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NOTE

Reference charts for young stands — a quantitative methodology for assessing tree performance

Lance A. Vickers, David R. Larsen, Benjamin O. Knapp, John M. Kabrick, and Daniel C. Dey

Abstract: Reference charts have long been used in the medical field for quantitative clinical assessment of juvenile development by plotting distribution quantiles for a selected attribute (e.g., height) against age for specified peer populations. We propose that early stand dynamics is an area of study that could benefit from the descriptions and analyses offered by similar references for various tree measures. Reference charts provide a flexible quantitative framework that would complement traditional methods for assessing tree development. In young, mixed stands, competitive dynamics are, in part, a function of intraspecific, interspecific, and temporal variation in height development. A suite of reference charts can explicitly describe each of these, offering additional context and potentially greater insight into the complex development patterns of young trees. We illustrate this possibility and potential applications by constructing height–age reference charts for several tree species in young, mixed stands within the Missouri Ozarks.

Key words: height growth, percentile, regeneration, recruitment, stand dynamics.

Résumé : Des abaques de référence ont longtemps été utilisés dans le domaine médical pour réaliser des évaluations cliniques quantitatives du développement juvénile en traçant les quantiles de distribution d'un attribut sélectionné (p. ex., la hauteur) en fonction de l'âge pour des populations homologues spécifiques. Nous croyons que la dynamique des jeunes peuplements est un domaine d'étude qui pourrait bénéficier des descriptions et des analyses offertes par de tels outils de référence pour diverses mesures d'arbre. Les abaques de référence offrent un cadre quantitatif flexible qui compléterait les méthodes traditionnelles d'évaluation du développement des arbres. Dans les jeunes peuplements mixtes, la dynamique de compétition est partiellement fonction des variations intraspécifique, interspécifique et temporelle du développement en hauteur. Une série d'abaques de référence peut décrire explicitement chacune de ces relations, ce qui offre un contexte supplémentaire et un aperçu potentiellement meilleur des schémas complexes du développement des jeunes arbres. Nous illustrons cette possibilité et des applications potentielles par la mise au point d'abaques de référence entre la hauteur et l'âge de plusieurs espèces d'arbres se développant dans de jeunes peuplements mixtes situés dans les monts Ozarks au Missouri. [Traduit par la Rédaction]

Mots-clés : croissance en hauteur, percentile, régénération, recrutement, dynamique des peuplements.

Introduction

The development of forest stands following disturbance includes general stages described through the study of stand dynamics. The early stages of this process are complex and dynamic, including the establishment of new trees, growth rates that may vary widely across species or site conditions, and widespread mortality as trees grow and populations reduce. As a result, early stand development is commonly considered stochastic, especially before the onset of crown closure and competition mortality. Simple tools for quantitative assessment of tree and population development can improve insight into the early stages of stand dynamics and help refine silvicultural applications.

Single-cohort stands often contain mixtures of species that differ in growth rates, longevity, and other life-history traits. Both the height of a tree and relative stature among neighbors can influence growth and survival in developing stands (Assmann 1970; Oliver and Larson 1996; Weiner 1990). It is common for performance assessments in these young stands to be conducted using qualitative or categorical metrics such as crown classes with no actual measurement of tree height. Such assessments are expedient and have proven useful for evaluating tree performance in single-cohort stands, particularly after the onset of stem exclusion (Ward and Stephens 1993, 1994, 1996). Though sufficient for some objectives, this level of examination may be too general to capture the nuanced ecology of early stand development.

Early in stand development, the height profile of mixed stands may exhibit turnover in species dominance (Kelty et al. 1992; Oliver and Larson 1996). Thus, an individual's early position among neighbors may not be indicative of long-term potential due to variation in development patterns. The relative stature of a tree in a young, mixed stand is a function of intraspecific, interspecific, and temporal variation in height development. Evaluations that do not explicitly consider each of these factors could be misleading, yet foresters lack simple tools that describe expected patterns in early height development. We suggest that a suite of quantitative references could offer improved insight into developmental patterns by providing much-needed context for measured attributes that influence growth and survival.

Reference chart methodologies have long been used in the medical field for quantitative clinical assessment of human development (Quetelet 1871; Ulijaszek et al. 1998). These charts typically include quantiles of a reference distribution plotted against age for an attribute of interest (e.g., height–age). Reference charts

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Table 1. Weibull distribution parameter estimates for the site class based height–age reference charts in this study.

			Weibull parameters		
Species group	Age (years)	*n*	Shape	Scale	AD
Exposed backslopes	2	336	1.7717 [1.6336, 1.9219]	1.5754 [1.4750, 1.6789]	0.7426
	5	324	2.0771 [1.9010, 2.2791]	2.7277 [2.5850, 2.28860]	0.7676
	10	307	2.0285 [1.8661, 2.2152]	4.3245 [4.0653, 4.5754]	0.0984
	16	1839	1.8869 [1.8201, 1.9607]	4.6629 [4.5377, 4.7889]	<0.0001
Protected backslopes	2	767	1.5909 [1.5115, 1.6897]	1.4920 [1.4235, 1.5632]	0.0228
	5	731	2.1540 [2.0316, 2.2865]	2.5812 [2.4906, 2.6757]	0.3150
	10	687	2.1825 [2.0596, 2.3184]	4.2253 [4.0762, 4.3724]	0.0046
	16	1664	1.8077 [1.7421, 1.8787]	5.0237 [4.8849, 5.1637]	0.0003

Note: Bracketed values are bootstrapped 95% confidence intervals (2000 iterations). The Anderson–Darling test (AD) was used to evaluate goodness of fit where *p* values ≤ 0.05 suggest rejecting the hypothesis that the data follows the specified distribution.

allow physicians to quantitatively compare the stature of an individual child at a given age with the mainstream using the distribution of statures attained by several children with similar demographics. This provides the physician valuable information to help determine if concern for irregular development is warranted (Ulijaszek et al. 1998).

