For. Sci. 61(1):114–122
http://dx.doi.org/10.5849/forsci.13-620

biometrics

Estimating Yields of Unthinned Eastern White Pine Plantations from Current Stocking in the Southern Appalachians

Todd E. Hepp, John P. Vimmerstedt, Glendon W. Smalley, and W. Henry McNab

Eastern white pine (*Pinus strobus* L.) is a highly productive native conifer of the southern Appalachian Mountains that has long been established in plantations for conventional purposes of afforestation and timber production and potentially for carbon sequestration both within and outside its natural range. Growth-and-yield models are not available, however, for use by land managers to evaluate potential economic value of plantations established on sites of various qualities over time. Data from 78 plantations in the southern Appalachian Mountains of Georgia, North Carolina, and Virginia were used to develop models for estimation of survival, basal area, and yields of cubic and board feet as functions of stand age, site quality, and stocking. Stand structure and volume yields were strongly related to stand age and site quality. Compared to plantations on sites of lower quality, stands on good sites had lower survival but higher basal area stocking, cubic volume, and sawtimber yields.

Keywords: basal area, board foot volume, cubic volume, *Pinus strobus*, site quality, survival

Eastern white pine (*Pinus strobus* L.) has long been recognized as a highly desirable native conifer with silvical characteristics favorable for management under various silvicultural systems on a range of sites in the northeastern United States (Wendel et al. 1983). In the South, eastern white pine (hereafter white pine) is primarily a species of mountainous landscapes of the Cumberland Mountains of Tennessee and the southern Appalachian Mountains of Georgia, North and South Carolina, and Virginia (Burns and Honkala 1990). Silvics of the species and its silviculture in pure and mixed natural stands are well known (Wendel and Smith 1990).

The species is favored for intensive culture in pure stands because it is easily established, is long lived, forms dense stands that respond to management, has few insect and disease problems, outgrows almost all other native species on low-quality sites, and is economically valuable (Wahlenberg and Doolittle 1950, Dierauf and Scrivani 1995, Smalley and Hollingsworth 1997, Clatterbuck and Ganus 2000, McNab and Ritter 2000, Myers et al. 2008). Plantations of white pine occupy nearly 50,000 acres in the southern Appalachian Mountains of North Carolina, of which nearly 80% is on private or industrial lands (Johnson 1991). As with loblolly pine (*P. taeda L.*) in the Georgia Piedmont (Hays 1989), white pine has been suggested as a suitable species for use by southern Appalachian landowners under the 1985 Conservation Reserve Program (Clatterbuck and Ganus 2000), which was implemented to reduce erosion from unstable soils on agricultural fields. As white pine plantations established under the Conservation Reserve Program approach maturity, practical guides are needed by landowners for evaluation of silvicultural options, such as thinning, to achieve management objectives for conventional products and emerging alternative purposes, such as carbon sequestration (McNab 2012).

White pine is the most widely planted tree species for restoration of surface-mined land in the eastern coalfields region of southwestern West Virginia, eastern Kentucky, and western Virginia (Andrews et al. 1998, Torbert et al. 2000). White pine plantations establish well on low- to medium-quality reclaimed sites, tolerate

Manuscript received June 17, 2013; accepted April 11, 2014; published online June 5, 2014.

Affiliations: *Todd E. Hepp (retired), Land and Forest Resources, Tennessee Valley Authority, Knoxville, TN. John P. Vimmerstedt, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster, OH. Glendon W. Smalley, USDA Forest Service, Southern Research Station, Sewanee, TN. W. Henry McNab (hmcnab@fs.fed.us), USDA Forest Service, Southern Research Station, Asheville, NC.*

Acknowledgments: *Research for this study was done when the senior author (TEH) was associated with the Tennessee Valley Authority, Norris, TN, as a programmer analyst. Field data for this study were provided by a coauthor (JPV) that were collected when he was a research forester with the Southeastern Forest Experiment Station. For their work in quality control and leadership during the field data collection phase of this study in 1957, the authors recognize the important contributions by Tim W. Jarrett, forest technician, and James W. McMinn, research forester, Southern Research Station, (now retired; then a participant in the Student Trainee Program of the USDA Forest Service). Other field assistance was provided by L.B. Woody, R.B. Nelson, E.R. Sluder, and L.B. Sumner. Mary Galt Vimmerstedt provided clerical assistance for coauthor JPV. We acknowledge the recent assistance of Ms. Nora Conley, Senior Community Service Employment Program for conversion of field data to digital format.*

competing herbaceous vegetation (Torbert et al. 1985) and respond to intermediate stand management (Casselman et al. 2007). Rodrigue et al. (2002) reported that plantings on reclaimed surface-mined sites were typically more productive than on adjacent unmined sites.

Relatively little information is available to resource managers for management options of white pine plantations in the southern Appalachians. Vimmerstedt (1961, 1962) published cubic and board feet yield tables for unthinned, fully stocked plantations of white pine in the southern Appalachian region. Dierauf and Scrivani (1995) present similar information for plantations in the Appalachian Mountains of Virginia. Existing (Vimmerstedt 1962) yield tables have several limitations. First, the yield tables require estimation of the initial density of seedlings planted, which may be difficult to determine for older plantations where mortality has occurred. Forest managers not only require flexibility to use the most appropriate models for their applications but also require robust procedures that allow inventory data to be substituted for estimates (e.g., estimated yields based on actual survival rather than initial planting density). Also, as an option to the site index curves developed by Vimmerstedt (1959), which were used for several models in his growth-and-yield study (Vimmerstedt 1962), some users could prefer estimation of site index based on height-age relationships developed from recent studies in their geographic area. For example, Dierauf and Scrivani (1995) constructed site index curves for white pine plantations in Virginia.

