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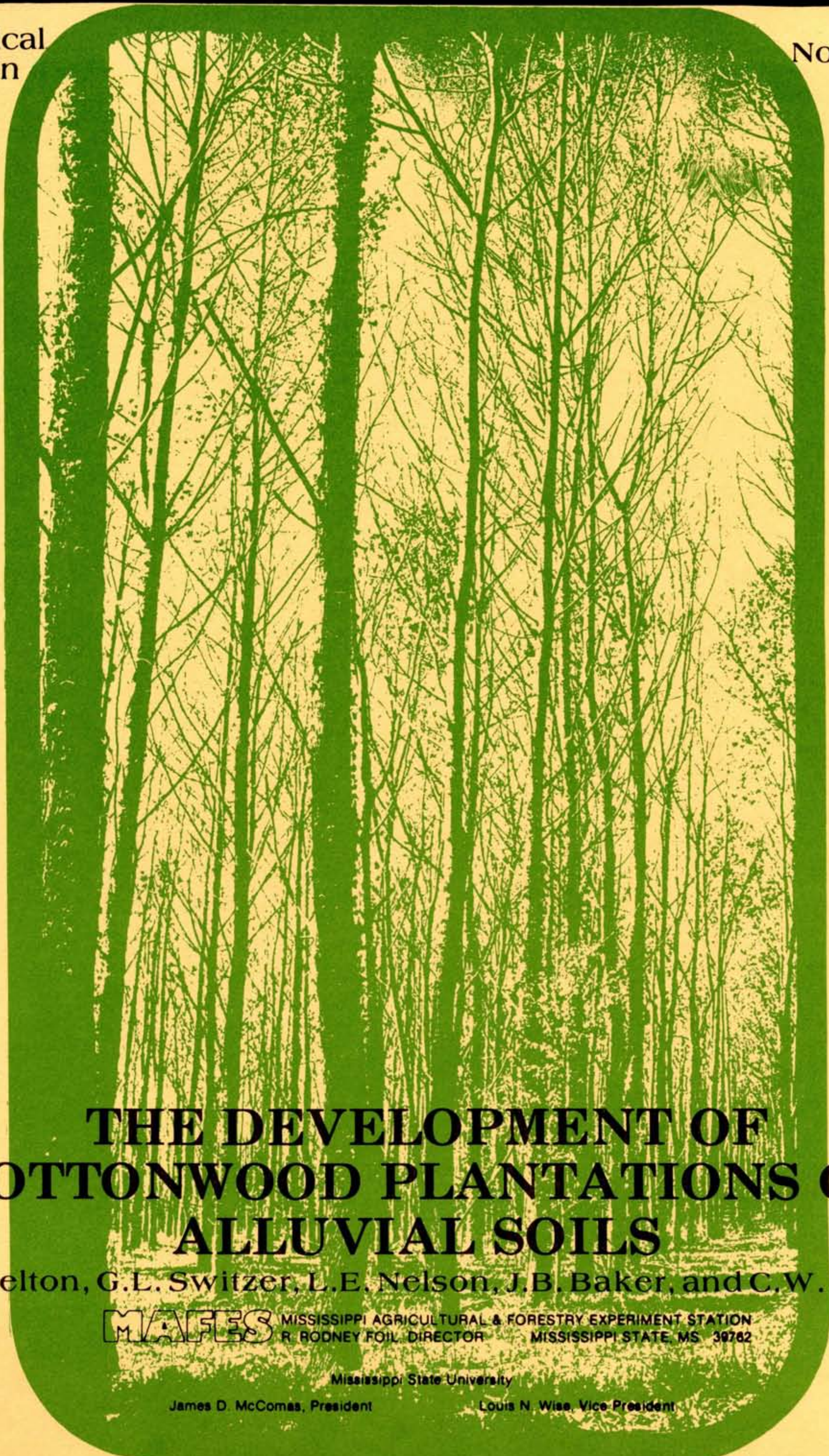