We used similar techniques to develop height–age reference charts for several tree species and present them as tools for assessing early tree performance and stand development. These charts provide an explicit description of the intraspecific and interspecific variation in height development, as well as the temporal dynamics of both. The objectives of this note are to (*i*) introduce reference charts as a complementary tool for performance assessments in young forest stands, (*ii*) describe the general process used to develop reference charts, and (*iii*) exhibit the potential utility of a suite of reference charts for assessing early height development. We also demonstrate how reference charts can extend the inference window of stand reconstruction techniques (i.e., stem analysis). We use early height–age data from single-cohort mixed stands in the Missouri Ozarks to illustrate the method.

Methods

Data from two long-term studies were combined to create a time series or chronosequence of height–age development in the southeastern Missouri Ozarks (ca. 37.2°N, 90.9°W). The region is predominately unglaciated, deeply dissected plateaus composed of Ordovician and Cambrian dolomites and sandstones (Kabrick et al. 2000). Average annual precipitation is 115 cm, and average annual temperature is 13.5 °C (Kabrick et al. 2008). The study sites spanned two ecological site classes: exposed (aspect: 136–315°) or protected (aspect: 316–135°) backslopes (Nigh et al. 2000). Average site index (*Quercus velutina* Lam.; McQuilkin 1974) on exposed backslopes was approximately 21.0 m (±1.3 m standard deviation (SD)) and 22.0 m (±1.1 m SD) on protected backslopes.

The studies monitored stand development following clearcutting or clearcutting with reserves (≤5 $m^2 \cdot ha^{-1}$ residual basal area). Retaining <5 $m^2 \cdot ha^{-1}$ of residual basal area has little impact on sapling height growth in the study region (Vickers et al. 2014). The first study included six mixed stands across the southeastern Missouri Ozarks, each with multiple, randomly located 0.0016 ha sample plots. The second study included 18 mixed stands across the southeastern Missouri Ozarks, each with a single, randomly located 0.02 ha plot. The two studies followed slightly different height measurement protocols during the targeted first 20 years since harvest. The first study measured heights of all woody stems at 2, 5, and 10 years since harvest starting in 1973–1974. The second study started in 1996 and measured heights for woody stems ≥ 1 m at 3 and 8 years since harvest and all woody stems at 16 years since harvest. We combined the height measurements from years 2, 5, 10, and 16 to provide four nontruncated height–age measurements. Stems with a diameter at breast height (dbh) > 6.3 cm at year 2 or 3 were considered residuals and removed from analyses.

Peer group selection is important for meaningful assessments of development. Just as gender and other attributes are often used in human assessments, we delineated two simple peer group categories along basic determinants of tree height: site-class groups and site class – species groups. The site-class groups used tree height measurements for all woody stems on an ecological site class (exposed or protected backslopes) as a reference distribution. The site class – species groups used height measurements for a species group (described below) on an ecological site class as a reference distribution.

Seven genera or subgenera species groups were identified: (1) red oaks (*Quercus rubra* L., *Quercus velutina* Lam., *Quercus coccinea* Münchh.), (2) white oaks (*Quercus alba* L., *Quercus stellata* Wangenh., *Quercus muehlenbergii* Engelm.), (3) hickories (*Carya tomentosa* Sarg., *Carya glabra* Mill., *Carya ovata* (Mill.) K. Koch., *Carya texana* Buckley, *Carya cordiformis* (Wangenh.) K. Koch.), (4) sassafras (*Sassafras albidum* J. Presl.), (5) blackgum (*Nyssa sylvatica* Marsh.), (6) dogwood (*Cornus florida* L.), and (7) maples (*Acer rubrum* L., *Acer saccharum* Marsh.). An eighth group (other species) was comprised of species that had insufficient representation to stand alone but were not included in previous groups: *Amelanchier arborea* F. Michx., *Carpinus caroliniana* Walter, *Celtis* spp., *Cercis canadensis* L., *Corylus americana* Marshall, *Crataegus* spp., *Diospyros virginiana* L., *Fraxinus* spp., *Gymnocladus dioicus* (L.) K. Koch., *Juglans nigra* L., *Juniperus virginiana* L., *Morus* spp., *Pinus echinata* Mill., *Platanus occidentalis* L., *Prunus* spp., *Rhamnus caroliniana* Walter, *Rhus* spp., *Sideroxylon lanuginosum* Michx., *Ulmus* spp., and *Viburnum* spp. The number of trees sampled in each species group, site class, and age is provided in Tables 1–3.

The objective of our statistical analyses was to estimate longitudinal height–age quantiles for the various peer groups. Given the relatively sparse measurement intervals of our dataset compared with many human growth studies (e.g., Cole and Green 1992; Wei et al. 2006), basic statistical approaches were preferred. For

Table 2. Weibull distribution parameter estimates for the species-based height–age reference charts for exposed backslopes in this study.

