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Growth of *Pinus caribaea hondurensis* Relative to Spacing and Trunk Diameter on Two Soils in Puerto Rico

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ABSTRACT.—Analysis of 19-year-old planted *Pinus caribaea* var. *hondurensis* on clay and sandy soils in the mountains of Puerto Rico showed the suitability of both sites for tree growth to commercial size. Growth rates were compared with tree densities ranging from 278 to 2,500 trees per hectare and tree dbh's (trunk diameters outside bark at breast height, 1.4 meters above ground on the upper side) from 10 to 40 cm. With angular spacing tree growth was found related to that of six equidistant adjacent trees. Frequent past remeasurements exposed tree growth trends with changes in the density of surrounding trees. Regressions of tree diameter growth based on relative basal area tree density had coefficients of determination (R^2) of 0.76 and 0.77 for clay and sand, respectively. As a guide to tree planting spacing and thinning for any plantation productivity goal a table is presented showing predicted time requirements to grow each 10 cm in dbh, mean annual dbh growth rates, and approximate periodic productivity of usable wood in m^3/ha/yr. On comparable sites this table permits managers of plantations with any spacing and mean tree dbh to predict current growth, number of years to any mature tree size, the approximate yield at that time, and tree growth stimulation after thinning of different intensities at different times.

KEYWORDS.—*Pinus caribaea*, tree plantations, tree growth, growing space, thinning, Puerto Rico

INTRODUCTION

Pinus caribaea Morelet var. *hondurensis* Barr. & Golf, one of the most tropical of pines (Critchfield and Little 1966) has been widely planted (Evans 1992). The wood is useful for pulp, poles, and sawn lumber (Plumptre 1984). Between 2004 and 2006 Puerto Rico imported such coniferous wood worth more than $35 millions annually.(Anonymous 2007). Yet plantations of *Pinus caribaea* introduced to Puerto Rico (Vozzo and Hacskaylo 1971), mostly have remained unthinned and unproductive because of slowed tree diameter growth before sawtimber is produced, leaving landowners disillusioned. There is no local scientifically supported guide for sustaining pine growth to sawtimber dimensions.

Craib (1939, 1947) in South Africa found that with a density of 1,500 Caribbean pine trees per hectare, a decline in growth rates due to competition began in the second year. With only 500 trees per hectare the decline still occurred by the sixth year. With no market for small trees there at the time, Craib prescribed early and heavy thinnings. Subsequently, with the appearance of a pulpwood market in South Africa closer spacings were used (Johnston 1962, Villiers 1971).

Sandrasegaran (1966) found the crown diameter/stem diameter ratio to be a guide for sustained growth of *P. caribaea*. Opie (1968) and Gerrard (1969) found in the overlap of circular zones around each tree a measure of competition. They concluded that an angle count (such as by prism) of surrounding plantation basal area is as good an indication of tree growth (R^2 = 0.80) as more complex calculations. Vries and others (1978) in Surinam concluded that an initial spacing of 2.5 × 2.5 m was best for maximum volume production of *Pinus caribaea*. A simulation study by Hogg (1993) in Queensland showed *P. caribaea* to peak in volume at 750 stems/ha and in economic value between 400 and 600 stems/ha.

Anderson, Bacon, and Shea (1981) found that precommercial thinning of *P. caribaea* in Queensland led to more profitability than repeated later commercial thinnings. Bacon, Hawkins, and Ward (1982) in New Zealand concluded that precommercial thinning of *P. caribaea* to a minimum of 600 stems/ha during the early, free growth period provided increased wood volumes from all later thinnings. They recommended thinning by entire rows early despite a resulting requirement of pruning up into the green crowns.