THE DEVELOPMENT OF COTTONWOOD PLANTATIONS ON ALLUVIAL SOILS

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The conversion of metric and English units follows:

Property	To Convert From	To	Multiply By
DBH	cm	inches	0.394
	inches	cm	2.54
Height	m	feet	3.28
	feet	m	0.305
Basal Area	m^2/ha	ft^2/acre	4.36
	ft^2/acre	m^2/ha	0.229
Phytomass	tons/ha	lbs/acre	892
	lbs/acre	tons/ha	0.00112
Nutrients	kg/ha	lbs/acre	0.892
	lbs/acre	kg/ha	1.12
	kg	lbs	0.454
	lbs	kg	2.20
Volume	m^3/ha	ft^3/acre	14.3
	ft^3/acre	m^3/ha	0.0699
	m^3	ft^3	35.3
	ft^3	m^3	0.283

THE DEVELOPMENT OF COTTONWOOD PLANTATIONS ON ALLUVIAL SOILS: Dimensions, Volume, Phytomass, Nutrient Content and Other Characteristics

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THE DEVELOPMENT OF COTTONWOOD PLANTATIONS ON ALLUVIAL SOILS: Dimensions, Volume, Phytomass, Nutrient Content and Other Characteristics

SUMMARY

Phytomass and nutrient accumulation are reported for eight intensively managed cottonwood plantations, ranging in age from four to 16 years on good sites. The results were developed from 24 sample trees and stand populations using the mean tree technique. The early growth of cottonwood plantations was rapid, and diameter and height growth averaged 3.6 cm and 2.6 m, respectively, during the first three years. At 16 years the mean tree was 33 cm in diameter, 32 m in height and had three logs to a 20-cm merchantability limit. From four to 16 years, the phytomass of the mean tree increased 13-fold while nutrient content increased 5- to 8-fold.

The plantations maximized current annual increment for the stem components at 10 tons/ha during the fifth and sixth years, while that of crown components maximized during the first three years at 7 tons/ha. The foliage of the standing crop was 4 tons/ha through nine years, after which thinning caused a gradual decline to 2 tons/ha at 16 years. Thinnings removed 53 tons/ha of stem material with a total volume of 150 m^3/ha. The mean annual increment of the stem maximized from eight to nine years at 7 tons/ha and 20 m^3/ha and remained within 90% of the maximum from six to 14 years. The total net primary productivity through 16 years was about 180 tons/ha, of which 60% was stem components. The phytomass and volume yields from the system of management employed in these plantations were slightly below those reported for unthinned plantations and natural stands on similar sites.

The annual nutrient requirements maximized from four to six years at 100, 12, 90, 150 and 18 kg/ha for N, P, K, Ca and Mg, respectively. By 14 years, the annual nutrient requirements declined to one half of the maximum levels. About two thirds of the annual requirements were necessary for foliage production. Much of the annual requirement was supplied through nutrient cycling. The patterns of plantation development, nutrition and productivity have distinct influences on the management of these plantations.

THE DEVELOPMENT OF COTTONWOOD PLANTATIONS ON ALLUVIAL SOILS: Dimensions, Volume, Phytomass, Nutrient Content and Other Characteristics

Cottonwood (*Populus deltoides*) has many characteristics that make it suitable for plantation culture. It is fast growing, produces high-quality wood with numerous marketing options and can be propagated vegetatively. However, despite these favorable features, the area currently in cottonwood plantations in the southern United States remains small (about 16,000 ha in 1976).

The major factors limiting plantation establishment are the specific site requirements of the species, high initial investments, future market uncertainties and competition from agronomic crops. Increases in cottonwood plantations are anticipated, but the area always will be a small fraction of that suitable for intensive management. Therefore, greater demands for wood production will be placed on existing cottonwood plantations.

