured diameter values available at a site to calibrate and validate the model, but it can then be used to produce estimates at similar sites with similar species where no field-measured diameter values are available. Values of BAI and biomass derived from model-estimated diameter were more accurate at representing absolute growth than values produced by using the sum of the ring widths. Assessing the interannual variations in tree-growth is dependent on having metrics that accurately reflect the area and mass of wood produced. Our results suggest that published estimates of BAI and biomass using the sum of the ring widths to estimate diameter have substantially underestimated these productivity metrics. Our new procedure allows for more reliable estimates of productivity metrics that use diameter-at-breast height derived from tree rings.

1. Introduction

The annual change in cross-sectional area of a tree stem, known as the basal area increment (BAI), is a widely used estimate of absolute growth and biomass (West, 1980; LeBlanc, 1990; Biondi and Qeadan, 2008). Basal area increment is often used to calculate total biomass and has been suggested as a reliable estimate of above-ground forest productivity (Belmecheri et al., 2014; Klesse et al., 2016; Babst et al., 2018), with BAI-based allometric equations being used to estimate total annual above-ground biomass at both the tree and stand levels (Jenkins, 2004; Foster et al., 2014). The relative ease of obtaining this metric using tree-rings makes BAI an attractive measure of annual growth. Used in

this way, BAI calculated from tree-rings also allows for long-term reconstructions of forest and stand biomass (Babst et al., 2018). In addition to the simplicity of the calculation, the massive global database of tree ring widths from the International Tree-ring Databank (ITRDB; (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>), which houses over 4000 chronologies of tree ring width from six continents, makes BAI estimated from ring-widths an attractive metric. However, the appropriateness of BAI as a growth metric is dependent on having an accurate value for tree-stem diameters, which are often not available, particularly for the ITRDB.

When the field-measured diameter is lacking, tree diameter can be calculated by doubling the sum of the annual ring widths (i.e., by

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Table 1

Site-species chronology data. PMMF = Pioneer Mothers Memorial Forest, Indiana. GW = Goll Woods, Ohio. ISC = Interseries correlation.

ID	Species	Site	Lat	Lon	No. of trees	No. of cores	ISC
CAOV	<i>Carya ovata</i>	PMMF	38.54	-86.45		12	0.58
QURU	<i>Quercus rubra</i>	PMMF	38.54	-86.45	25	45	0.59
ACSA	<i>Acer sacharrum</i>	PMMF	38.54	-86.45	10	20	0.51
LITU	<i>Liriodendron tulipifera</i>	PMMF	38.54	-86.45	20	22	0.60
QUAL	<i>Quercus alba</i>	PMMF	38.54	-86.45	22	29	0.58
JUNI	<i>Juglans nigra</i>	PMMF	38.54	-86.45	12	22	0.60
QUAL	<i>Quercus alba</i>	GW	41.55	-84.36	9	18	0.63
QUMA	<i>Quercus macrocarpa</i>	GW	41.55	-84.36	8	16	0.52
CAOV	<i>Carya ovata</i>	GW	41.55	-84.36	8	15	0.53

assuming that the core's full length is the tree's radius). While using the sum of the ring widths to estimate tree-stem diameters allows for the use of samples with no diameter measurements available, this method may be problematic. If one fails to reach the pith while obtaining a core sample, then the resulting increment core will not represent the full radius of the stem. This scenario is common during dendrochronological fieldwork due to either sampling error or the presence of heart rot. Indeed, recent studies integrating BAI and forest biomass have noted consistent underestimations when using increment cores to estimate diameter and BAI (Klesse et al., 2016; Babst et al., 2018; Dannenberg et al., 2020). Pith-locators have been commonly used in dendrochronological studies to estimate the distance to the pith using the curvature of the inner rings, however this process is somewhat labor intensive, requires access to the physical samples or high resolution images of those samples, and may not provide accurate estimates. An additional problem is that tree radial growth occurs asymmetrically around the stem. Thus, the sum of the increment core ring widths may deviate from the true radius of the stem depending on the degree of asymmetry. The proportional method for reconstructing historical stem diameter, proposed by Bakker (2005), attempts to solve this issue by multiplying the current stem diameter by the proportion of the increment core ring width sum that occurs before the historical date of interest. However, this method does not address any biases introduced by the aforementioned lack of inner rings.

While these biases have been documented in a few species, it remains a common practice to use increment cores to estimate tree-stem diameter. Here, we explore the impact of these introduced biases across different species and also evaluate the extent to which the bias influences BAI and biomass estimates. If these biases are systematic, they also should be predictable based on the geometric principles of tree growth. Given the recognized biases of using increment cores to estimate tree-stem diameter, the objectives of this study are a) to systematically quantify the bias in estimating diameter from tree-rings for a range of eastern deciduous species, b) to quantify the resulting biases when using tree-ring estimated diameter to calculate BAI and biomass and c) to develop a model that is calibrated using a site with field-measured DBH to produce better diameter, BAI, and biomass estimates at sites where field-measured DBH is lacking.

2. Methods

2.1. Tree ring data

We used published ring-width chronologies for six different species that were developed from Pioneer Mothers Memorial Forest, Indiana (Maxwell et al., 2015; Maxwell et al., 2016; Au et al., 2020; Maxwell et al., 2020) and three newly sampled chronologies from Goll Woods Preserve, Ohio (Table 1). A single diameter-at-breast-height (DBH) measurement was taken for each sampled tree at both sites. Diameter-at-breast-height measurements were taken at standard height (1.37 m) above ground. For the newly collected samples, we used standard field sampling and laboratory methods (Stokes et al., 1968; Fritts, 1976) that were identical to those used for the Pioneer Mothers

samples. We targeted at least ten canopy dominant trees for each species and used a hand-held increment borer to extract core samples. For the majority of trees, two cores per tree were obtained per tree. We mounted the samples in wooden mounts and sanded them with progressively finer-grit sandpaper until the ring structure was visible under a microscope. We then visually crossdated the samples using the list method (Yamaguchi, 1991) and statistically verified the visual crossdating using the program COFECHA (Holmes, 1983). Cores from the same tree were averaged to reduce the effects of stem asymmetry. All analyses were performed twice, using both a single core per tree, or averaged cores from the same tree for those from which two were obtained. Unless otherwise stated, we report only the results for the averaged cores here because the results did not change and this is standard dendrochronological practice.