The objective of the present study was to expand the usefulness of a previous study (Vimmerstedt 1962) by developing alternative yield equations that use surviving number of trees per acre, and current stand height and plantation age as independent variables. The final result is a yield-estimation procedure that should have improved utility for land managers planning for management options in the following ways:

- Volume yield for established plantations may be estimated more accurately when the number of surviving trees per acre is known.
- Height of dominants rather than site index is used as the measure of site quality. This allows the user flexibility to substitute the site index equation of choice (e.g., see Beck 1971) into the yield-estimation procedure.
- Survival and volume yield estimates for established plantations may be projected and volume growth rates determined by differencing.

The scope of our study is limited to planted, fully stocked, unthinned stands of white pine established on old-field sites.

Methods

Our study is based on the data set used by Vimmerstedt (1962) because resources were not currently available for collection of more recent field data. The Vimmerstedt (1962) dataset was remodeled in 1981 to develop a comprehensive system of equations suitable for implementation in the YIELD personal computer software (Hepp 1982) that was deployed to hundreds of users.

Study Area and Field Techniques

A total of 78 plantations were examined during 1957 and 1958 in North Carolina, Tennessee, and Georgia (Figure 1) that had been established on old-field sites. Sampling was limited to unburned, unthinned plantations without large openings or numerous trees of other species in the main canopy. Small plots were established in fully stocked parts of plantings on uniform topography and with two or more buffer rows of trees along boundaries. Plots were laid out to include about 64 living trees; the area sampled varied with original spacing of planted seedlings and survival. The following data were collected: (1) total height and age of five or six dominant and codominant trees; (2) stem taper, total height, and bark thickness on a total of 241 trees; (3) a complete tally by 1-in. diameter classes of all live trees; and (4) dbh and total height of two trees in each diameter class (Table 1). Although 130 plots had been established by Vimmerstedt (1962), data from some were eliminated that had been recently damaged by ice (e.g., unsuitable for site index but satisfactory for other variables) or were missing certain parameters (e.g., some plantations were too young to exhibit merchantable volume). Therefore, the number of plots used in development of each model varied. Multiple plots were established in large plantations to sample variation in site quality and density. There was a scarcity of plots for older plantations (i.e., greater than age 30) and for high-quality sites (i.e., greater than site index 65 base age 25) (Table 2). The board-foot volume was estimated using the International 1/4-Inch Rule for trees 7 in. dbh and larger to a 6-in. inside bark top diameter. Additional information on field methods was presented by Vimmerstedt (1962).

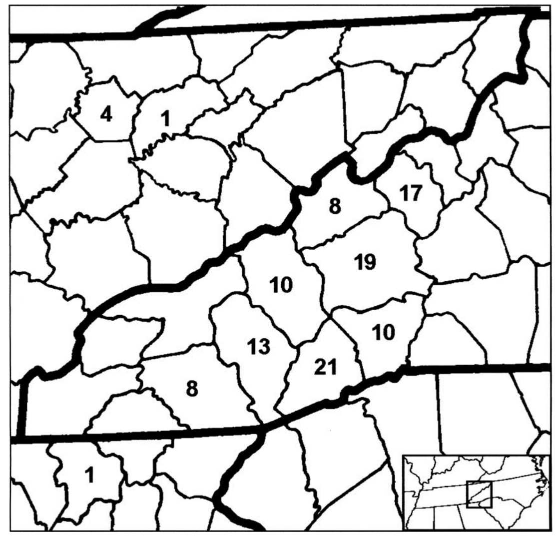

Figure 1. Distribution of sample plots in eastern white pine plantations by county in the southern Appalachian Mountains of northeastern Georgia and western North Carolina and the Clinch Mountains of eastern Tennessee.

Table 1. Minimum, mean, and maximum stand parameters on sample plots established in unthinned eastern white pine plantations in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Parameter	Minimum	Mean	Maximum
Plantation age (years)	10	23	58
Site index (ft, base 25 yr)	45	57	78
Dominant stand height (ft)	18	48	104
Planted density (per acre)	170	1,412	6,226
Surviving density (per acre)	51	970	4,098
Survival ratio (%)	10	74	100
Basal area (ft^2/acre)	31	158	279
Quadratic dbh (in.)	2	6	14
Cubic volume (ft^3/ac, ob.)	40	3,091	9,720
Board feet volume (Int. 1/4)	50	9,212	47,097

Table 2. Distribution by stand age, site index, and density classes of sample plots established in unthinned eastern white pine plantations in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Stand age class	Site index class	Trees surviving per acre				
		100–699	700–1,099	1,100–1,499	1,500-over	Total
Years	Ft	. . . .	.Number.	. . . .		
15 (10–19)	30–49	2	2	0	0	4
	50–69	2	15	10	8	35
	70–89	1	2	3	0	6
	Total	5	19	13	8	45
25 (20–29)	30–49	0	0	0	0	0
	50–69	6	24	8	2	40
	70–89	0	5	0	0	5
	Total	6	29	8	2	45
35 (30–39)	30–49	0	0	0	0	0
	50–69	2	0	0	0	2
	70–89	2	1	0	0	3
	Total	4	1	0	0	5
50+ (40–60)	30–49	0	0	0	0	0
	50–69	14	3	0	0	17
	70–89	0	0	0	0	0
	Total	14	3	0	0	17
All classes	Total	29	52	21	10	112

Model Development

Survival rates were modeled following methods used by Smalley and Bailey (1974a, 1974b) in unthinned loblolly (*P. taeda* L.) and shortleaf pine (*P. echinata* Miller) plantations with the relationship

$$\ln(T_p/T_s) = A \cdot f(A, H, T_p)$$

where: ln is natural logarithm, T_p is number of trees planted (per acre), T_s is number of trees surviving (per acre), A is plantation age (years), f denotes function, and H is average height (ft) of dominant and codominant trees. The YIELD software (Hepp 1982) uses a two-step process with the above relationship to project $T_s(A_1)$ to $T_s(A_2)$. First, T_p is calculated using $T_s(A_1)$. Then $T_s(A_2)$ is calculated by substituting T_p from the first step.