The pine spacing experiment reported here, initiated by C. B. Briscoe in 1962, has produced three published reports. At 11 to 14 years Whitmore and Liegel (1980) compared survival, height growth, dbh growth, and basal area (tree dbh/$2^2 \times \pi$) and volume increment. Liegel, Balmer and Ryan (1985) reported that dbh growth had peaked between ages of 3 to 6 years and tree height growth peaked between ages of 4 to 7 years, depending on the site. They recommended thinning before the declines. Francis (1997) found that increasing mortality among the trees in the most closely spaced treatment (1.6 × 1.6 m) had caused its former wood increment superiority to be surpassed by that of those trees spaced 4.3 × 4.3 m).

Materials and Methods

Two of the sites of the Briscoe experiment were selected. Both are in the subtropical moist life zone (Ewel and Whitmore 1973). One, here denominated 'clay' (in the municipality of Lares) is at an elevation of 420 m, with rainfall averaging about 250 cm per year (Calvesbert 1970). The soil, Alonso clay, is a typic Dystropept, derived from volcanic saprolite, deep, well drained, and strongly acid (Anonymous 1975). The other site, designated 'sand', (located near the Caonillas reservoir in the Municipality of Utuado) is at an elevation of 300 m, with rainfall averaging about 200 cm per year. Its soil is Utuado sandy loam, a typic Humitropept, derived from intrusive granitic rock, relatively shallow, well drained, and strongly acid. Deforestation, cultivation, and grazing preceded the experiment on both sites. Between 1962 and 1964 eight 60-tree plantations were established on each site. Tree configuration was angular with 6 x 10 rows (Figure 1). Replicated plantations were established at tree spacings of 1.6, 2.7, 3.5, and 4.3 meters. Measurements of tree dbh (trunk diameter outside bark 1.4 m above the ground on the upper side), including border strips, were made on the clay site at plantation ages of 4.1, 7.6, 11.4, and 17.9 years, and on the sand site at 5.3, 9.9, 12.6, and 19.0 years.

Twelve central trees from each plantation were selected for the study, surrounded by a two-row border strip (Figure 1). Each central tree originally was surrounded by six others, all equidistant. The present analysis, unlike its predecessors, relates tree growth to concurrent, not original spacing, reflecting periodic changes during the life of the plantation due to tree growth and mortal-

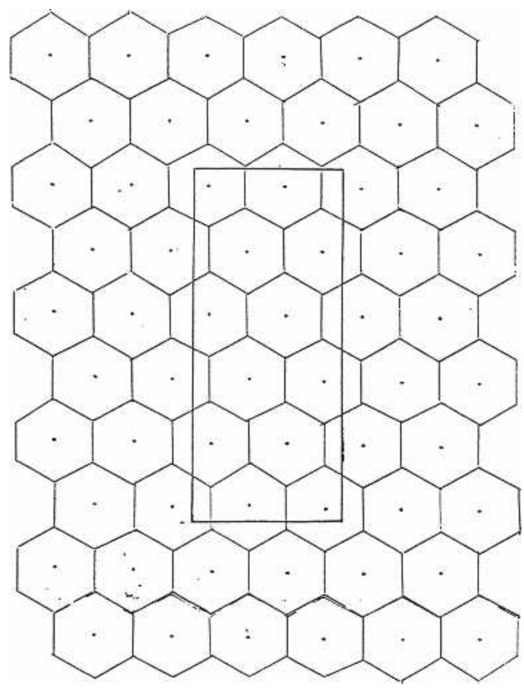

FIG. 1. The arrangement of angular spaced plantation trees illustrating the six equidistant neighbors from each and the technique used to extract a sample of twelve trees with a two-row border strip for study.

ity. Stem growth of a tree, if superior to that of its neighbors, is assumed to use a proportionally larger portion of the space available to its group. The opposite relation is assumed to reduce its proportion. Tree mortality released space to surrounding trees. These changes, added to the experiment's designed, replicated differences in initial spacing and the series of remeasurements provided comparison of a broad range of tree diameters and growing spaces (Table 1).