Cottonwood plantations require rigorous site preparation, genetically improved planting stock, control of plant competition and deer browse, short rotations and occasional fertilization (McKnight and Biesterfeldt, 1968; Kaszkurewicz and White, 1976). Nutrient content of cottonwood trees is high relative to that of other tree species, and preliminary studies of growth-nutrient relationships have demonstrated the importance of nutrient status in stand development (Carter and White, 1971 and 1971a; Blackmon and White, 1972; Gilmore, 1976; Shelton et al, 1981). The nutrient removals incurred by cropping plantations also may be high and may influence the nutrient status of a site for subsequent productivity.

Published results of research indicate that the intensive management and cropping techniques employed with cottonwood plantations require understanding of the nutrition requirements of these systems, especially with their continued use in subsequent rotations. Therefore, this study was designed with the primary objective of assessing the phytomass and nutrient content during the development of cottonwood plantations. This assessment enables estimates of growth, yield and nutrient removals for the short rotations envisioned for cottonwood.

Description of the Study Area and Plantations

The study area is in the alluvial floodplain of the Lower Mississippi River and its major drainages and centers around 33°00′N latitude and 91°15′W longitude. The area has a subtropical humid climate with a mean annual precipitation of 1300 mm. About one half of the annual precipitation occurs during the growing season, with winter the wettest season and summer the driest. Average temperatures are 9.5° C in winter and 26.2° C in summer.

The eight plantations selected for study are located in Bolivar, Issaquena and Warren Counties, Mississippi and Chicot County, Arkansas (Table 1). The plantations are located on soils derived from two geologic land forms, but the soils are similar in physical properties and in cottonwood productivity. The plantations in Warren County are on a drainage in the loessial bluffs adjacent to the Mississippi River floodplain, and the soils belong to the Adler series (Aquic Udifluvents). The other plantations are on batture land (land between the river and the levees), and the soils are Commerce silt loams (Typic Fluvaquents) and Robinsonville fine sandy loams (Typic Udifluvents).

All plantations had a site index greater than 36 m at 30 years (Broadfoot, 1960). The plantations were established with unselected growing stock and received intensive culture during their development. Cultural practices included early cultivation and frequent thinnings; however, the type, timing and intensity of thinning regimes varied among plantations. Ages of the plantations ranged from four to 16 years, and the 16-year old plantation was the oldest found that had received satisfactory culture. Other characteristics of the plantations are presented in Table 2.

Table 1. General characteristics of the cottonwood plantations used in the study.

Plantation Number	Location	Identity	Age-yrs	Number of Sample Trees	Thinnings		
					Type*	Age-yrs	Removal-%
1	Bolivar Co., MS	Catfish	4	3	None	--	--
2	Chicot Co., AR	Leavenworth	6	3	None	--	--
3	Bolivar Co., MS	Catfish	9	3	Mechanical	4	50% Basal Area
					Free	7	38% Stem Count
4	Issaquena Co., MS	Fitler	9	3	Mechanical	6	50% Basal Area
5	Issaquena Co., MS	Fitler North	12	2	Mechanical	7	50% Basal Area
6	Issaquena Co., MS	Fitler South	12	2	Mechanical	7	33% Basal Area
					Free	9	31% Basal Area
7	Warren Co., MS	Warren	15	4	Low	5	50% Stem Count
					Low	7	50% Stem Count
					Crown	13	33% Stem Count
8	Warren Co., MS	Warren	16	4	Low	4	50% Stem Count
					Low	7	50% Stem Count
					Crown	13	33% Stem Count

*Mechanical thinning removes entire rows; low thinning removes trees from below the general level of the canopy, while crown thinning removes trees from above the canopy level; free thinning removes trees from all canopy levels (Smith 1962).

Table 2. Mensurational characteristics of the studied cottonwood plantations in May 1975.