Results and Discussion

Average Plantation Height and Site Index

Average height of dominant and codominant trees ranged from 18 to 104 ft and site index (base age 25) ranged from 45 to 78 ft (Table 1); the majority of stands sampled were in the 50–69-ft class (Table 2). The following model was developed to describe the relationship between height and age of white pine plantations for 111 sample plots

$$\ln(H) = \ln(S) + 18.0964\,(1/25 - 1/A) \quad (1)$$

$$R^2 = 0.88;\ S_{y.x} = 0.1271$$

where H is total tree height in ft, S is site index in ft (base age 25), and A is stand age in years. Anamorphic site index curves (base age 25) can be generated from Equation 1.

Survival Rate

Data from 102 plots were used to determine coefficients for the survival model. The equation selected as most appropriate used transformations of A, H, and T_p identical to those of Smalley and Bailey (1974a, 1974b); the variables A, H, and T_p are the same as

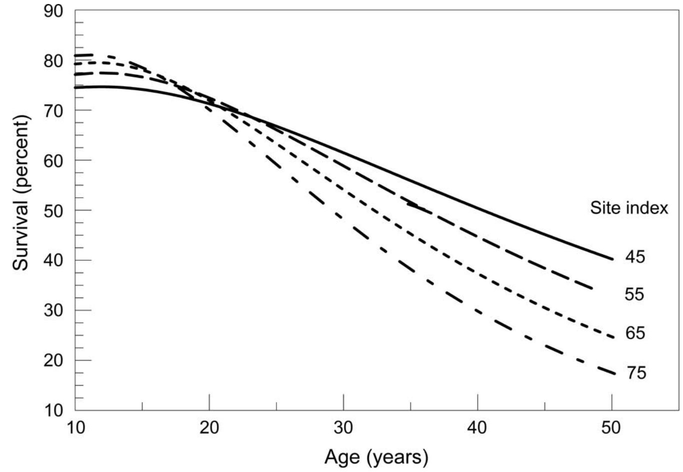

Figure 2. Percentage survival by plantation age class and site index class for an initial planting density of 1,500 eastern white pine seedlings per acre.

previously defined. Residual plots revealed a homogeneous distribution over the range of independent variables.

$$\ln(T_p/T_s) = A[0.011959\ln(T_p) + 0.001514\,H - 0.020786\sqrt{H}] \quad (2)$$

$$R^2 = 0.78;\ S_{y.x} = 0.1736$$

where T_p/T_s is the ratio of total number of trees planted to the number of trees surviving at a specified age and $\sqrt{H}$ is the square root of the average height of dominant and codominant trees. Using Equation 2, the projected number of trees per acre surviving was calculated for each plot in the data set and compared with the observed number. Of the predicted values, 41% were within ± 10% of the observed. There was a slight tendency to overpredict survival (average difference was 26 trees, or 2%). Figure 2 illustrates survival patterns for a planting density of 1,500 stems per acre, which was near the study average of 1,445 seedlings per acre.

Yield Equations

Equations to predict cubic foot volume (*CUFT*), basal area (*B*), and board foot volume (*BDFT*) per acre were derived as functions of A, H, and T_s, as previously defined. A model similar to one developed by Burkhart et al. (1972) was determined to be most suitable. The general form of the model is

$$\ln(Y) = b_0 + b_1(1/A) + b_2(H/A) + b_3(T_s)$$

where Y = yield (*CUFT, B, BDFT*) per acre and b_0–b_3 are coefficients derived from analysis of the field data.

Various transformations of the independent variables in the above model were tested. Criteria used to refine the equation were the coefficient of determination (R^2), standard error of the estimate ($S_{y.x}$), residual patterns, and projections that follow expected biological behaviors such as stand senescence and competition-related effects relative to site quality.

A total of 111 plot records was used to fit the following equation for CUFT.

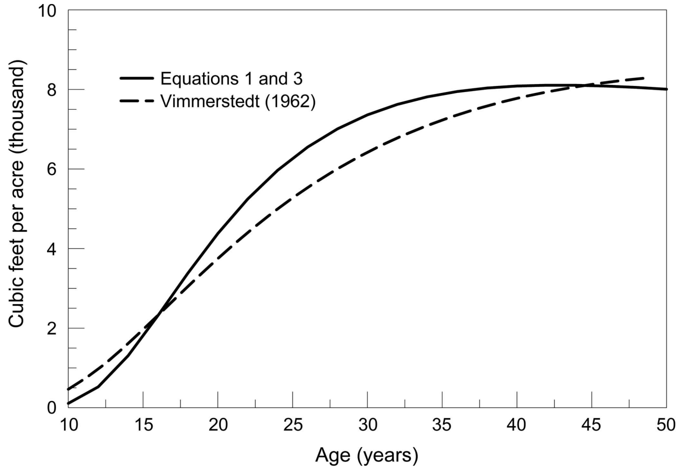

Figure 3. Comparison of volume (ft^3/ac of trees ≥ 3 in. dbh to 3-in. diameter outside bark top) by plantation age for an initial planting density of 1,500 eastern white pine seedlings per acre and site index of 60 ft (25 years) for this study and Vimmerstedt (1962).