			Weibull parameters		
Species group	Age (years)	*n*	Shape	Scale	AD
Red oaks	2	79	1.3645 [1.1543, 1.6274]	1.3603 [1.1443, 1.6068]	0.5929
	5	74	1.5322 [1.2859, 1.8581]	2.7684 [2.3542, 3.2307]	0.6560
	10	73	1.6410 [1.3815, 2.0126]	4.6457 [3.9644, 5.3729]	0.1860
	16	214	1.9372 [1.7463, 2.1583]	6.8135 [6.3294, 7.3088]	0.3702
White oaks	2	79	1.9901 [1.6849, 2.3713]	1.6694 [1.4760, 1.8628]	0.6122
	5	79	2.8443 [2.4161, 3.4237]	3.2753 [3.0133, 3.5705]	0.7569
	10	78	3.0268 [2.5397, 3.6208]	5.3653 [4.9445, 5.8081]	0.1475
	16	522	1.7298 [1.6279, 1.8518]	4.3494 [4.1270, 4.5728]	0.0001
Hickories	2	58	1.8134 [1.4940, 2.2484]	1.2696 [1.0807, 1.4605]	0.5690
	5	57	2.5988 [2.1581, 3.2373]	2.2189 [1.9923, 2.4416]	0.7246
	10	58	2.2867 [1.8936, 2.8180]	3.5402 [3.1100, 3.9639]	0.3305
	16	205	2.0123 [1.8041, 2.2422]	4.8651 [4.5114, 5.2301]	0.1605
Sassafras	2	39	1.9409 [1.5473, 2.5244]	1.6686 [1.3891, 1.9702]	0.5013
	5	35	2.4406 [1.9193, 3.2265]	2.5673 [2.1813, 2.9356]	0.9640
	10	29	2.1002 [1.5813, 2.8900]	3.3248 [2.7234, 3.9576]	0.4807
	16	136	3.5347 [3.0978, 4.0634]	5.6207 [5.3353, 5.9088]	0.6287
Blackgum	2	26	2.8292 [2.0963, 4.0078]	1.9500 [1.6750, 2.2469]	0.8227
	5	26	3.4368 [2.5637, 4.7823]	2.6670 [2.3440, 2.9816]	0.9283
	10	26	3.4319 [2.5649, 4.6539]	3.6531 [3.2109, 4.1094]	0.9504
	16	115	2.8113 [2.4250, 3.2528]	4.1355 [3.8554, 4.4321]	0.7108
Dogwood	2	27	2.9456 [2.2338, 4.1274]	2.1596 [1.8600, 2.4658]	0.9931
	5	26	2.8399 [2.1311, 4.0168]	2.3404 [1.9776, 2.7028]	0.6724
	10	17	2.7853 [1.9255, 4.2239]	3.4969 [2.8707, 4.1852]	0.7596
	16	214	2.9359 [2.6631, 3.2968]	3.6804 [3.5000, 3.8610]	0.4657
Maples	2	8	2.3536 [1.3921, 4.8552]	1.6283 [1.0787, 2.2167]	0.4671
	5	8	2.3727 [1.3912, 4.8264]	2.9437 [1.9966, 4.0299]	0.9526
	10	8	2.5941 [1.5547, 5.3275]	4.5223 [3.0935, 5.9955]	0.9581
	16	130	2.1484 [1.8935, 2.4674]	3.8051 [3.4828, 4.1376]	0.0776
Other species	2	20	2.0986 [1,5222, 3.1211]	1.3001 [1.0027, 1.6097]	0.7614
	5	19	2.7475 [1.9698, 4.0641]	2.2262 [1.8276, 2.6370]	0.8522
	10	18	2.4285 [1.7243, 3.6798]	3.5935 [2.8698, 4.4057]	0.8280
	16	302	2.0657 [1.8972, 2.2581]	4.2625 [4.0181, 4.5055]	0.2388

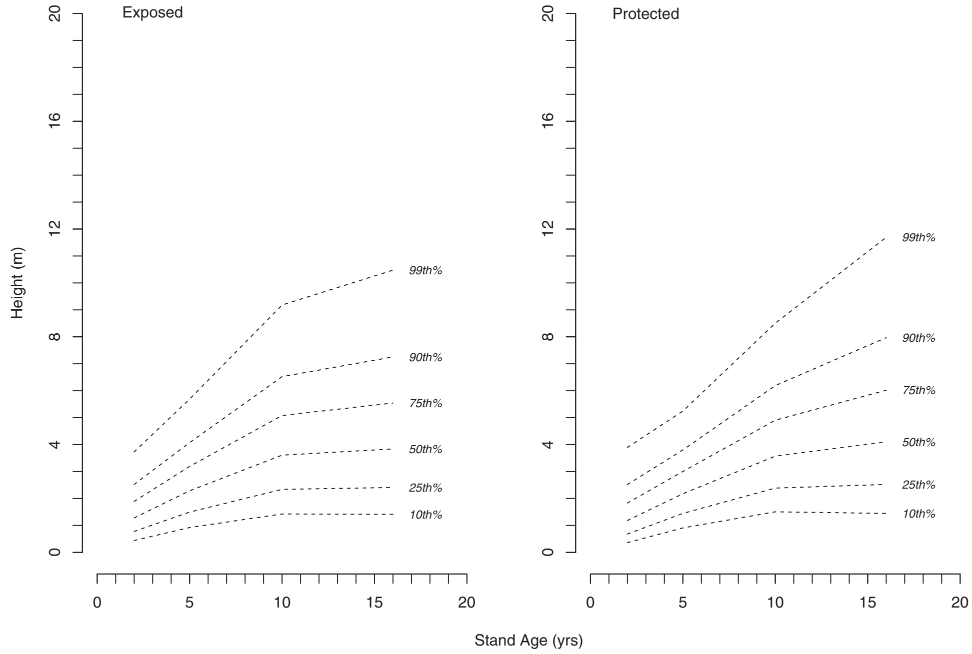
Note: Bracketed values are bootstrapped 95% confidence intervals (2000 iterations). The Anderson–Darling test (AD) was used to evaluate goodness of fit where *p* values ≤ 0.05 suggest rejecting that the data follows the specified distribution.

Table 3. Weibull distribution parameter estimates for the species-based height–age reference charts on protected backslopes used in this study.