Identity	Age	Trees		Mean DBH	Mean Height	Basal Area
		Initial	Current			
	-yrs-	------no/ha------		---cm---	--m--	--m^2/ha--
Catfish	4	756	665	14.1	11.7	10.0
Leavenworth	6	756	670	18.1	17.0	16.5
Catfish	9	1345	295	22.4	19.8	10.9
Fitler	9	1345	287	25.3	24.3	14.1
Fitler North	12	1345	243	27.2	27.3	13.7
Fitler South	12	1345	184	28.7	28.2	11.8
Warren	15	1060	158	29.8	30.5	10.5
Warren	16	1345	125	35.3	34.0	11.7

Procedure

The mean-tree technique was used to assess the phytomass and nutrient content of the cottonwood plantations. This technique involves destructive sampling of trees that best represent the mean size of a plantation and uses the number of trees in the plantation to expand mean-tree values to an area basis. Crow (1971) and Satoo (1967) found that estimates of total tree phytomass of a stand by the mean-tree technique are within 2% of true values, with the greatest deviation for components being -7% for branches.

Total accumulation of phytomass and nutrients during plantation development was estimated by summing values of the standing crop and estimated values of thinnings. The phytomass and nutrients contained in the thinnings could be estimated because thinning histories of the plantations were available.

Sample Tree Selection

The selection of sample trees was based on the quadratic mean diameter of the plantation and on the means of total height and crown dimensions. Ovington et al (1967) found that sample tree selection based on multiple characteristics greatly improved estimates of phytomass and gave results comparable to estimates obtained by the regression method.

Variable-size plots containing about 100 trees were established in each plantation, with numbers of plots per plantation ranging from two to four. Diameters of all trees on each plot were measured in May 1975, and the quadratic mean diameter was calculated for each plot. Total height, crown width and crown height were measured for all trees within 5% of the quadratic mean diameter for each plot. Numbers of trees on each plot were calculated from (1) the percentage of planting spaces with living trees and (2) planting density, which was rigidly maintained during plantation establishment.

The single tree closest to the means for diameter, height and crown features of each plot and with good form and vigor was selected for destructive sampling. The sample totaled 24 trees (Table 1).

Destructive Sampling

Each sample tree was cut at ground level in August 1975 and was divided into four components---stemwood, stembark, branches and foliage. The stem was severed into 1.2-m bolts, and stemwood and stembark samples were obtained from disks cut from the center of each bolt. The branches were divided into older branches, branches of intermediate age, current branches and dead branches. Green weights of all components were determined in the field, and samples were collected for moisture and chemical analysis. Total phytomass and nutrient content of the stem components were obtained by summing the values for all bolts of each sample tree. Likewise, the values for the branch component were a summation of the four branch categories.

Diameter and Height

A stem analysis technique was used to trace diameter development of the sample trees. The annual increment of inside-bark diameter at breast height was determined for each sample tree by linear interpolation from cross sections taken at heights of 0.61 and 1.83 m. The diameter of the tree at earlier ages was determined by subtracting the annual increment from the inside-bark diameter at the time of sampling. The outside-bark diameter was obtained by adding an estimate of bark thickness, which was assumed to have the same proportional increase as the wood. Diameters for the five years before sampling were calculated for all sample trees except those in the four- to six-year old plantations, where diameters were calculated for three years of age and older. The overall prediction equation[1] for DBH derived from these diameters and ages is

$$\ln(\text{DBH}) = 1.6574 + 0.6644 \ln(\text{Age}) \quad (1)$$

where DBH and Age are cm and

[1] *Bias in the application of logarithmic equations was corrected according to Baskerville (1972).*

years, respectively. The coefficient of determination (r^2) is 0.95, and the standard error of estimate (SEE) is 0.062. This approach probably provided a more accurate expression of the diameter of the mean tree than had only current diameters been used, despite the assumption that each sample tree represented the mean of the plantation.

Height and DBH of 447 trees were measured, and the measurements were used to obtain a composite height-prediction equation which is

$$HT = -6.6782 + 1.3999\ DBH - 0.0066\ DBH^2 \qquad (2)$$

where height and DBH are m and cm, respectively. R^2 is 0.93, and the SEE is 1.89.