2.2. Diameter Bias

Using the data from Pioneer Mothers Memorial Forest (PMMF), we compared the field-measured diameter of the trees to the diameter estimated using the sum of the tree rings from the increment cores. We measured the ring widths from each core and, after crossdating, used the sum of the ring widths as an estimate of tree radius. This value was then doubled to estimate tree diameter. We then subtracted the double of the sum of the ring widths from the field-measured diameter to produce a "difference error" value. This error was compared to published estimates of bark width for given species (Thomas and Bennett, 2014), in order to rule out the possibility that the difference error is the result of an overestimation by including the width of the bark in DBH measurements. We then statistically and visually assessed the relationship of the difference error to tree size.

2.3. Basal area increment bias

Basal area increment calculations were all performed from the outside-in (bark to pith), using the "dplr" R program library (Bunn, 2008). To create site-level BAI chronologies, we first calculated BAI at the individual tree core (series) level, then averaged BAI across all series at each site. To examine the influence of diameter bias in BAI estimates, we created multiple site chronologies using the data from PMMF. The first BAI estimate, which we presume to be "correct", was calculated using the field-measured DBH values. The second version was computed using twice the sum of the ring widths (i.e., two times the radius of the tree). To model how BAI changes with increasing missing rings, we then simulated additional field-measurement error due to a misaligned core, asymmetric growth, or heart rot by subtracting the innermost 10 and 20 rings of each ring-width series respectively to create three additional estimates of BAI (four versions for both the conventional method of calculating the area of each ring by subtracting subsequent ring widths from the diameter, and the aforementioned proportional method, for a total of 8 estimates). We compared the different versions of BAI estimates visually and statistically by quantifying difference measures.

Basal area increment is sometimes detrended to remove the increasing biological growth trend related to the increase in tree size

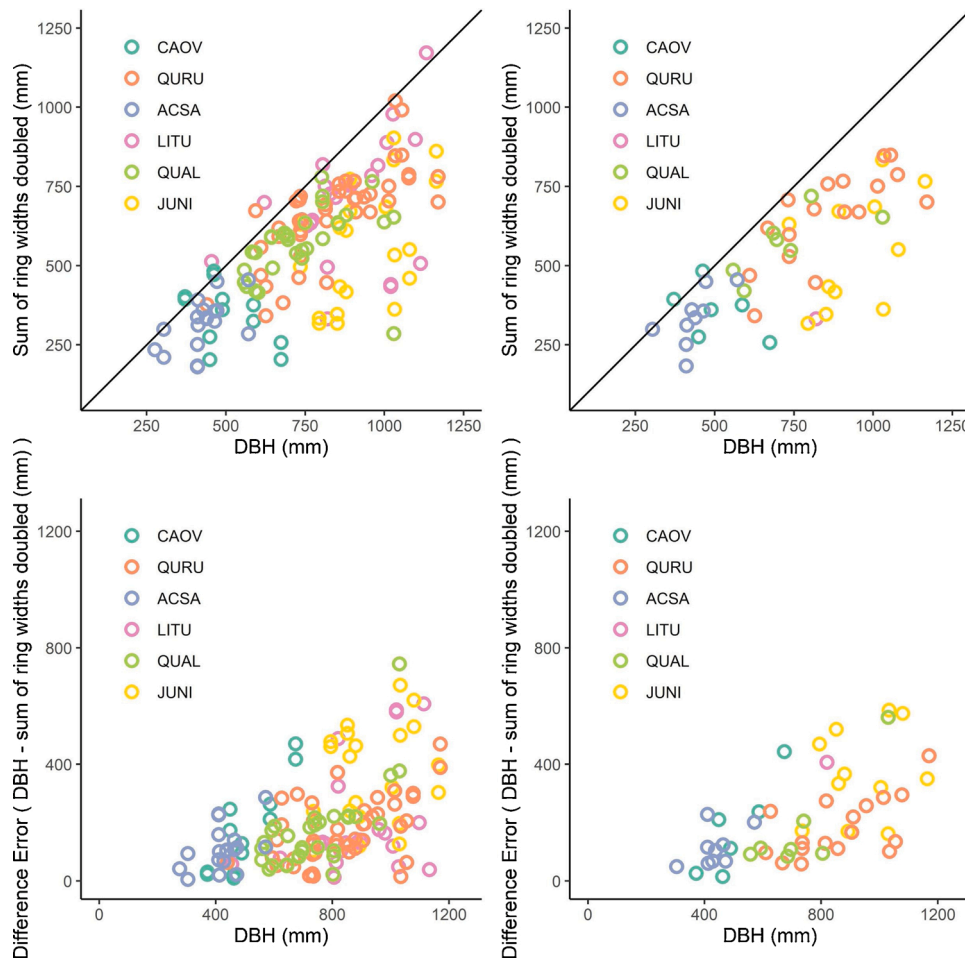


Fig. 1. Ring-width estimated diameter vs field-measured diameter for the full Pioneer Mothers Memorial Forest dataset (left) and the subgroup of trees with two cores averaged per tree (right).

over time. To evaluate any influences this has on resulting biases, we detrended the BAI chronologies and used the residuals of an autoregressive model (Bunn, 2008). The resulting detrended BAI chronologies were compared visually via timeseries.

2.4. Biomass bias

To further assess the impact of biased diameter values on productivity estimates, we calculated tree and stand-level biomass at PMMF. Biomass values were calculated using published family-level equations acquired from Chojnacky et al. (2014), which were available for all species sampled. Here we again used different versions of the diameter to calculate

different versions of biomass. First we used the field-measured DBH to establish a “true” biomass measure. Then we used the sum of the ring widths doubled to estimate the diameter, and in order to assess the sensitivity of biomass to missing inner rings we removed 10 and 20 inner rings to produce two more estimates of biomass. We also visually and statistically compared the biomass estimates to identify bias, again using difference estimates.

2.5. Model calibration, validation and testing

To reduce the bias introduced by using DBH derived from the sum of the ring widths, we constructed a linear multiple regression model (Eq. 1):

$$\widehat{DBH} = 0 + b_1(DBH_{RW}) + b_2(D) \tag{1}$$

$$D = (DBH_{RW} - DBH_{RW-k})/DBH_{RW} \tag{2}$$

where DBH_{RW} is the diameter calculated by summing the ring widths, DBH_{RW-k} is the diameter calculated by summing the ring widths after removing a designated k number of innermost rings, and D (Eq. 2) is the difference error ratio by taking the difference of these two diameters divided by the diameter of the total ring width.