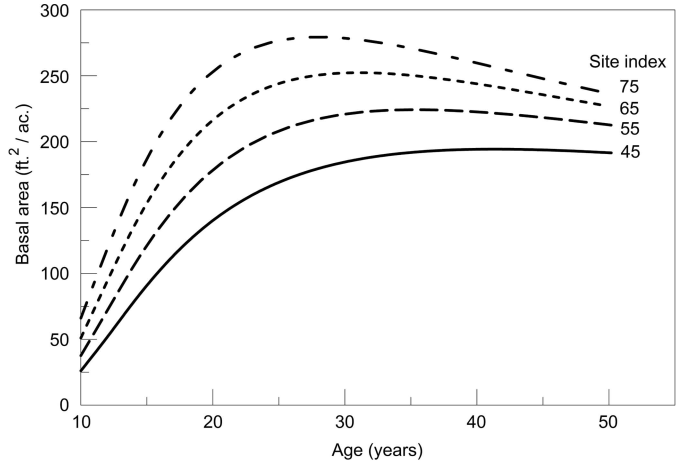

Figure 5. Basal area stocking (ft^2/ac) by plantation age and site index class for an initial planting density of 1,500 eastern white pine seedlings per acre.

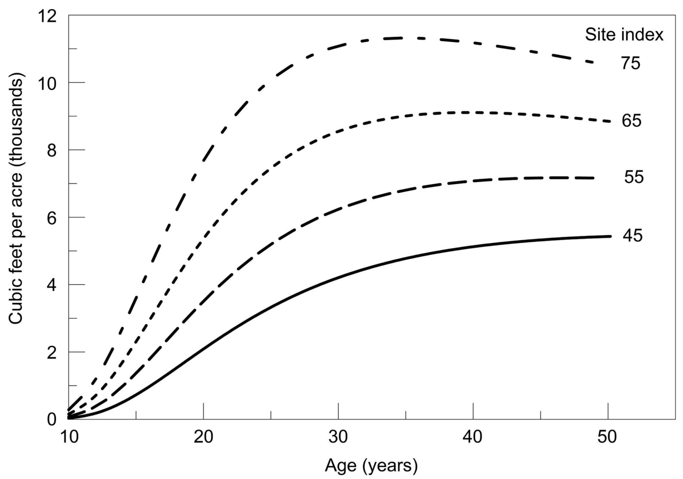

Figure 4. Volume (ft^3/ac of trees ≥ 3 in. dbh to 3-in. diameter outside bark top) by plantation age and site index class for an initial planting density of 1,500 eastern white pine seedlings per acre.

$$\ln(CUFT) = 3.9875 - 124.3106(1/A) + 0.9526\ln(H) + 0.0184\sqrt{T_s} + 32.0889\ln(H)/A \quad (3)$$

$$R^2 = 0.96;\ S_{y.x} = 0.1844$$

where *CUFT* is cubic foot volume per acre (outside bark to 3-in. top) for all stems 3 in. dbh or greater.

Equation 2 is used to calculate T_s from T_p. T_s is then substituted in Equation 3 to calculate *CUFT* across the range of *A* and *H*. In contrast to Vimmerstedt's equation, volume estimates tend to be less at very young ages, noticeably greater at intermediate ages, and about equal at older ages (Figure 3).

Also, the culmination of yield predictions occurs in the age range of 35 to 50 years and is strongly influenced by site quality (Figure 4). A similar trend has been modeled in other studies of pine plantation yields (Dell et al. 1979, Smalley and Bailey 1974a, 1974b).

Vimmerstedt's equation for estimating cubic foot volume uses T_p as the measure of stand density. Predicted yields assume an implicit survival rate. For the present study, cubic foot volume is estimated with Equation 3. This requires that an estimate of T_s from T_p be made first using Equation 2.

A comparison of our modeling procedure with that of Vimmerstedt (1962) was made using the original data set. Of the predicted values from the Vimmerstedt equation, 37% were within ± 10% of the observed compared to 46% using Equations 2 and 3. When observed T_s and Equation 3 alone are used, this increased slightly to 51%.

Predictions by both Vimmerstedt (1962) and our model tended to slightly underpredict observed cubic volumes calculated from relationships developed by Vimmerstedt (1961). The average difference by the Vimmerstedt (1962) relationship was −10.1 cubic feet per acre and for Equations 2 and 3 of this study the average difference was −8.9 cubic feet per acre. When observed T_s was substituted into Equation 3, the average difference was −3.5 cubic feet per acre. This is evidence that more reliable yield estimates for established plantations are possible when T_s is measured rather than estimated with the survival relationship.

A total of 111 plot records was used to fit the following equation for basal area.

$$\ln(B) = 2.0973 - 44.3744\,(1/A) + 0.5906\ln(H) + 0.0251\sqrt{T_s} + 11.5969\ln(H)/A \quad (4)$$

$$R^2 = 0.90;\ S_{y.x} = 0.1218$$

where *B* is basal area (ft^2/acre outside bark) for all stems 3 in. dbh or greater.

Culmination of basal area per acre development is modeled to occur in the age range of 25 to 45 years depending on site quality (Figure 5).