			Weibull parameters		
Species group	Age (years)	*n*	Shape	Scale	AD
Red oaks	2	209	1.5980 [1.4398, 1.7814]	1.2733 1.1658, 1.3910]	0.3955
	5	200	2.0828 [1.8755, 2.3186]	2.4012 [2.2318, 2.5715]	0.3158
	10	188	2.1323 [1.9088, 2.3821]	4.5675 [4.2546, 4.9033]	0.0870
	16	106	2.0334 [1.7678, 2.3986]	7.5384 [6.8656, 8.2946]	0.1104
White oaks	2	145	1.3813 [1.2206, 1.5718]	1.3764 [1.2104, 1.5467]	0.2131
	5	142	1.9790 [1.7468, 2.2638]	2.5916 [2.3552, 2.8175]	0.2468
	10	141	2.0103 [1.7797, 2.2777]	4.4001 [4.0258, 4.7930]	0.0395
	16	204	1.3897 [1.2524, 1.5531]	4.9691 [4.4868, 5.5134]	0.0022
Hickories	2	149	1.4285 [1.2657, 1.6247]	1.3983 [1.2368, 1.5642]	0.0970
	5	151	2.1972 [1.9466, 2.4995]	2.4495 [2.2655, 2.6389]	0.4384
	10	148	2.7111 [2.3990, 3.0825]	4.0356 [3.7939, 4.2887]	0.6502
	16	173	1.7836 [1.5839, 2.0009]	4.5505 [4.1476, 4.9608]	0.2467
Sassafras	2	77	2.0858 [1.7724, 2.4964]	1.6240 [1.4459, 1.8101]	0.3572
	5	61	2.3446 [1.9328, 2.8933]	2.4676 [2.1924, 2.7549]	0.9576
	10	47	1.6265 [1.3158, 2.0764]	3.0997 [2.5467, 3.6927]	0.2360
	16	170	3.6604 [3.2544, 4.1296]	7.1522 [6.8395, 7.4667]	0.6960
Blackgum	2	60	1.9969 [1.6417, 2.4988]	1.9619 [1.7012, 2.2406]	0.4493
	5	57	2.4996 [2.0654, 3.0776]	3.0371 [2.6970, 3.3825]	0.8936
	10	51	2.2757 [1.8518, 2.9061]	4.3899 [3.8237, 4.9744]	0.4349
	16	81	2.3465 [1.9893, 2.8052]	5.2334 [4.7246, 5.7739]	0.9879
Dogwood	2	62	2.8471 [2.3620, 3.5346]	1.9975 [1.8157, 2.1862]	0.8348
	5	56	4.7364 [3.9136, 5.8354]	2.9855 [2.8135, 3.1649]	0.8167
	10	53	4.4983 [3.6978, 5.6395]	4.1785 [3.9170, 4.4513]	0.5624
	16	246	2.8455 [2.5848, 3.1466]	3.8783 [3.6982, 4.0564]	0.4731
Maples	2	19	1.5688 [1.1096, 2.3780]	1.8849 [1.3482, 2.5261]	0.8294
	5	19	1.7321 [1.2311, 2.6332]	3.4787 [2.5572, 4.5571]	0.9279
	10	18	2.3087 [1.6513, 3.5091]	4.9485 [3.9020, 6.1303]	0.9188
	16	388	1.7884 [1.6534, 1.9362]	4.2140 [3.9755, 4.4703]	0.0048
Other species	2	46	2.1680 [1.7557, 2.7295]	1.4063 [1.2062, 1.6094]	0.6912
	5	45	3.2356 [2.5801, 4.1159]	2.3111 [2.0837, 2.5508]	0.8569
	10	41	2.4435 [1.9364, 3.1307]	3.3813 [2.9301, 3.8209]	0.8191
	16	296	2.0285 [1.8485, 2.2277]	4.9351 [4.6442, 5.2191]	0.9353

Note: Bracketed values are bootstrapped 95% confidence intervals (2000 iterations). The Anderson–Darling test (AD) was used to evaluate goodness of fit where *p* values ≤ 0.05 suggest rejecting that the data follows the specified distribution.

Fig. 1. Site class based height–age reference charts for mixed stands following a clearcut (residual basal area ≤ 5 m²·ha⁻¹) on exposed or protected backslopes in the Missouri Ozarks. Measurements for all woody species encountered (see text) are included.



each peer group, we first fit Weibull parameters (shape and scale) to the empirical height distribution at each measurement interval (i.e., ages 2, 5, 10, and 16) using the "fitdist" function in the MASS package (Venables and Ripley 2002) of R version 3.2.2 (R Core Team 2015). Next, we derived bootstrapped estimates (2000 iterations) of the shape and scale parameters along with 95% confidence intervals using the "bootdist" function in the fitdistrplus package (Delignette-Muller and Dutang 2015). Goodness of fit was assessed via the Anderson–Darling (AD) statistic using the "ad.test" function in the goftest package (Faraway et al. 2017) and visual inspection of cumulative distribution function (CDF) comparison curves. Finally, quantiles were estimated at each measurement interval using the "qweibull" function with the bootstrapped shape and scale parameters. Linear interpolation was used to plot trajectories between measurements.

Results

The best fitting Weibull parameters in almost all cases (64 out of 72) passed the AD test (p values > 0.05), suggesting that the parameter estimates effectively captured the empirical data distribution (Tables 1–3). In the eight cases with p values ≤ 0.05, visual CDF comparisons suggested that the lack of fit was minor for most (6 out of 8). In the remaining two cases (ages 10 and 16 for white oaks, protected backslopes; Table 3), the lack of fit was somewhat more noticeable, but there was little to no improvement using alternative distributions (gamma, lognormal) or removing *Q. stellata* (plausibly slower growing) from the peer group. The reference charts created from the parameters in Tables 1–3 are shown in Figs. 1–3. These reference charts display the 10th, 25th, 50th, 75th, 90th, and 99th quantiles, but additional quantiles are readily obtained with the parameters in Tables 1–3 and basic statistical software.