If no inner rings are removed to simulate field-sampling error (i.e. $k = 0$), then the model is reduced to a simple linear regression model (Eq. 3) where DBH_{RW} is the diameter calculated by summing the ring widths :

$$\widehat{DBH} = 0 + b_1(DBH_{RW}) \tag{3}$$

The chronologies from Pioneer Mothers Memorial Forest in Indiana were used for calibration and validation using a random one-half split. We assessed the performance of the model using standard univariate metrics. However, because these metrics insufficiently summarize a model’s predictive ability (Willmott, 1981; Willmott et al., 2009), we additionally report the mean absolute error of the model fitted values and decompose mean squared error into its systematic and unsystematic components. After model calibration, we used the validation set to compare the model-produced DBH values to the corresponding field-measured DBH values using the same methods as with the calibration set. Model error for both the calibration and validation sets was compared to the error of using only the sum of the ring widths for estimating diameter.

To assess how well the model generalizes to other sites with similar species, we used three additional chronologies from Goll Woods, Ohio

Table 2

Values for average bark width as a percentage of total diameter and error of ring width estimated diameter as a percentage of total diameter; indicating that field-sampling error contributes to a greater portion of error than including bark widths in diameter measurement. Average bark width values obtained from Thomas and Bennett (2014) for available species.

Species	Bark Width Percent	Error Percent
<i>Carya ovata</i> (CAOV)	N/A	27.6
<i>Quercus rubra</i> (QURU)	2.69	19.9
<i>Acer saccharum</i> (ACSA)	2.38	25.1
<i>Liriodendron tulipifera</i> (LITU)	N/A	19.3
<i>Quercus alba</i> (QUAL)	2.64	21.6
<i>Juglans nigra</i> (JUNI)	N/A	39.1

(“GW” Table 1). This independent “testing” dataset contained two species that were in the calibration dataset (*Carya ovata*, *Quercus alba*) and one new species (*Quercus macrocarpa*) that is closely related to *Q. alba*. We compared the model-produced DBH to the field-measured diameter and ring-width-summed diameter, and then used the model values to calculate BAI and biomass to additionally assess the model’s performance.

We also examined the accuracy of a pith locator to correct the DBH bias. Here we used a single species subset (*Q. alba*) from Goll woods and used a pith locator to generate estimated distances to the pith for each core. These distances were added to the sum of the ring widths and compared to the field-measured diameter.

3. Results

3.1. Diameter

Using the sum of the ring widths to estimate tree diameter produced underestimations of DBH by an average of 25 % (Fig. 1, top row). These underestimations persisted when cores from the same tree were averaged to account for stem asymmetry, where the sum of the ring widths underestimated DBH by an average of 27 % (Fig. 1, bottom row). The difference between DBH and DBH_{Rw} (i.e., difference error) was positively correlated with the measured DBH in both individual and averaged cores ($r = 0.51$, $r = 0.59$). Average difference error as a percentage of DBH ranged from 19.3–39.1 (Table 2). Difference error percentages were nearly an order of magnitude greater than bark width percentage of diameter for the three species that had bark width estimates: *Quercus rubra*, *Acer saccharum*, and *Quercus alba* (Thomas and Bennett, 2014).

3.2. Basal area increment

Timeseries of BAI show that the three different methods for estimating DBH that use sums of ring widths (sum of the ring widths, sum of the ring widths with 10 rings removed, and sum of the ring widths with 20 rings removed) produce substantial difference in BAI (Fig. 2). As expected, BAI estimated using DBH from the sum of the ring widths consistently underestimated those computed using the field-measured DBH, by an average of 40 % across all species. In the BAI versions that simulate field-measurement error (i.e. removing an additional 10 or 20 rings), subtracting more of the innermost rings produced nonlinearly underestimated values of BAI, where the difference between the field-measured diameter version and ring width version is greater than the difference between the ring width version and those removing the innermost rings. Growth trends vary expectedly in magnitude with increased inner rings removed, however differences in covariance among the BAI versions are more common, particularly in early portions of the chronologies.

Using the proportional method proposed by Bakker (2005) did not reduce the biases that result from missing inner rings (A.1). Here, the distributions of the difference errors across the timeseries were altered, with more error observed for later years and converging to zero at earlier years. Overall, the proportional method produced a greater variation and magnitude of difference error across all chronologies of all species compared to the conventional method (Fig. 3).

The amount of absolute error in the BAI chronologies was substantially different across the six species (Fig. 3; Table 2). The greatest amount of error was observed in the *Quercus rubra* and *Liriodendron tulipifera* chronologies, the two species with the largest DBH and BAI values (Figs. 1 and 2). The least amount of error was observed in the *Acer saccharum* and *Carya ovata* chronologies, with these two species also exhibiting the least amount of variation in bias across all chronologies. These species also corresponded to the smallest trees sampled (Fig. 1).

3.3. Biomass

Tree-level biomass calculated using the ring width-estimated diameter was underestimated compared to using the field-measured diameter (Fig. 4, left panel). These underestimations tended to be greater for large trees than small trees, which was consistent with diameter trends. Even though the biomass equations were nonlinear, the degree to which the ring-width diameter underestimated biomass decreased by an average of 62 % and 72 % when 10 and 20 inner rings were removed (Fig. 4, middle and right panels respectively).

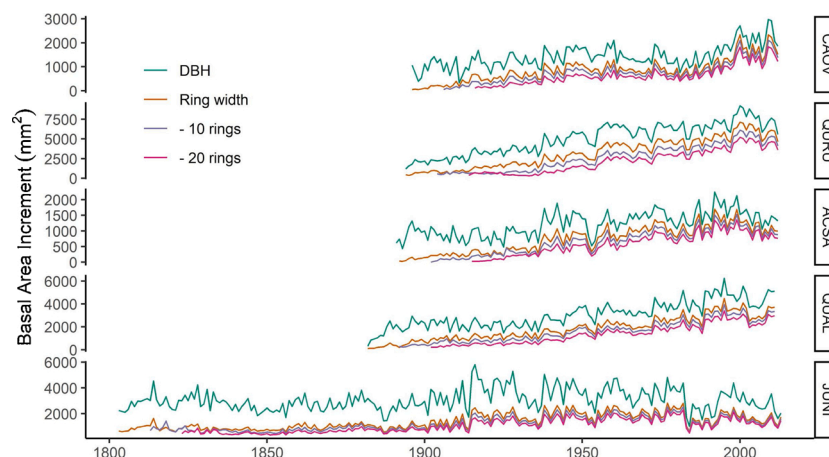


Fig. 2. BAI chronologies calculated using the conventional method, and using different estimates of DBH for all six species (Table 1) from Pioneer Mothers memorial Forest. Note that y-axis limits differ across subplots.