To fit the following equation for *BDFT*, 94 plot records were available.

$$\ln(BDFT) = 9.4631 - 479.1162\,(1/A) + 122.1485\ln(H)/A - 0.7930\,T_s/1{,}000 \quad (5)$$

$$R^2 = 0.88;\ S_{y.x} = 0.6162$$

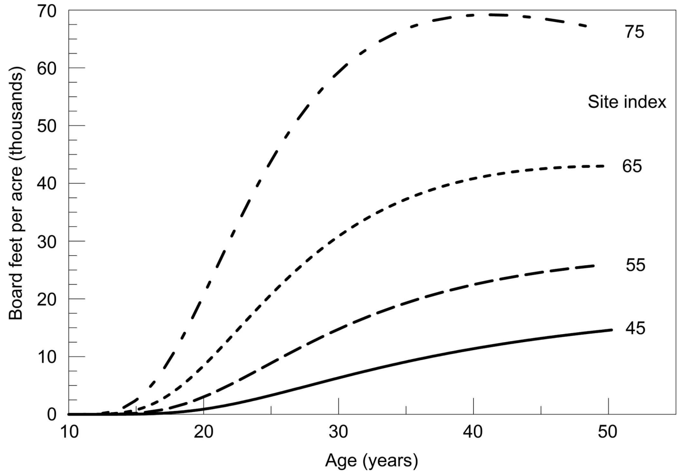

Figure 6. Volume (bd ft/ac, International 1/4-Inch Rule of trees ≥ 7 in. dbh to 6-in. diameter inside bark top) by plantation age and site index class for an initial planting density of 1,500 eastern white pine seedlings per acre.

where *BDFT* is board foot volume per acre, to a 6.0-in. top diameter inside bark (diameter inside bark), International 1/4-Inch Rule for all stems 7 in. dbh or greater.

Of the predicted board foot volume estimates, 30% were within ± 10% of the observed values. The estimating procedure used by Vimmerstedt also generated a 30% precision level, with a slight bias to under predict (average difference was −231 board feet). In comparison, Equations 1 and 5 together tended to over predict slightly (average difference was 280 board feet). Neither of these average differences is significant at the 95% confidence level. The trend of board foot volume production varies greatly by site quality with a marked increase for site index 75 (Figure 6). As expected, culmination for board foot yield occurs at a later age than for cubic foot volume.

Yield Tables

Equations 1–5 were used to generate estimated survival, basal area, and volumes for combinations of plantation ages, planting densities, and site indexes (Tables 3–9). Planting density ranges from 500 to 2,500 trees/acre in increments of 500, site index ranges from 45 to 75 ft in increments of 5 ft, and age ranges from 10 to 50 years in increments of 5 years. Users should take notice of certain combinations of ages, density, and site index represented by sparse field data. Particularly conspicuous is the lack of data for intermediate ages (30–39 years) and for plantations of high stocking densities on sites of high site index. Quadratic mean diameters (D) are not presented in the tables but may be calculated from estimated stem density and basal area (B) as

$$D = \sqrt{B/kN}$$

where k is 0.00545415, and N is number of trees/acre. Table 10 provides both a comparison of measured with predicted parameter values for a selected sample plot from the field data set and a means for managers to check results of solving the models, for example, using a computer spreadsheet application.

Implications for Management

Predicted survival and growth are believed to be representative of the natural development of undisturbed, nearly pure white pine plantations established on a range of site qualities throughout the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee. For conciseness, graphical examples in Figures 2–6 are limited to a planting density of 1,500 trees per acre, or a spacing of about 5 by 6 ft. Where discussions relate to changes in planting density, trends can be verified from the table.

Survival.—On all sites survival percentage decreased as planting density and age increased. With an increase in site quality, however, survival was slightly higher at early ages and lower at older ages. This is likely a result of increased competition on higher quality sites as age increased.

Table 3. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 45 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft^2)	(ft^3)	(bd ft)
500	10	–	–	19	26	0
	15	–	–	67	583	69
	20	463	93	106	1,701	1,456
	25	464	93	131	2,762	5,062
	30	456	91	147	3,564	9,149
	35	443	89	157	412,9	12,452
	40	426	85	164	4,518	14,775
	45	408	82	167	4,785	16,295
	50	388	78	170	4,964	17,272
1,000	10	–	–	23	30	0
	15	797	80	80	663	52
	20	785	79	125	1,917	1,128
	25	754	75	152	3,079	4,022
	30	711	71	168	3,929	7,474
	35	662	66	177	4,500	10,466
	40	612	61	181	4,871	12,749
	45	562	56	183	5,103	14,422
	50	513	51	183	5,241	15,642
1,500	10	1,117	74	26	33	0
	15	1,112	74	91	729	41
	20	1,069	71	140	2,089	901
	25	1,002	67	169	3,326	3,304
	30	922	61	185	4,206	6,322
	35	839	56	192	4,776	9,096
	40	756	50	194	5,125	11,373
	45	677	45	194	5,325	13,165
	50	604	40	192	5,430	14,552
2,000	10	1,440	72	29	36	0
	15	1,408	70	101	787	32
	20	1,331	67	154	2,240	732
	25	1,225	61	184	3,537	2,769
	30	1,109	55	199	4,439	5,451
	35	991	50	204	5,003	8,063
	40	878	44	205	5,330	10,324
	45	773	39	203	5,503	12,200
	50	678	34	199	5,578	13,723
2,500	10	1,752	70	32	38	0
	15	1,691	68	110	841	26
	20	1,577	63	167	2,377	602
	25	1,433	57	198	3,728	2,348
	30	1,280	51	211	4,646	4,760
	35	1,129	45	216	5,202	7,227
	40	987	39	214	5,508	9,469
	45	857	34	210	5,654	11,413
	50	741	30	205	5,700	13,054

Bold, underlined ages indicate range of data.