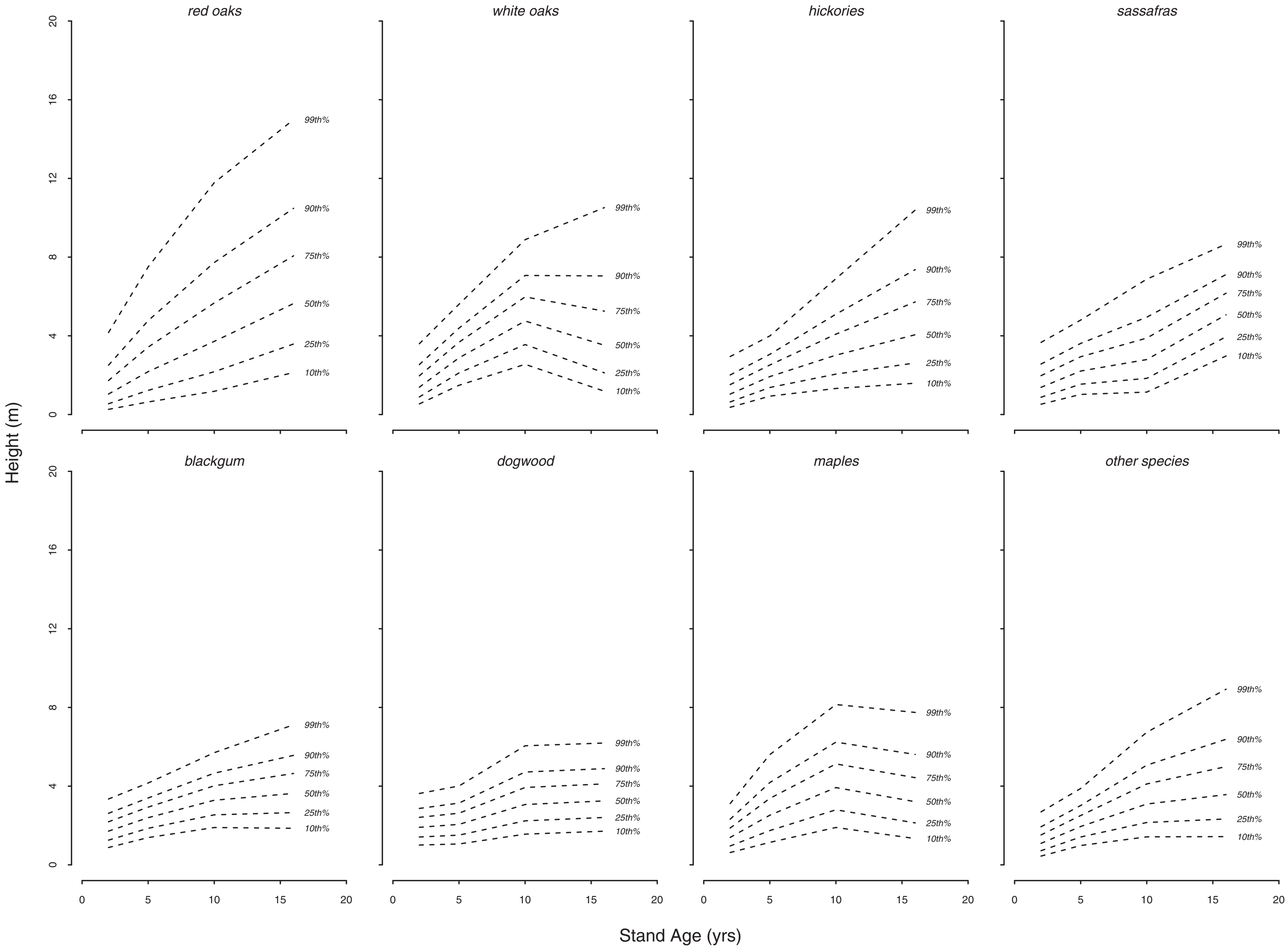
The slope of all quantile lines tended to be positive through stand age 10 on both site-class reference charts (Fig. 1). Though many reference lines were quite similar on both site types, by age 16, noticeable expression of within-site differences in developmental dynamics appeared to be underway. Some quantiles did not increase with age, while others increased at varying rates. After age 10, height development was more limited on exposed backslopes than on protected backslopes.

The site class – species charts (Figs. 2 and 3) showed considerable overlap in the height distributions of many species groups, particularly early in stand development (through age 5) and in the low distribution quantiles (i.e., at the median or below). Both intergroup and intragroup differences in height development trends became more pronounced with stand age. For example, red oaks exhibited a broad distribution of heights, spanning 4.9 m and 13.1 m at ages 2 and 16 on protected backslopes, respectively. In contrast to the broad variation within red oaks (as well as white oaks, hickories, and other species), the sassafras, blackgum, maple, and dogwood species groups exhibited much lower intragroup variation in heights. For example, the measured dogwood heights distribution on protected backslopes spanned only 3.4 m and 7.6 m at ages 2 and 16, respectively.

An application

Consider the stem analysis derived height development of an example tree in Fig. 4. At the time of sampling (2014), this white oak (*Q. alba*) had attained a codominant canopy position in a 19-year-old mixed-species, single-cohort stand on a protected backslope in the Missouri Ozarks (L.A. Vickers, D.R. Larsen, B.O. Knapp, J.M. Kabrick, and D.C. Dey, unpublished data). To demonstrate a cross-sectional assessment, the 5th-year height (3 m) of a tree on a protected backslope in a Missouri Ozarks clearcut is highlighted (diamond symbol) on the corresponding site class – species reference chart in Fig. 4. A height of 3 m at age 5 approximates the 75th quantile for white oaks on this site class. Without any additional field measures, it can be determined that the example tree was taller than about 75% of all white oaks on similar sites at the same age. Further, comparing the height of this example tree with those of other species groups via the site class – species references indicates that on similar sites, about 20% of red oaks, hickories, or sassafras, 40% of blackgum or dogwood, 46% of maples, and about 10% of trees in the other species group would be taller at age 5.

Fig. 2. Site class – species based height–age reference charts for mixed stands following a clearcut (residual basal area ≤ 5 m²·ha⁻¹) on exposed backslopes in the Missouri Ozarks. See text for species group definitions.