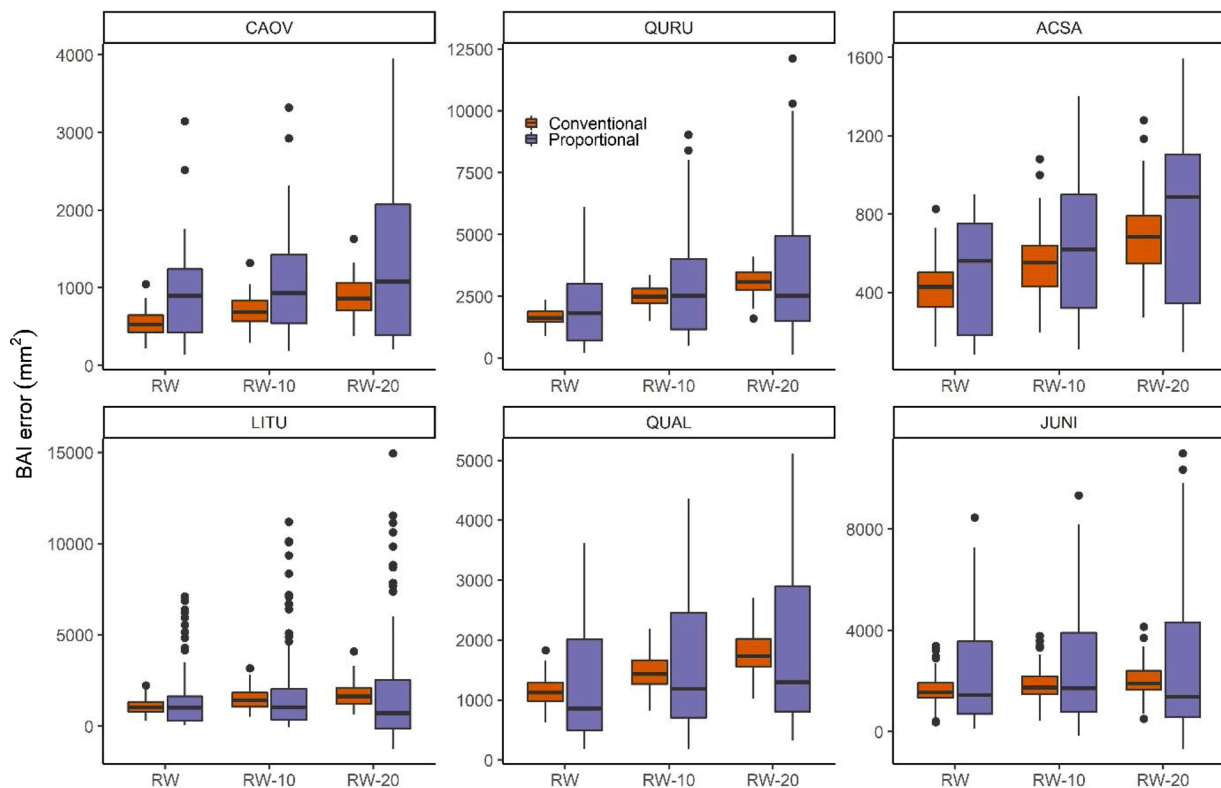


Fig. 3. Boxplots of error by species for the annual BAI chronologies from Pioneer Mothers Memorial Forest (Table 1) for both the conventional (orange) and proportional (purple) method. Difference error distributions are shown for the three different approaches for estimating DBH: sum of ring widths (RW), sum of ring widths with 10 inner rings removed (RW-10), and sum of ring widths with 20 inner rings removed (RW-20).

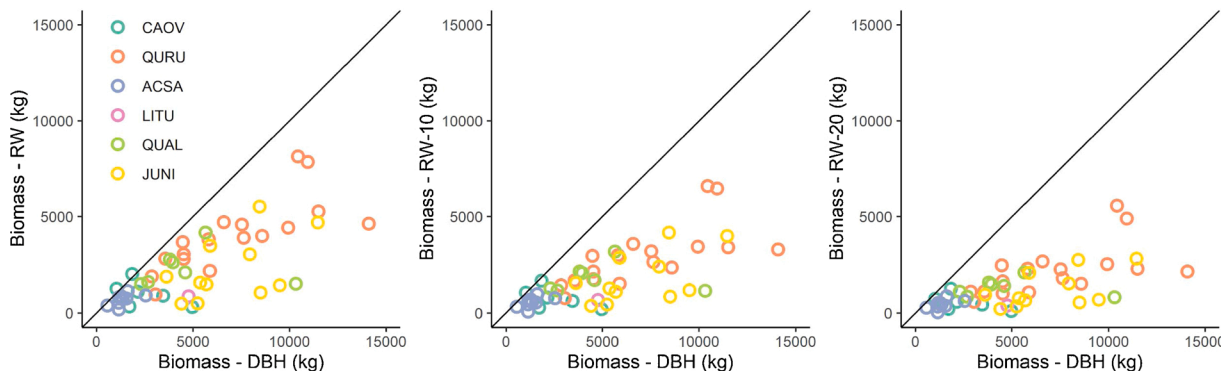


Fig. 4. Biomass calculated using the sum of the ring widths (RW) vs biomass calculated using the field-measured diameter for all species at Pioneer Mothers Memorial Forest. Ring width estimates of diameter were calculated using the total ring width (RW, left), total ring width after subtracting 10 inner rings (RW-10, middle), and subtracting 20 inner rings (RW-20, right).

3.4. Model calibration and validation at Pioneer Mothers Memorial Forest

The two regression models (Eqs. 1 and 3) performed well, with both having explained variances over 50 % (Table 3). Model two (with difference term) had a slightly improved fit compared to model one (no difference term, $R^2 = 0.56$, $R^2 = 0.55$, respectively), and so it was chosen for final model implementation. The model-estimated diameters contained substantially reduced errors compared to the ring-width-estimated diameter (Table 3), with mean absolute error being reduced by 42 % in both the calibration and validation datasets. Model-estimated diameters also exhibited a lower proportional total error that is systematic in both the calibration and validation stages. Visual inspection

of the model-estimated diameters further supported model performance for producing values with less overall error - and lower systematic error - than using only the sum of the ring widths (Fig. 5).