Table 4. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 50 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft²)	(ft³)	(bd ft)
500	10	–	–	23	40	0
	15	–	–	78	811	161
	20	469	94	120	2,232	2,759
	25	463	93	147	3,494	8,477
	30	449	90	163	4,396	14,128
	35	428	86	172	4,995	18201
	40	405	81	177	5,384	20,725
	45	380	76	180	5,629	22,177
	50	354	71	181	5,777	22,952
1,000	10	–	–	28	46	0
	15	812	81	93	923	122
	20	794	79	142	2,517	2,132
	25	753	75	170	3,896	6,736
	30	700	70	185	4,844	11,578
	35	641	64	193	5,439	15,372
	40	581	58	196	5,793	18,025
	45	523	52	196	5,990	19,799
	50	468	47	194	6,084	20,968
1,500	10	1,138	76	32	51	0
	15	1,133	76	106	1,015	95
	20	1,081	72	159	2,744	1,698
	25	1,001	67	189	4,209	5,533
	30	908	61	203	5,183	9,818
	35	811	54	209	5,764	13,433
	40	718	48	209	6,087	16,170
	45	631	42	207	6,243	18,174
	50	551	37	203	6,294	19,632
2,000	10	1,466	73	35	56	0
	15	1,435	72	118	1,097	75
	20	1,346	67	175	2,943	1,376
	25	1,225	61	206	4,477	4,633
	30	1,091	55	219	5,466	8,491
	35	959	48	222	6,034	1,1945
	40	834	42	221	6,324	14,749
	45	720	36	216	6,443	16,936
	50	618	31	210	6,456	18,617
2,500	**10**	1,784	71	39	60	0
	15	1,723	69	129	1,173	59
	20	1,595	64	190	3,125	1,129
	25	1,432	57	221	4,717	3,931
	30	1,259	50	233	5,718	7,432
	35	1,092	44	234	6,270	10,750
	40	937	37	230	6,529	13,592
	45	798	32	224	6,613	15,920
	50	676	27	217	6,593	17,780

Bold, underlined ages indicate range of data.

Table 5. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 55 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft²)	(ft³)	(bd ft)
500	10	–	–	27	60	0
	15	–	–	89	1,092	349
	20	471	94	135	2,851	4,930
	25	459	92	162	4,316	13,548
	30	436	87	177	5,301	21,043
	35	408	82	185	5,916	25,789
	40	378	76	189	6,285	28,327
	45	347	69	191	6,493	29,487
	50	316	63	191	6,598	29,856
1,000	10	–	–	33	69	0
	15	824	82	106	1,244	263
	20	798	80	159	3,216	3,804
	25	746	75	187	4,810	10,790
	30	681	68	202	5,834	17,327
	35	611	61	208	6,428	21,954
	40	543	54	209	6,747	24,853
	45	478	48	207	6,891	26,577
	50	418	42	204	6,930	27,536
1,500	**10**	1157	77	38	77	0
	15	1149	77	121	1,369	203
	20	1086	72	178	3,506	3,027
	25	991	66	208	5,193	8,885
	30	883	59	221	6,236	14,762
	35	774	52	224	6,806	19,292
	40	670	45	223	7,075	22,472
	45	576	38	218	7,168	24590
	50	492	33	213	7,155	25,967
2,000	**10**	1,490	75	42	83	0
	15	1,455	73	135	1,480	159
	20	1,352	68	196	3,761	2,451
	25	1,213	61	226	5,523	7,451
	30	1,062	53	237	6,575	12,809
	35	915	46	238	7,117	17,251
	40	779	39	234	7,344	20,611
	45	658	33	228	7,389	23,042
	50	552	28	220	7,330	24,760
2,500	10	1,813	73	47	90	0
	15	1,748	70	148	1,583	126
	20	1,603	64	213	3,994	2,009
	25	1,418	57	243	5,818	6,333
	30	1,225	49	252	6,873	11,255
	35	1,041	42	251	7,386	15,610
	40	875	35	244	7,573	19,100
	45	729	29	235	7,574	21,780
	50	604	24	226	7,477	23,760

Bold, underlined ages indicate range of data.

Basal Area.—Total basal area (trees of all sizes) for site indexes of 65 and 75 culminated before age 40 for all planting densities. For stands with site index of 55, however, culmination occurred at densities greater than about 2,000 trees per acre. On sites where site index is 45 or less, culmination of basal area increment will probably occur at ages greater than 50 years. As planting densities increased, mean diameter declined for plantings of all ages and site qualities. Improvement in site quality always resulted in stands with larger mean diameter. For all stands of all site qualities and densities, diameter growth was essentially linear past age 20.

Yields.—Total cubic-foot volume (trees ≥ 3.0 in. dbh to a 3.0-in. diameter inside bark top) and board foot (trees ≥ 7.0 in. dbh to a 6.0-in. diameter inside bark top) yields increased with site quality and planting density, but the effect of density was small for stands where site index was less than 55 ft. Yield increased with age for all planting densities on site indexes 40 and 50. For planting densities of 1,000–2,500 trees per acre on site qualities 60 and 70, yield culminated at 30–35 years. In effect, the loss of volume from mortality began to exceed both total and merchantable growth on the remaining trees.