The basal area increment of each central tree between measurements was related to its dbh at the beginning of each period and the space available to it. This space was determined from the percent of the space assigned by the planting distance to the tree and its six neighbors that corresponds to their respective basal areas. As an example, at initial spacing of 2.5 m, a tree plus its six immediate neighbors would be entitled to an aggregate space of 43.75 m^2 (10000/1600 x 7). Continuing the example, if the basal area of the central tree were 0.02 m^2 and that of the seven were 0.12m^2 the space considered available to the central tree would be $0.02/0.12 \times 43.75 = 7.3$ m^2. Such estimates, averaged for the beginning and end of each period between measurements, were accepted as the spacing concurrent with the basal area increment of each central tree during the period.

Tables 1 and 2 summarize the number, size, and range of spacing and basal area increment of the selected trees. Of a possible 768 measurements (two sites, eight plantations per site, twelve trees per plantation, four growth periods) mortality of central trees in these unthinned plantations, with some closely spaced trees, left only 333, 49 percent on clay and 38 percent on sand. Nevertheless, a wide range of trunk diameters and spacings on both sites was available (Tables 1 and 2). ANOVA regressions supplied a basis for prediction of tree basal area increment, for clay and sand as follows:

TABLE 1. The 19-year-old pines studied on clay and sand, their numbers by trunk diameter at 1.4 m above ground level and the range of densities (spacings) between their remeasurements, in trees per hectare

DBH	Study trees		Per hectare spacing			
	Clay	Sand	Clay		Sand	
cm	No.	No.	Max	Min.	Max.	Min.
10	9	8	2,630	1,060	2,700	1,430
15	47	50	2,630	760	2,780	400
20	53	41	2,630	390	2,500	380
25	32	21	2,130	540	1,120	640
30	25	19	1,300	390	1,120	390
35	18	6	830	330	480	390
40	4	0	420	320		

TABLE 2. The range of increments of the pines studied in trunk diameter and the corresponding numbers of trees on clay and sand

Increment	Study trees	
	Clay	Sand
cm^2/yr	No.	No.
0-9	20	24
10-19	32	23
20-29	26	32
30-39	32	19
40-49	36	25
50-99	31	20
100+	11	2

Tree basal area increment on clay (cm^2/yr) = [$99.42 \times$ space (m^2) $\div$ initial d(cm)] − 11.63 ($n = 188$ $R^2 = 0.77$).

Tree basal area increment on sand (cm^2/yr) = [$84.83 \times$ space (m^2) $\div$ initial d(cm)] − 12.22. ($n = 145$ $R^2 = 0.76$)

Usable wood volumes per tree inside bark were calculated from regressions developed for *Pinus caribaea* in Surinam by Bower (Voorhoeve). The measured diameters and corresponding average heights of the trees in the study led to regressions for estimation of approximate local tree volume based on dbh alone, as follows:

Useful tree volume on clay (m^3) = [$0.000647 \times$ d $(cm)^2$] − 0.0679 ($n = 94$ $R^2 = 0.86$)

Useful tree volume on sand (m^3) = [$0.000692 \times$ d $(cm)^2$] − 0.0758 ($n = 83$ $R^2 = 0.91$)

The time required for passage of each tree dbh class was estimated by dividing the difference in basal area per tree at the beginning and end of each dbh class by the annual stem increment as determined from the regression. Volume increment per hectare per year was calculated from the difference in mean volume per tree at the beginning and end of each growth period, divided by the number of years required and multiplied by the number of trees per hectare.

RESULTS

Averages resulting from the analyses for both sites appear in Table 3 covering seven spacings and seven growth periods defined by tree size. Table 3 indicates a slight inferiority of growth on the sandy soil. This seems at odds with the occurrence of the pine naturally on so many sandy soils elsewhere in the world and may be a result of only strictly local site quality. In practical terms this difference should not rule out planting on sands but more importantly it means that the more widespread local clays may be just as favorable for the pine.

The importance of competition as a cost to tree increment is sharply displayed in Table 3. Initial spacing of 3x3 meters instead of 2x2 can almost triple early increment. Even among trees 35 cm dbh a difference in mean spacing of 278 trees/ha, as compared to 400 almost doubles increment.