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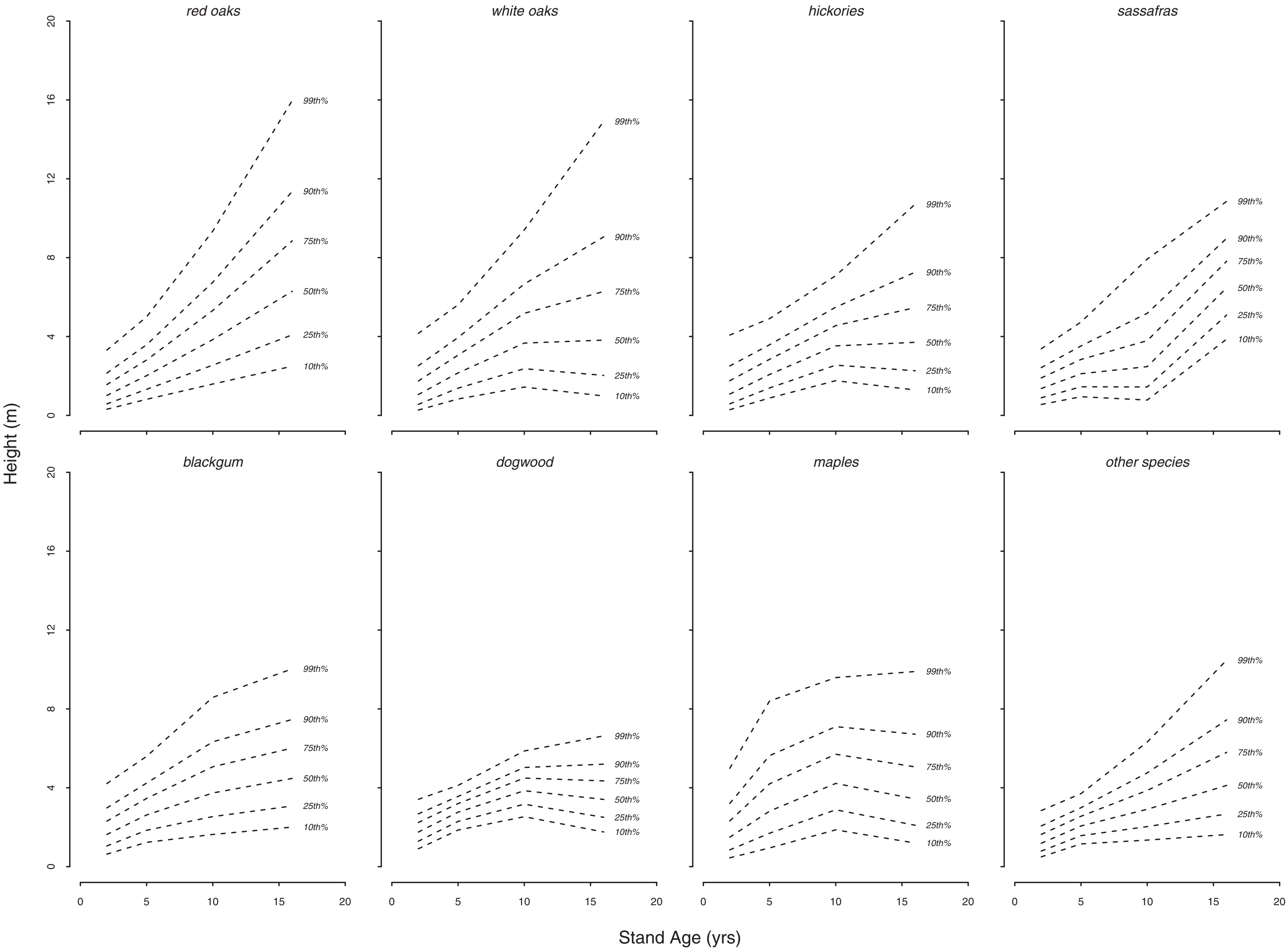
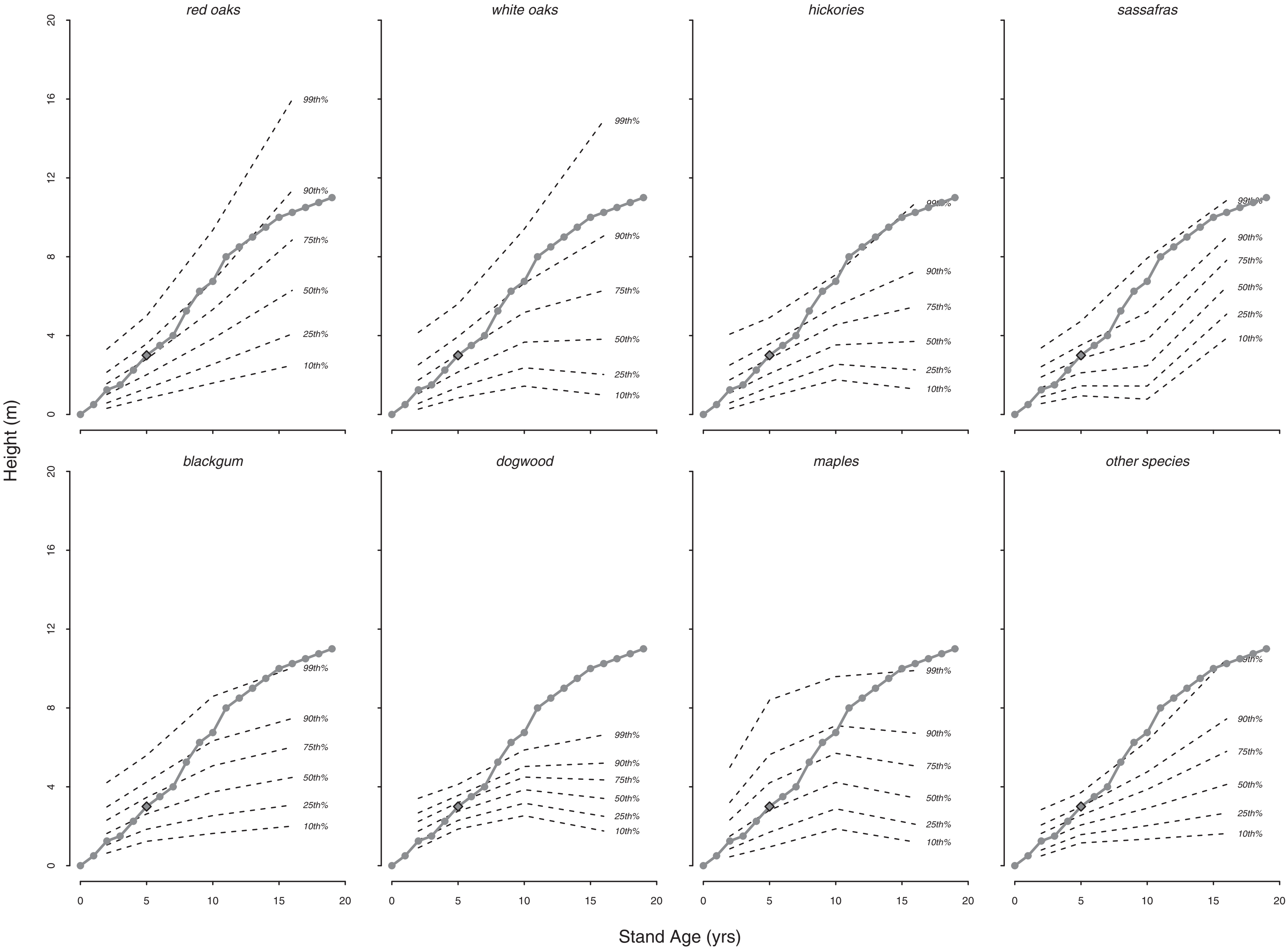