Mean Annual Increment.—For total volume, mean annual increment culminated for all site qualities and planting densities. Age

Table 6. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 60 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft²)	(ft³)	(bd ft)
500	10	–	–	32	87	0
	15	472	94	100	1,432	706
	20	470	94	149	3,560	8,394
	25	451	90	176	5,225	20,858
	30	420	84	191	6,276	30,372
	35	385	77	198	6,887	35,582
	40	348	70	200	7,216	37,838
	45	311	62	200	2,370	38,424
	50	277	55	199	7,423	38,087
1,000	10	–	–	38	100	0
	15	833	83	120	1,633	530
	20	797	80	176	4,016	6,476
	25	733	73	204	5,818	16,678
	30	655	66	217	6,893	25,208
	35	576	58	221	7,465	30,581
	40	499	50	220	7,722	33,568
	45	429	43	216	7,799	34,991
	50	366	37	212	7,771	35,492
1,500	10	1,173	78	44	111	0
	15	1,162	77	137	1,798	408
	20	1,085	72	198	4,379	5,154
	25	974	65	227	6,278	13,777
	30	850	57	237	7,360	21,596
	35	729	49	238	7,888	27,087
	40	617	41	234	8,085	3,0569
	45	517	34	228	8,095	32,633
	50	430	29	220	8,004	33,735
2,000	10	1,511	76	49	120	0
	15	1,471	74	153	1,944	320
	20	1,351	68	217	4,697	4,174
	25	1,191	60	246	6,671	11,599
	30	1,022	51	255	7,751	18,843
	35	862	43	253	8,238	24,375
	40	717	36	246	8,379	28,239
	45	591	30	237	8,333	30,773
	50	483	24	227	8,189	32,347
2,500	10	1,839	74	55	130	0
	15	1,767	71	167	2,081	253
	20	1,601	64	236	4,987	3,423
	25	1,393	56	264	7,025	9,882
	30	1,180	47	270	8,098	16,623
	35	981	39	265	8,541	22,180
	40	805	32	256	8,628	26,335
	45	655	26	245	8,532	29,250
	50	529	21	233	8,344	31,188

Bold, underlined ages indicate range of data.

Table 7. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 65 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft²)	(ft³)	(bd ft)
500	10	–	–	37	122	0
	15	475	95	112	1,836	1,351
	20	468	94	163	4,365	13,707
	25	440	88	191	6,220	31,111
	30	401	80	204	7,315	42,713
	35	359	72	209	7,900	48,029
	40	316	63	210	8,171	49,557
	45	275	55	209	8,260	49,131
	50	238	48	206	8,247	47,768
1,000	10	–	–	44	140	0
	15	839	84	134	2,095	1,012
	20	792	79	192	4,920	10,601
	25	715	72	220	6,915	25,015
	30	626	63	231	8,019	35,732
	35	537	54	233	8,539	41,706
	40	454	45	230	8,719	44,420
	45	379	38	225	8,710	45,242
	50	315	32	218	8,607	44,938
1,500	10	1,188	79	51	155	0
	15	1,170	78	153	2,307	779
	20	1,079	72	216	5,364	8,443
	25	950	63	244	7,455	20,762
	30	811	54	252	8,546	30,856
	35	679	45	250	9,004	37,264
	40	560	37	244	9,106	40,838
	45	458	31	236	9,025	42,494
	50	371	25	227	8,850	42,986
2,000	10	1,531	77	57	169	0
	15	1,482	74	171	2,497	608
	20	1,342	67	238	5,751	6,854
	25	1,162	58	265	7,916	17,549
	30	976	49	270	8,991	27,072
	35	803	40	265	9,389	33,774
	40	651	33	255	9,421	37,995
	45	523	26	245	9,272	40,359
	50	416	21	234	9,037	41,479
2,500	10	1,863	75	63	182	0
	15	1,780	71	187	2,672	480
	20	1,591	64	258	6,106	5,626
	25	1,359	54	284	8,331	15,011
	30	1,126	45	286	9,382	24,036
	35	914	37	278	9,722	30,928
	40	731	29	265	9,688	35,659
	45	579	23	252	9,478	38,606
	50	455	18	239	9,193	40,216

Bold, underlined ages indicate range of data.

at culmination decreased from 25 years on poor sites to about 19 years on the best sites, regardless of planting density. Increment at culmination increased with planting density up to 2,000 trees per acre on all site qualities. Merchantable volume increment culminated on all sites at all planting densities. However, the culmination occurred at older ages than for total volume (for example, at ages 35–40 years) for site index 40 ft and ages 20–23 for site index 70.

Direct comparison of our results with those reported elsewhere is difficult because of a lack of other studies on white pine or inconsistent measurement variables, such as different base age for site index. In comparison with similar studies of loblolly and shortleaf pine plantations (Smalley and Bailey 1974a, 1974b), however, white pine exhibits similar growth-and-yield relationships with age and site quality. Dale et al. (1989) developed yield equations for white pine plantations in Ohio, but comparisons with our results were not attempted because a base age of 35 years was used for site index in that study.

The yield relationships developed in our study may have broader application than for old-field sites in the southern Appalachians, such as evaluation of management options on reforested surface-mined sites in the southern part of the native range of white pine.

Table 8. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 70 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft²)	(ft³)	(bd ft)
500	10	–	–	42	166	1
	15	477	95	124	2,311	2,466
	20	463	93	178	5,264	21,638
	25	426	85	204	7,296	45,185
	30	380	76	216	8,415	58,727
	35	331	66	220	8,949	63,603
	40	284	57	219	9,149	63,740
	45	241	48	217	9,165	61,720
	50	202	40	212	9,077	58,906
1,000	10	–	–	51	191	1
	15	843	84	149	2,638	1,845
	20	784	78	209	5,931	16,775
	25	693	69	236	8,100	36,562
	30	592	59	244	9,198	49,638
	35	495	50	244	9,642	55,846
	40	407	41	238	9,726	57,816
	45	331	33	232	9,626	57,469
	50	267	27	224	9,439	55,947
1,500	**10**	1,201	80	58	212	0
	15	1,176	78	170	2,906	1,417
	20	1,067	71	235	6,462	13,403
	25	921	61	261	8,722	30,514
	30	768	51	266	9,788	43,172
	35	627	42	261	10,150	50,295
	40	503	34	252	10,137	53,578
	45	400	27	242	9,951	54,409
	50	314	21	232	9,682	53,900
2,000	10	1,548	77	66	231	0
	15	1,489	74	189	3,145	1,105
	20	1,328	66	258	6,927	10,897
	25	1,126	56	283	9,252	25,936
	30	924	46	284	10,284	38,148
	35	741	37	276	10,565	45,948
	40	585	29	264	10,470	50,204
	45	456	23	251	10,202	52,045
	50	353	18	238	9,874	52,258
2,500	10	1,884	75	73	249	0
	15	1,788	72	208	3,367	872
	20	1,574	63	280	7,351	8,966
	25	1,317	53	303	9,729	22,290
	30	1,066	43	301	10,719	34,085
	35	843	34	289	10,924	42,377
	40	657	26	274	10,753	47,418
	45	506	20	258	10,418	50,022
	50	386	15	244	10,031	50,908