3.5. Model testing at Goll woods

Using the test dataset from Goll woods (“GW”, Table 1), mean absolute error was reduced by 55 % from 228.3 mm in the ring width-estimated diameter to 101.3 mm in the model-estimated diameter (Table 3). The model reduced both systematic and unsystematic errors. Visual inspection also provides additional support that the model effectively reduces the bias present in diameter values (Fig. 6). The systematic underestimation was improved for both species included in

Table 3

Mean absolute error (MAE), systematic root mean squared error (RMSEs), un-systematic root mean squared error (RMSEu), and the proportion of total mean squared error that is systematic (MSEs/MSE) for both the ring width-estimated diameter and the model-estimated diameter in the calibration, validation, and independent testing datasets. Model 1 ($R^2 = 0.55$): $DBH = 223 + 0.998(DBH_{RW})$, Model 2 ($R^2 = 0.56$): $DBH = 156.4 + 1.03(DBH_{RW}) + 446.5(D)$.

Method	MAE	RMSEs	RMSEu	MSEs/MSE
Calibration				
Ring width	223.6	246.3	117.3	0.81
Model 1	130.3	103.7	117.1	0.44
Model 2	129.4	104.5	117.2	0.44
Validation				
Ring width	220.0	246.3	117.7	0.77
Model1	128.9	96.2	128.9	0.36
Model 2	126.7	92.3	117.2	0.34
Testing				
Ring width	228.3	243.5	204.8	0.83
Model 1	102.5	92.9	106.1	0.43
Model 2	101.3	99.7	105.5	0.47

the calibration and validation set (QUAL, CAOV), as well as the new species (QUMA). Using a pith-locator to add the missing pith distances to the sum of the ring widths for *Q. alba* at Goll Woods improved the underestimations somewhat, but not as much as the model-estimated diameters (A.2.). Here, mean absolute error for the sum of the ring widths plus the pith locator distance was 105.6 mm, compared to 85.2 mm for the model-estimated diameter, which was a reduction of 19 %.

Basal area increment calculated from model-estimated diameter using the test dataset from Goll Woods produced more accurate values than using only the sum of the ring width (Fig. 7, top). For all three species, the model-produced values were a better fit with BAI derived from field-measured DBH values than those produced from summing the ring widths. The median, mean, and interquartile range of the difference error of BAI was lower using model-estimated diameter than ring-width produced estimates across all species (Fig. 7, bottom). However, total difference error and the variation in error were reduced more for the two species included in the calibration and validation dataset (QUAL, CAOV), compared to that of the one additional species (QUMA), likely because this out-of-sample species had larger diameters overall which were somewhat underestimated in the DBH model (Fig. 6).

Tree-level biomass calculated using model-estimated diameters was more accurate than using the ring width-estimated diameter (Fig. 8). All three species exhibited substantially lower error in estimating biomass when using the modeled DBH compared to the ring width estimated DBH. Here, mean absolute error was reduced 70 %, from 4225 kg using the ring width-estimated diameters to 1308 kg using the model-estimated diameters.

4. Discussion

4.1. Diameter

The use of increment cores to estimate tree diameter produces consistently underestimated diameter values (Fig. 1). Previous studies have suggested that stem asymmetry and the inclusion of bark width are

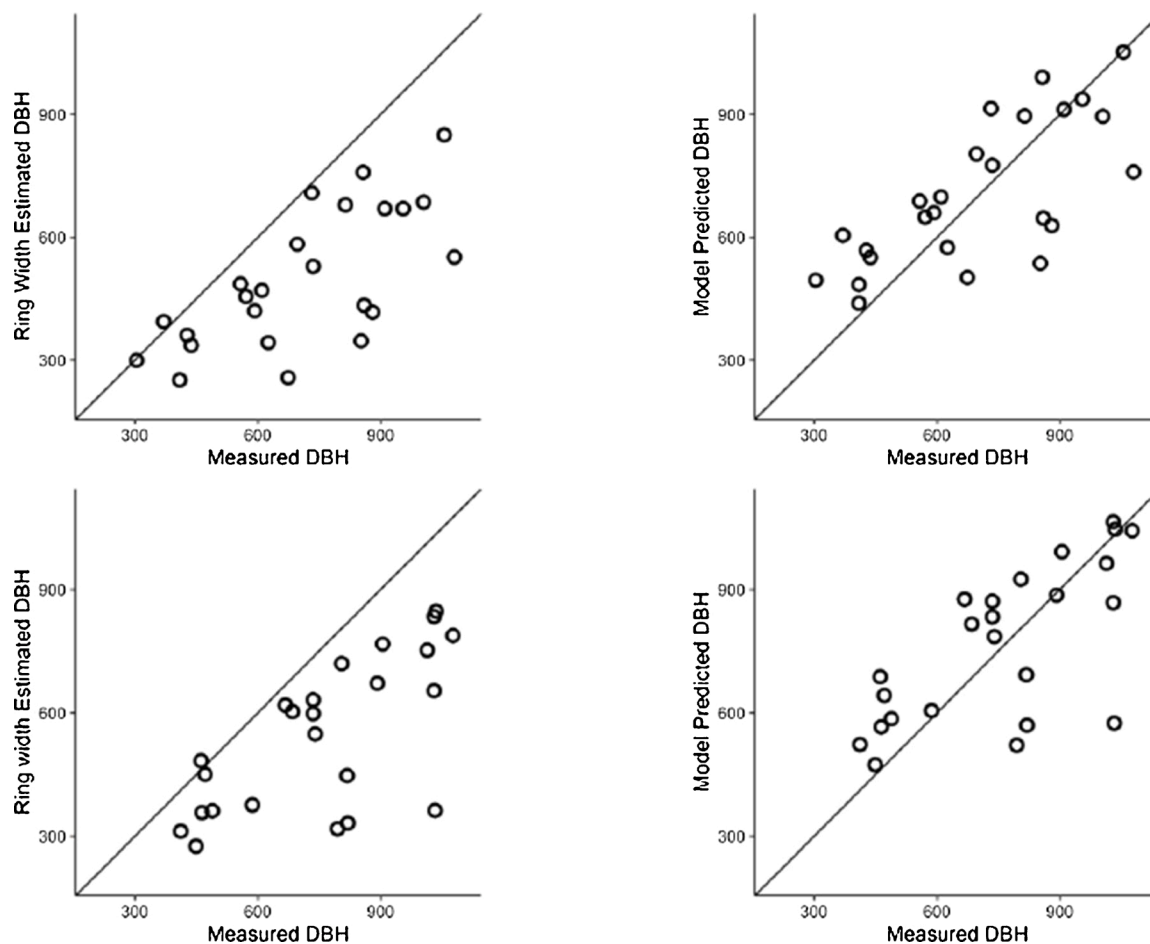


Fig. 5. Model-estimated diameter vs field-measured diameter (left) and ring width-estimated diameter vs field measured diameter (right) for the calibration dataset (top row) and validation dataset (bottom row).