Fig. 4. Application of site class – species reference charts for assessment of height. A stem analysis derived height development pattern from a 19-year-old codominant white oak (*Quercus alba*) on a similar site (protected backslope) in the Missouri Ozarks is plotted to demonstrate a longitudinal assessment. To demonstrate a cross-sectional assessment, the 5th-year height of the example tree is highlighted (diamond symbol).



Although this tree was in a favorable canopy position at the time of sampling (age 19), a longitudinal assessment suggests that before age 7, the height development of this tree was not exceptional for white oaks on similar sites. Moreover, through about age 6, this tree was between the 25th and 75th quantiles across all species groups, including the short-statured dogwood. However, after age 8–10 through age 16, an extant neighbor of many species had, at most, a 1% marginal chance of being taller than this tree. A nearby red oak would have had, at most, about a 15% marginal chance of being taller, while neighboring white oaks or hickories had, at most, about a 5% marginal chance.

Discussion

A clear advantage of reference chart methodology is the explicit focus on distributions rather than on averages or categorical conditions. The focus on distributions provides broad context for field-measured heights, allowing outlier detection relative to mainstream development trends for a given peer group, as well as quantitative assessment of an individual's stature independent of neighbors. Such assessments present opportunities to refine silvicultural applications in young mixed stands (e.g., precommerical thinning and crop tree release) by identifying release candidates based on antecedent species-specific performance in addition to, or perhaps despite, current relative stature among neighbors.

The focus on distributions when utilizing reference charts provides context for stand reconstruction techniques and creates opportunities for more comprehensive interpretations of developmental dynamics. A recognized shortcoming of stand reconstruction techniques has been the inability to account for the influence of trees that did not survive to be sampled. Reference charts can extend the inference obtained from stand reconstruction methods by providing comparative references for longitudinal data and quantitative information on temporal variation in early stand development patterns. A suite of reference charts creates a valuable framework for comparisons of intraspecific and interspecific development by examining the expected strength and duration of competition among species based on the degree of overlap and timing of divergences in their distributions. Such comparative examinations would suggest, based on mainstream trends, if and when one species might be expected to outpace another. For example, the species with more narrow height distributions in Figs. 2 and 3 are rarely (sassafras, blackgum, or maples) or never (dogwood) components of the overstory canopy in mature forests of the Missouri Ozarks, but given the considerable overlap in early height distributions, they are clearly capable of being a source of competition in young stands (Burns and Honkala 1990; Johnson et al. 2009).

Interpretation of development patterns should be done with some caution. The quantile lines reflect the height distribution of a peer group at a given point in time rather than the distribution of growth. This seemingly minor distinction in stature vs. growth can have profound inferential consequences and has led to separate reference chart categories for stature and growth in the medical literature (Cole 1994; Wei et al. 2006). To strengthen this distinction, recall the height development pattern of the white oak used in the application example. When the development pattern of this tree was plotted against the white oak site class – species reference chart (Fig. 4), it appeared to exhibit extraordinary growth between stand ages 7–11, ultimately resulting in a much higher quantile assessment. However, this interpretation may be misleading as it cannot be determined from our stature-based charts if the growth displayed between ages 7–11 is atypical of what might be expected from other white oaks with a similar stature at the start of their 7th growing season. It should also be expected that an individual tree may cross quantiles as it develops. This is common in human growth assessments (Cole 1994), and similar tree growth dynamics have been reported over the course of stand development (Dahms 1963; Rennolls 1978).

Our reference charts were constructed with data from open populations rather than a finite number of individuals, and naturally occurring population changes (e.g., stochastic disturbances, mortality, late germinants) can influence the height distributions. Our reference charts, like many of the most widely used anthropometric reference charts (Kuczmarski et al. 2002; de Onis et al. 2007), were developed with multiple datasets pieced together and analyzed cross sectionally. Thus, latent differences in the combined datasets, as well as any other deficiencies in the data used to construct the reference charts, may influence both parameter and quantile estimates.

While Boulfroy et al. (2012) present a related application of reference values for diameter increment of *Thuja occidentalis* L., we note that quantiles reported from reference chart methodology conceptually differ from most others previously utilized for forestry applications (e.g., Stage 1973; Bohora and Cao 2014). This is due to differences in the peer groups that the respective evaluations used for inference. Generally, the peer groups used by reference chart methods will represent a broader population that is derived from many individuals that share some common characteristic across multiple stands (e.g., site class and (or) species). In contrast, neighborhood or stand-level peer groups draw inference from a more restricted population and have no replication within a neighborhood or stand. Thus, the generality of that information will be a function of interneighborhood or interstand variance. This is not to imply that localized inference is invalid or subsidiary to the reference chart methodology. Both size and relative stature can influence growth in developing stands (Assmann 1970; Oliver and Larson 1996; Weiner 1990). Accordingly, combining reference chart quantiles with localized stature hierarchies may yield improved predictions of growth and mortality. We suggest that this is an area worth exploring as it may offer insight into the relative importance of individual growth and neighborhood competition on developmental processes.

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References

Assmann, E. 1970. The principles of forest yield study. Pergamon Press, New York.

Bohora, S.B., and Cao, Q.V. 2014. Prediction of tree diameter growth using quantile regression and mixed-effects models. For. Ecol. Manage. **319**: 62–66. doi:10.1016/j.foreco.2014.02.006.

Boulfroy, E., Forget, E., Hofmeyer, P.V., Kenefic, L.S., Larouche, C., Lessard, G., Lussier, J.-M., Pinto, F., Ruel, J.-C., and Weiskittel, A. 2012. Silvicultural guide for northern white-cedar (eastern white cedar). USDA Forest Service, Northern Research Station, Newtown, Penn., Gen. Tech. Rep. NRS-98.