Dimensional development of the mean trees through time was estimated by use of equations (1) and (2). The diameter at each age was predicted, and the corresponding height was calculated.

Taper

The inside- and outside-bark taper of the sample trees was described by a modification of the technique of Bruce et al (1968). The resulting taper equations[2] are

$$\frac{di}{DBHIB} - 1 = 1.217(X-1) + 1.195(X^2-1) - 3.442(X^3-1) + 2.027(X^4-1) \qquad (3)$$

$$\frac{do}{DBH} - 1 = 1.342(X-1) + 0.657(X^2-1) - 2.752(X^3-1) + 1.749(X^4-1) \qquad (4)$$

where

DBHIB = diameter inside bark in cm at a height of 1.37 m

DBH = diameter outside bark in cm at a height of 1.37 m

di = diameter inside bark in cm at a height of h

do = diameter outside bark in cm at a height of h

$X = (H-h)(H-1.37)$

H = total tree height in m

h = height of a point on the stem in m

The range of the equations was from breast height (1.37 m) to the stem apex. Diameters below breast height were not included because they were erratic and influenced by butt swell. The equations fitted the data well and had a constant error variance. The R^2 for each equation is 0.998, with SEE of 0.0303 and 0.0310 for the inside- and outside-bark equations, respectively.

Solving equations (3) and (4) for the 483 upper-stem diameters of the 24 sample trees revealed close correspondence of the predicted and actual diameters. No differences in predicted and actual diameters were larger than 2.5 cm, and the mean absolute deviation (sign ignored) was 0.5 cm for both inside- and outside-bark diameters.

The development of upper-stem diameters of the sample trees was estimated from the diameter and height calculated from equations (1) and (2). These values for diameter and height then were used to calculate upper-stem diameters from equations (3) and (4).

Volume Prediction

Inside- and outside-bark volumes of the sample trees were determined by calculating the volume of bolts by the Smalian formula and the volume of stemtips by the volume formula for a cone. The total volume of each tree was the sum of all bolts and the stemtip (Appendix Table 1). The merchantable volume to 8- and 10-cm outside-bark diameter limits was the sum of all bolts with a small-end diameter larger than the merchantibility limit plus an interpolated value for the final bolt.

Prediction equations for the total volume of sample trees were developed using total height and DBH as predictors. The equations for outside- and inside-bark volumes are

$$VOB = 8.648 + 0.03296(DBH^2)HT \qquad (5)$$

$$VIB = 10.66 + 0.02871(DBH^2)HT \qquad (6)$$

where

volume is in $10^{-3}m^3$

DBH is in cm

HT is in m.

The r^2 is 0.99 for both equations, with SEE of 41.5 and 33.2 for equations (5) and (6), respectively. Development of the mean tree was estimated by solving these equations for the diameter and height generated by equations (1) and (2).

The form factor of the sample trees was calculated as the ratio of the volume of each tree to the volume of a cylinder of the same dimensions (i.e., DBH and total height).

Plantation Volume

Volume of the standing crop of each plantation was calculated as the product of the number of trees and the adjusted volume of the sample trees. Volume of the sample trees was adjusted as described in the procedure for predicting phytomass (page 6).

[2] *Users of equation (3) may estimate DBHIB from the mean ratio of DBHIB to DBH found in this study (0.934), which did not vary significantly with stem dimensions.*

Basal Area

Basal area development of plantations was estimated from the stem analysis results for a three- to five-year period after the most recent thinning. The basal area of the sample trees was expanded to a plantation basis by using the number of trees from the May 1975 inventory. The trees in this inventory were those remaining after the most recent thinning of the plantation.

Wetwood

The quantity and distribution of wetwood were assessed from the stem cross sections collected for moisture determinations. The dark stain typical of wetwood in cottonwood was used to delineate affected areas, and the width of each affected area was measured at its widest axis and perpendicular to this axis. The wetwood area was calculated from these dimensions as an ellipse. Two sample trees were not measured for wetwood because other discolarations masked the limits of the wetwood infection.