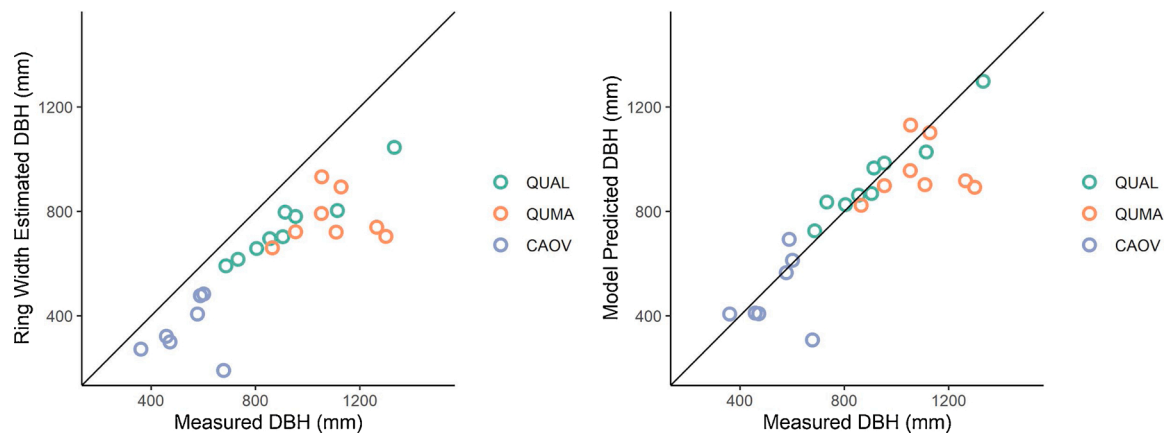


Fig. 6. Ring-width estimated DBH vs field-measured DBH (left) and model-predicted DBH vs field-measured DBH (right) using the Goll Woods testing data set.

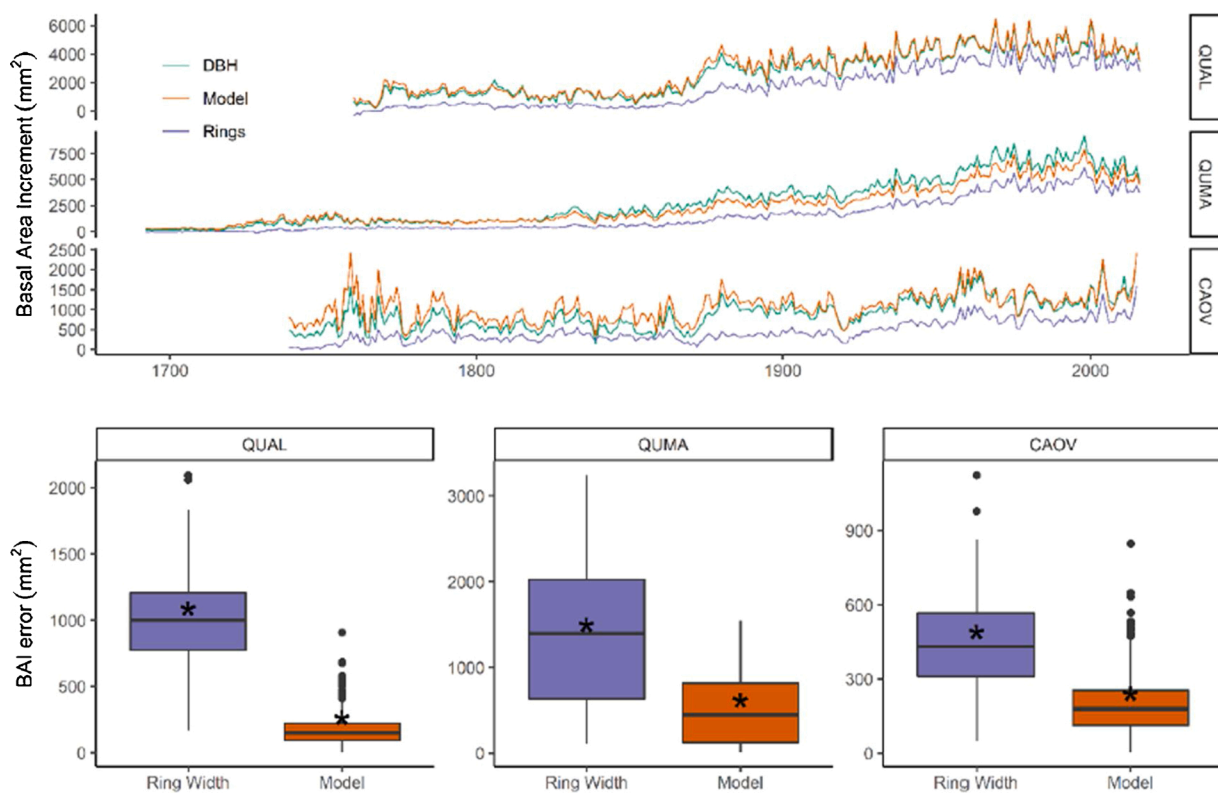


Fig. 7. Top: Basal area increment produced using the measured diameter, the sum of the ring widths, and the multiple regression model using the test dataset (GW, Table 1). Bottom: Error in the annual BAI values using ring-width-estimated DBH (purple) and the model-produced DBH (orange) using chronologies from Goll Woods (Table 1). The * symbol indicates mean absolute error.

substantial contributors to biases in ring-width estimated diameter, and thus BAI (Visser, 1995; Biondi, 1999). While this is true, we found that most errors were far greater than that which could be attributed solely to the inclusion of bark width in DBH measurements for the species examined here. In addition, the issue of stem asymmetry appears to be independent to the problem of bias in ring-width estimated diameter, given that accounting for stem asymmetry by obtaining two cores per tree does not resolve the issue of underestimation.