Burns, R.M., and Honkala, B.H. (*Editors*). 1990. Silvics of North America, Volume 2: hardwoods. USDA Forest Service, Washington, D.C., Agric. Handb. 654.

Cole, T.J. 1994. Growth charts for both cross-sectional and longitudinal data. Stat. Med. **13**(23–24): 2477–2492. doi:10.1002/sim.4780132311. PMID:7701148.

Cole, T.J., and Green, P.J. 1992. Smoothing reference centile curves: the LMS method and penalized likelihood. Stat. Med. **11**: 1305–1319. doi:10.1002/sim.4780111005. PMID:1518992.

Dahms, W.G. 1963. Correction for a possible bias in developing site index curves form sectioned tree data. J. For. **61**: 25–27.

de Onis, M., Onyango, A.W., Borghi, E., Siyam, A., Nishida, C., and Siekmann, J. 2007. Development of a WHO growth reference for school-aged children and adolescents. Bull. W.H.O. **85**(9): 660–667. PMID:18026621.

Delignette-Muller, M.L., and Dutang, C. 2015. fitdistrplus: an R package for fitting distributions. J. Stat. Softw. **64**(4): 1–34. doi:10.18637/jss.v064.i04.

Faraway, J., Marsaglia, G., Marsaglia, J., and Baddeley, A. 2017. goftest: classical goodness-of-fit tests for univariate distributions [online]. R package version 1.0-4. Available from http://CRAN.R-project.org/package=goftest.

Johnson, P.S., Shifley, S.R., and Rogers, R. 2009. The ecology and silviculture of oaks. 2nd ed. CABI, Wallingford, U.K. doi:10.1079/9781845934743.0000.

Kabrick, J.M., Meinert, D., Nigh, T., and Gorlinsky, B.J. 2000. Physical environment of the Missouri Ozark forest ecosystem project sites. *In* Missouri Ozark Forest Ecosystem Project: site history, soils, landforms, woody and herbaceous vegetation, down wood, and inventory methods for the landscape experiment. *Edited by* S.R. Shifley and B.L. Brookshire. USDA Forest Service, North Central Forest Experiment Station, St. Paul, Minn., Gen. Tech. Rep. NC-208. pp. 41–70.

Kabrick, J.M., Zenner, E.K., Dey, D.C., Gwaze, D., and Jensen, R.G. 2008. Using ecological land types to examine landscape-scale oak regeneration dynamics. For. Ecol. Manage. **255**: 3051–3062. doi:10.1016/j.foreco.2007.09.068.

Kelty, M.J., Larson, B.C., and Oliver, C.D. (*Editors*). 1992. The ecology of mixed-species forests: a festschrift for David M. Smith. Springer, Dordrecht, Netherlands. doi:10.1007/978-94-015-8052-6.

Kuczmarski, R.J., Ogden, C.L., Guo, S.S., Grummer-Strawn, L.M., Flegal, K.M., Mei, Z., Wei, R., Curtin, L.R., Roche, A.F., and Johnson, C.L. 2002. 2000 CDC growth charts for the United States: methods and development. National Center for Health Statistics. Vital Health Stat. **11**(246). PMID:12043359.

McQuilkin, R.A. 1974. Site index prediction tables for black, scarlet, and white oaks in southeastern Missouri. USDA Forest Service, North Central Forest Experiment Station, St. Paul, Minn., Res. Pap. NC-108.

Nigh, T., Buck, C., Grabner, J., Kabrick, J., and Meinert, D. 2000. Ecological classification system for the current River Hills subsection. Missouri Department of Conservation Publication, Jefferson City, Mo.

Oliver, C.D., and Larson, B.C. 1996. Forest stand dynamics. 2nd ed. John Wiley & Sons, New York.

Quetelet, A. 1871. Anthropometrie. Muquardt, Brussels.

R Core Team. 2015. R: a language and environment for statistical computing [online]. R Foundation for Statistical Computing, Vienna, Austria. Available from http://www.R-project.org/.

Rennolls, K. 1978. “Top Height”; its definition and estimation. Commonw. For. Rev. **57**: 215–219.

Stage, A.R. 1973. Prognosis model for stand development. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Res. Pap. INT-137.

Ulijaszek, S.J., Johnston, F.E., and Preece, M.A. 1998. The Cambridge encyclopedia of human growth and development. Cambridge University Press, Cambridge, U.K.

Venables, W.N., and Ripley, B.D. 2002. Modern applied statistics with S. 4th ed. Springer, New York. doi:10.1007/978-0-387-21706-2.

Vickers, L.A., Larsen, D.R., Knapp, B.O., Kabrick, J.M., and Dey, D.C. 2014. The impact of overstory density on sapling height growth in the Missouri Ozarks: implications for interspecific differentiation during canopy recruitment. Can. J. For. Res. **44**(11): 1320–1330. doi:10.1139/cjfr-2014-0237.

Ward, J.S., and Stephens, G.R. 1993. Influence of crown class and shade tolerance on individual tree development during deciduous forest succession in Connecticut, USA. For. Ecol. Manage. **60**: 207–236. doi:10.1016/0378-1127(93)90081-W.

Ward, J.S., and Stephens, G.R. 1994. Crown class transition rates of maturing northern red oak (*Quercus rubra* L.). For. Sci. **40**: 1–17.

Ward, J.S., and Stephens, G.R. 1996. Influence of crown class on survival and development of *Betula lenta* in Connecticut, U.S.A. Can. J. For. Res. **26**: 277–288. doi:10.1139/x26-031.

Wei, Y., Pere, A., Koenker, R., and He, X. 2006. Quantile regression methods for reference growth charts. Stat. Med. **25**: 1369–1382. doi:10.1002/sim.2271. PMID:16143984.

Weiner, J. 1990. Asymmetric competition in plant populations. Trends Ecol. Evol. **5**: 360–364. doi:10.1016/0169-5347(90)90095-U. PMID:21232393.