The wetwood volume of each infected bolt was computed by expressing the wetwood area of each cross section as a proportion of the total inside-bark area of the cross section and multiplying this proportion by the total inside-bark volume of the bolt. The wetwood volume of the tree was obtained by summing the wetwood volume of the infected bolts.

Apparent Specific Gravity (ASG)

The ASG was the ratio of the phytomass of stem components to their volume and was used as a rough estimate of wood density. ASG provides an estimate of the mean specific gravity of the whole stem. However, ASG does not involve the rigid controls used in specific gravity determinations but is useful in converting overall stem volume to phytomass.

Phytomass Prediction

Phytomass[3] of the components of the sample trees (Appendix Table 1) was used to develop prediction equations (Table 3), using stem dimensions as predictors. The range of the equations was from a tree 15 cm in DBH and 12 m tall to a tree 37 cm in DBH and 35 m tall. Only a few of the possible DBH-height combinations were sampled, and the sample trees did not represent the full range of diameters and heights found in the plantations. Therefore, the general applicability of the equations is not known.

Table 3. Equations for predicting phytomass of components of cottonwood trees.

Component	Regression Coefficients* b_0	b_1	r^2	SEE
Wood	-2.02946	0.01057	0.99	11.95
Bark	0.44348	0.00153	0.96	4.23
Stem	-1.57439	0.01210	0.99	14.83
Branches	-1.39328	1.54242	0.77	0.23
Foliage	-1.37684	1.16530	0.71	0.20
Tree	21.73395	0.01357	0.99	22.46

* For wood, bark, stem and tree, the equation is:

$$\text{Phytomass} = b_0 + b_1 (\text{DBH})^2 (\text{HT})$$

where the units are: Phytomass in kg, DBH in cm and HT in m.

For branches and foliage, the equation is:

$$\ln(\text{Phytomass}) = b_0 + b_1 \ln(\text{DBH})$$

Merchantable Volume and Phytomass

Equations were developed for predicting the merchantable inside- and outside-bark volume and the merchantable stemwood and stem phytomass to any diameter limit (Burkhart 1977, Van Deusen et al 1981). These equations estimate the fraction of the total volume or stem phytomass that is merchantable for a specific outside- or inside-bark diameter limit

[3] *Phytomass is the oven-dry (70°C) weight of plant tissues.*

(Table 4). Equations were developed for both inside- and outside-bark volumes and for the stemwood and stem phytomass. For example, suppose the phytomass to a merchantability limit of 10 cm outside bark is desired for a tree with a DBH of 20 cm and a total height of 20 m. From the appropriate equation in Table 3, the total stem phytomass is 95 kg. The fraction of total weight occurring from the stem base to the 10 cm diameter limit is

$$F = e^{-1.9442(10/20)^{4.5890}}$$
$$=0.922$$

Thus, the merchantable phytomass is 95 X 0.922 = 88kg.

Table 4. Equations for predicting the fraction of total stem phytomass and volume that is merchantable to any diameter limit.

Component	Diameter Limit	Coefficients* a	Coefficients* b	SEE
Inside Bark Volume	IB	-2.5686	4.8201	0.042
	OB	-1.8566	4.7364	0.041
Outside Bark Volume	IB	-2.5412	4.7674	0.042
	OB	-1.8443	4.6867	0.041
Stemwood Phytomass	IB	-2.6585	4.7320	0.044
	OB	-1.9396	4.6642	0.044
Stem Phytomass**	IB	-2.6471	4.6503	0.047
	OB	-1.9442	4.5890	0.044

* The equation is:

$$F = e^{a(DL/DBH)^b}$$

where: F = fraction merchantable

DL = upper diameter limit inside bark (IB) or outside bark (OB)

DBH = diameter breast height

Units may be either metric or English.