We suspect that the presence of internal decay of the tree (i.e. heart rot) is a large contributor to the errors shown here. Internal decay frequently prevents increment borers from reaching the pith. While many previous studies have examined growth trends for gymnosperms, angiosperms have been shown to experience higher rates of internal decay (Weedon et al., 2009; Kahl et al., 2017). This may explain the high

degree of error observed here and suggests that estimates of DBH and BAI may differ in the degree of bias depending on the species being used, particularly between gymnosperms and angiosperms. However, Fig. 1 shows considerable variation within the sampled species. This highlights the greater difficulty of locating the pith of larger trees irrespective of species.

4.2. Basal area increment bias

When using the sum of ring-widths to estimate DBH, BAI appears to be highly sensitive to missing inner rings. By simulating sampling error by removing inner rings, we show that the number of missing inner rings increases the degree to which BAI values are underestimated. Furthermore, the use of the proportional method by Bakker (2005) also does not

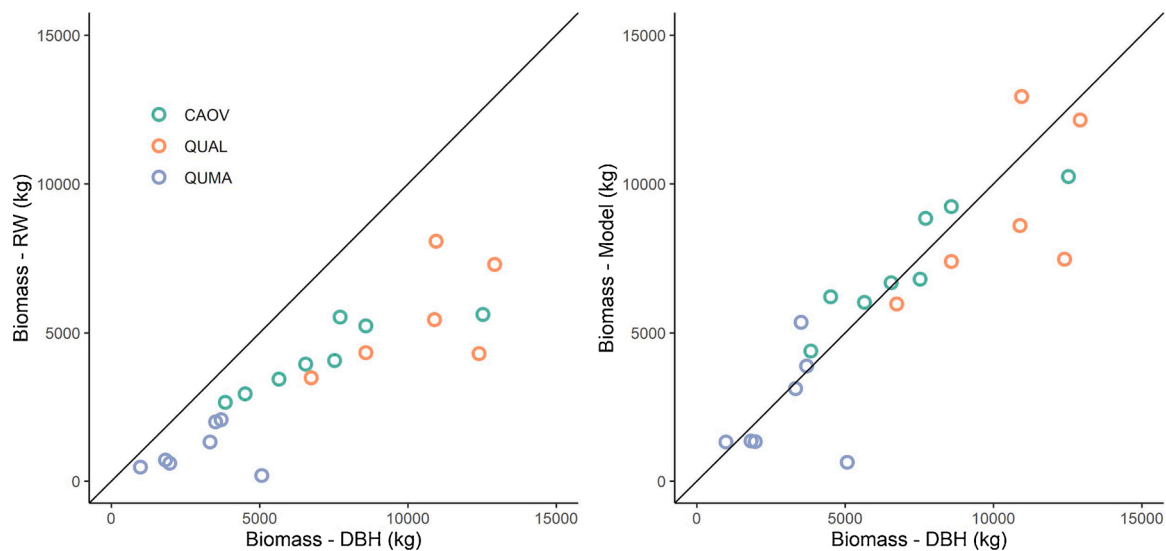


Fig. 8. Estimates of tree-level biomass using the ring width to estimate diameter vs using the field-measured diameter (left) and using the model-estimated diameter vs using the field-measured diameter (right) at Goll Woods, OH.

resolve this issue, and may be more problematic when using the sum of the ring widths to estimate DBH, because this method assumes that the increment core reaches the pith (which is often not the case). As a result, using the sum of the ring widths method consistently underestimated values of BAI in all species by an average of 40 %. However, the degree of the error in the resulting BAI chronology appears to exhibit some differences across the species sampled here. This suggests that differing growth rates among species and size classes can result in differing amounts of bias in the respective chronologies.

Basal area increment produced by using the sum of the ring widths also produces altered growth trends compared to the field-measured DBH version. This is likely the result of the full ring-width series of each core not being a full representation of the actual radius (and subsequent diameter), which is especially problematic given that unsampled early years tend to have larger ring widths. The magnitude of errors in estimating DBH from summing ring widths is evident in the larger differences between the field-measured DBH version of BAI and those using ring-width chronologies compared to differences among the simulated error ring-width chronologies.

4.3. Biomass

Biomass also appears to be highly sensitive to missing rings when using the sum of the ring widths to estimate DBH. We again found underestimated biomass corresponding to the number of missing inner rings. This is troubling, because forest biomass is frequently reconstructed and predicted using tree-ring estimates of diameter and area (Babst et al., 2014; Dye et al., 2016; Alexander et al., 2018). Given the results presented here, it is reasonable to assume that some published estimates of DBH, BAI, and biomass produced by using only the sum of the ring widths have substantially underestimated the magnitude of growth and biomass. The degree of underestimation likely varies across species and sites. Moreover, altered growth trends as a result of DBH and BAI underestimations may influence the interpretation of historical patterns of forest biomass change. The continued use of tree-rings to estimate biomass is predicated on having a full understanding of the limitations of these methods, and also any potential solutions to mitigate these limitations.

4.4. Reducing bias

Given the influence that field-sampling error has on BAI estimates

when direct measurements of DBH are absent, we recommend carefully weighing the implications of underestimating BAI by using only the sum of the ring widths. There are considerable opportunity costs, however, in not calculating BAI or biomass using data from tree-ring repositories like the ITRDB that routinely do not include DBH measurements (Zhao et al., 2019; Rayback et al., 2020). Thus, the potential of a reliable solution is of considerable value to the research community.

While detrending the timeseries does appear to reduce the errors in the resulting chronologies (A.3.), this method may not be desirable because it removes the units of the chronology, which is one of the motivations for using BAI in the first place. Alternative solutions for estimating the diameter of a tree using tree rings have been commonly used in dendrochronological studies (Speer, 2010), such as a “pith locator” that uses the curvature of the inner rings to estimate the distance to the center of the tree (Applequist, 1958). Various modifications have been made to this basic approach, although these methods remain time and labor intensive and have a number of limitations that may produce even larger errors (e.g., non-circular rings). We show that adding the distance from a pith locator to the sum of the ring widths is still likely to underestimate the field-measured diameter. Here, our model produced diameter estimates that outperformed the pith locator, so we recommend this approach.