Another characteristic of growth is seen in comparing tree diameters in Table 3. A tendency is seen for rapid early growth to subside despite subsequent reduced tree density. The importance of this is not only its effect on the length of the rotation to maturity but on the quality of the wood. Trees with growth rate contrasts tend to produce wood that is refractory and be-

TABLE 3. *Pinus caribaea* stem growth and volume increment relative to initial space during successive growth periods. The numbers to the left of the strike marks are for clay soil, those to the right for sand. The uppermost numbers show the time required to advance to the next dbh class, in years. The middle level numbers show mean annual radial growth in centimeters. The lower numbers show predicted mean annual volume production during the period, in m^3/ha

Growth	Trees per hectare, square spacing, meters separation						
Period Dbh cm	2,500 2 × 2	1,600 2.5 × 2.5	1,111 3 × 3	816 3.5 × 3.5	625 4 × 4	400 5 × 5	278 6 × 6
0	7.1/9.3	4.5/5.3	3.2/3.8				
↓	0.70/0.54	1.1/0.94	1.6/1.3				
	—	—	—				
10	3.5/4.5	1.9/2.3	1.2/1.5				
↓	0.72/0.55	1.3/1.1	2.0/1.6				
	56/44	64/57	68/58				
15							
		4.6/6.0	2.9/3.6	1.7/2.4	1.5/1.8		
↓		0.54/0.42	0.87/0.70	1.5/1.0	1.7/1.4		
		39/32	44/38	54/41	48/43		
20			5.3/6.8	2.9/4.4	2.6/3.2	1.6/1.9	
↓			0.47/0.37	0.86/0.56	0.96/0.79	1.6/1.3	
			30/25	41/29	35/31	37/33	
25							
				5.8/7.4	4.2/5.1	2.5/3.0	1.6/2.0
↓				0.43/0.34	0.60/0.49	1.0/0.84	1.5/1.3
				25/21	35/23	29/26	30/27
30							
					6.2/7.7	3.6/4.4	2.4/2.8
↓					0.41/0.32	0.70/0.57	1.0/0.88
					21/18	23/21	25/22
35							
						5.0/6.1	3.2/3.9
↓						0.50/0.41	0.77/0.64
						20/17	21/18
40							

comes distorted upon drying. This problem can be met by maintaining approximately uniform growth rates throughout the rotation.

The lower figures in Table 3 show an overall downward trend in mean productivity in wood volume per hectare with tree diameter. Since these data are cumulative the mean volume to any size must be the average including the previous periods. It is also apparent that reduced competition increases productivity less where there remain fewer trees.

An example illustrated the utility of Table 3. For posts to 20 cm dbh one might plant at 2.5 × 2.5m and after 6.5 years on clay or 7.6 years on sand thin 15 cm fence posts, leaving about 1,111 trees per hectare for a final yield at 20 cm after three more years on clay and 4 on sand. The predicted final yield in addition to thinnings, should be about 250 m^3/ha. To continue to 35 cm sawtimber, the same calculations of time and growth rates, assuming thinning to 816 trees per hectare at 20 cm dbh, and to 625 trees at 25 cm dbh, trees averaging 35 cm in dbh should be produced in 23 years on the clay and 28 on the sand, with predicted final yields (in addition to thinnings) of about 525 m^3/ha of clay and 580 m^3/ha on sand, overall annual averages of 23 and 21 m^3/ha respectively.

These predictions assume no mortality, a hazard largely avoidable by timely thinning. Nor do they reflect the instant increase in mean tree dbh resulting from thinning trees below average size. These gains can be substantial.

CONCLUSIONS

Both clay and sandy soils in the interior of Puerto Rico are capable of producing *Pinus caribaea* trees to sawtimber dimensions with wood currently imported.

Angular plantation spacing and frequent tree measurements relate tree basal area increment to the size and proximity of surrounding trees.

For uniform rapid growth from pine early and repeated thinnings are necessary. Past growth records as analyzed by the study provide guidance to managers of current plantations of any age, size, or density.

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