Bold, underlined ages indicate range of data.

Table 9. Predicted survival, basal area, and volumes (trees ≥ 3 in. dbh to 3-in. dob top; sawtimber trees ≥ 7 in. dbh to 6-in. dib top) per acre by planting density and plantation age for unthinned eastern white pine plantations of site index 75 (25 yr) in the southern Appalachian Mountains of Georgia, North Carolina, and Tennessee.

Planted stems	Age	Surviving stems		Basal area	Volume	
(T_p)	(yrs)	(T_s)	(%)	(ft²)	(ft³)	(bd ft)
500	10	–	–	47	221	2
	15	478	96	137	2,862	4,322
	20	456	91	192	6,261	33,162
	25	411	82	218	8,455	64,054
	30	357	71	228	9,569	79,206
	35	303	61	230	10,035	82,735
	40	252	50	228	10,142	80,711
	45	208	42	223	10,075	76,406
	50	169	34	218	9,909	71,569
1,000	10	849	85	57	255	1
	15	844	84	164	3,267	3,233
	20	772	77	225	7,047	25,811
	25	668	67	251	9,368	52,244
	30	557	56	257	10,434	67,588
	35	453	45	253	10,776	73,456
	40	362	36	246	10,748	73,968
	45	286	29	238	10,547	71,823
	50	224	22	229	10,274	68,515
1,500	10	1,213	81	66	283	1
	15	1,178	79	187	3,599	2,481
	20	1,051	70	253	7,674	20,688
	25	887	59	277	10,072	43,914
	30	722	48	279	11,081	59,299
	35	573	38	271	11,315	66,788
	40	447	30	260	11,174	69,147
	45	345	23	248	10,874	68,540
	50	263	18	237	10,513	66,428
2,000	10	1,563	78	74	309	1
	15	1,491	75	208	3,895	1,936
	20	1,308	65	278	8,221	16,873
	25	1,086	54	300	10,677	37,503
	30	869	43	297	11,626	52,773
	35	678	34	286	11,761	61,451
	40	520	26	271	11,521	65,257
	45	394	20	256	11,132	65,928
	50	295	15	242	10,700	64,763
2,500	10	1,903	76	82	333	1
	15	1,791	72	228	4,170	1,526
	20	1,551	62	302	8,722	13,916
	25	1,270	51	320	11,217	32,411
	30	1,002	40	314	12,100	47,491
	35	772	31	298	12,145	57,037
	40	584	23	280	11,814	62,028
	45	437	17	263	11,350	63,717
	50	323	13	247	10,858	63,341

Bold, underlined ages indicate range of data.

For example, using information for an unthinned white pine stand on a reclaimed surface-mined site in southwestern Virginia (Casselman et al. 2007), our models predicted basal area and quadratic mean dbh within 10% of actual. We do not imply that our survival and yield prediction equations are applicable for sites other than old fields, however, and suggest only that the models receive further test and evaluation elsewhere.

In summary, white pine is a native conifer that occurs at low to middle elevations in mixed and nearly pure stands throughout the southern Appalachian Mountains. For over 100 years, the species has also been planted for resource management objectives ranging from controlling erosion and increasing productivity on previously cultivated slopes to production of high-quality sawtimber on more favorable sites. Also, improved genotypes are now available for planting. Results of this study are applicable for estimating yields of conventional cubic and sawtimber volumes in unmanaged plantations on old-field sites. Users should be aware that the reliability of yield projections from our equation system is inversely related to the scope of extrapolation. Except for several case studies (McNab and Ritter 2000, McNab 2012), guides are not available for the response of white pine stands to intermediate stand management, such as reduction of basal area to increase yields of conventional products.

Table 10. Comparison of observed with predicted values for yield models developed in this study and by Vimmerstedt (1962) using data from a selected sample plot.

Parameter	Observed	Hepp (1982)	Vimmerstedt (1962)
T_p per acre (N)	1,210	–	–
Age (yrs)	20	–	–
Height of dominants (ft)	48	–	–
T_s per acre (N)	908	923	n/a
Basal area (ft^2/ac)	187	176	n/a
Stand dbh (in.)	6.4	5.9	n/a
Cubic volume (ft^3/ac)	3,590	3,734	3,375
Board feet volume (Int. 1/4-in.)	6,176	4,583	4,025[a]

[a] Interpolated from Table 8, Vimmerstedt (1962).
n/a, not applicable.

Carbon sequestration is an emerging, unconventional product that has been identified as a management option for conifer plantations in the South, particularly loblolly pine (Johnsen et al. 2004) and should be considered as a potential management option for white pine plantations (McNab 2012). Because our results were derived from plantations inventoried more than 50 years earlier, users should be aware of potential limitations when applying the models to current young white pine plantations, such as the unknown effects of possible changes of climate on site index, survival, and growth and yield (Huang et al. 2011).

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