5. Conclusion

A combination of internal decay and field-sampling error contribute to the bias in ring-width estimated diameter values and this bias has downstream effects on growth and productivity metrics calculated using these underestimated diameters. This is likely to impede understanding of forest ecological processes and may result in inappropriate management decisions given the degree of underestimation present in productivity metrics calculated using the sum of the ring-widths to estimate DBH.

The method developed here provides a simple, data-driven approach to modeling the diameter using simulated bias. This method produces estimates of DBH that are more accurate than using the sum of the ring widths alone, and thus also produces more accurate estimates of both BAI and biomass. The method is also highly portable and has been demonstrated to generalize well using data from another site and species. This suggests that a diameter prediction model could be developed from existing and reasonably-sized data sources when DBH measurements are not available at the site of interest, but are available at other

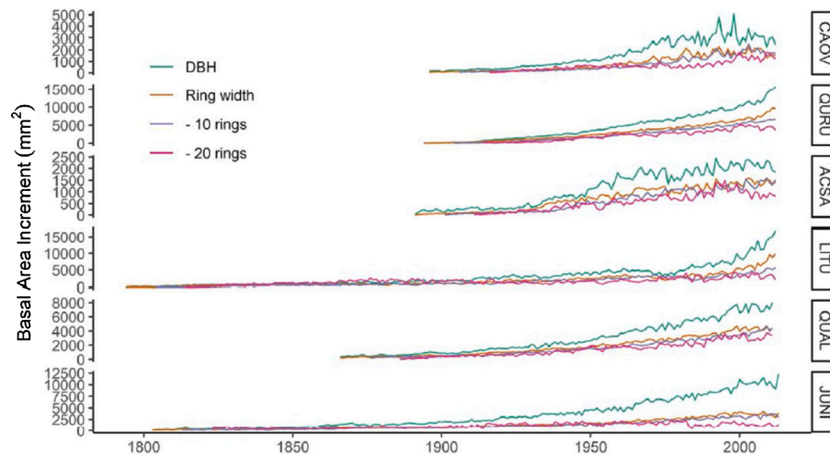


Fig. A1. BAI chronologies calculated using the proportional method, and using different estimates of DBH for all six species (Table 1) from Pioneer Mothers Memorial Forest. Note that y-axes limits differ across subplots.

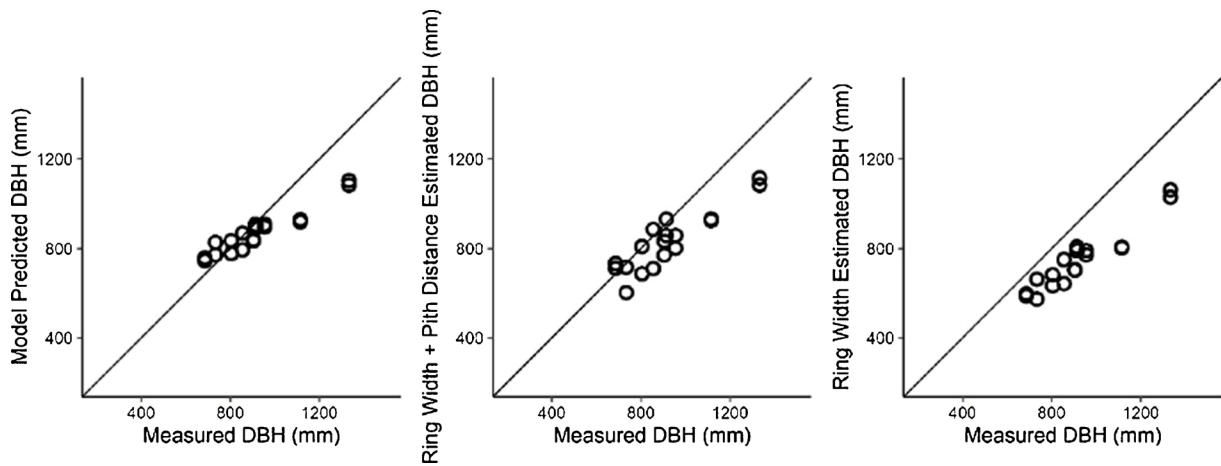


Fig. A2. Measured DBH compared to model estimates, ring with plus pith distance estimates, and ring width estimates for *Q. alba* at Goll Woods.

sites. However, we recommend that calibration and validation datasets be of similar species composition and from similar climate regimes to allow comparisons across species and sites. Additionally, this method could likely be improved upon by creating multiple domain-specific models for different age and size classes, and climate regimes.

Nevertheless, the modeling approach developed here produces a more accurate estimate of woody growth than simply using the sum of the ring widths and is the method we recommend for future calculations of diameter when DBH measurements are available for some, but not all sites.

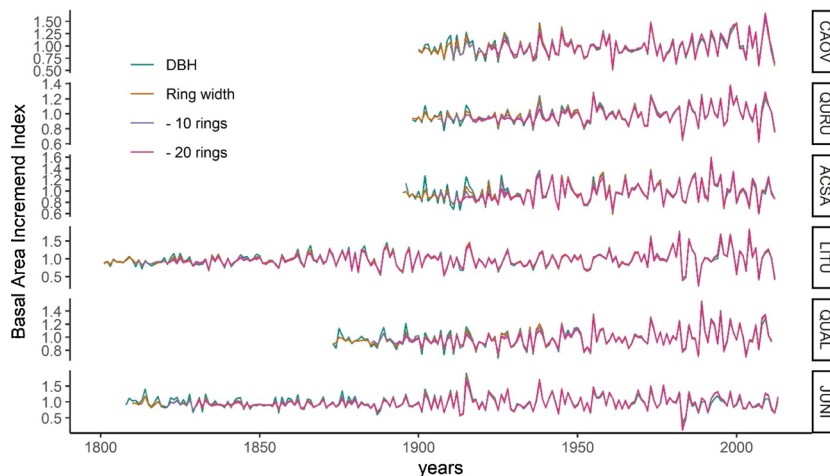


Fig. A3. Detrended BAI chronologies calculated using different estimates of DBH for all six species (Table 1) from Pioneer Mothers Memorial Forest. Note that y-axes limits differ across subplots.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Figs. Fig. A1, Fig. A2, Fig. A3A1–A3

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