** Stemwood plus stembark.

Sample Tree Adjustment

It was necessary to adjust the characteristics of sample trees taken in August because of changes that occurred after the May inventory; i.e., the mean tree did not exist in some cases, and tree growth occurred between the time of the May inventory and the time of destructive sampling in August. The greatest discrepancy in dimensions was in the four-year-old plantation, where the mean DBH of the August sample trees was 1.9 cm greater than that of the May inventory. For the other plantations, difference in DBH averaged only 0.5 cm.

Adjustments were made by using the phytomass equations in Table 3. The adjusted value for a sample tree component was determined by

$$AST = ST-(RS-RM) \qquad (7)$$

where

AST = adjusted sample tree value
ST = phytomass of the sample tree
RS = regression estimate based on dimensions of sample trees in August
RM = regression estimate based on dimensions of the mean tree from the plantation inventory in May.

Using this technique, the characteristics of the mean sample tree in August were adjusted to correspond with the dimensions of the mean tree from the inventory in May. This adjustment was a 33% reduction in the total tree phytomass of the sample trees from the four-year-old plantation. The adjustment for the other plantations averaged 5% of the total tree phytomass. Phytomass of the standing crop of each plantation was obtained by using the number of trees to expand adjusted sample tree values to an area basis.

Annual Increment in Phytomass

The current annual increment (CAI) in phytomass of the mean tree was estimated by use of the DBH, height and phytomass prediction equations. The DBH at each age was estimated from equation (1), and the corresponding height was estimated from equation (2). These dimensions were used to estimate the component phytomass using the equations in Table 3. Annual production of the permanent components was the increase in value from one year to the next. Foliar production, which was shed annually, was simply the quantity of foliage carried by the mean tree. Data from these calculations are reported in Appendix Table 13.

Thinning Removals

Thinning removals were estimated from the thinning history of the plantations and the stem analysis of the sample trees. Assumptions made were that (1) the sample trees were an approximation of the mean trees since the last thinning, (2) the development of thinned plantations before the first thinning was the same as for the unthinned plantations of this study and the seven- and eight-year-old plantations of Carter and White (1971a) and (3) the mean tree removed in mechanical and free thinnings equalled the mean tree of the residual stand.

The three types of thinning regimes used in the plantations (Table 1) and the methods of estimating thinning removals were

(1) mechanical thinning---Fitler nine-year old and Fitler North 12-year old. Thinning removed alternate rows and one half of the phytomass. Values before thinning were estimated from the development of unthinned plantations.

(2) mechanical and free thinning---Catfish nine-year old and Fitler South 12-year old. Removals by mechanical thinning were one third or one half of the rows and the phytomass. The basal area removed by free thinning was estimated by

(a) The basal area after thinning was the product of the number of trees remaining (the number in 1975 plus 1% annual mortality) and the mean after-thinning basal area of the sample trees as determined by stem analysis.

(b) The basal area removed was determined from the percentage removals (Table 1) and the residual basal areas.

(c) The calculation is

$$\text{BA removal} = \frac{\%\text{removal} \times \text{BA residual}}{100 - \%\text{ removal}} \quad (8)$$

The phytomass removed was obtained by employing the ratio of phytomass to basal area for the sample trees at the time of thinning.

(3) low thinnings and crown thinning---Warren 15- and 16-year old. Removals in the low thinnings came from the smaller diameter classes, and this influenced the mean tree of the residual plantation. One half of the stems were removed by the first low thinning, and this was assumed to be the lower one half of the diameter distribution of the unthinned plantations at comparable ages. The corresponding phytomass removal was estimated by use of the prediction equations (Table 3). Diameter growth of the sample trees and stand table projection were used to arrive at a diameter distribution before the second thinning.

The lower one half of the diameter distribution was removed by the second thinning, and the corresponding phytomass was estimated. Stand table projection again was used to determine the diameter distribution before the third thinning, which was a crown thinning.

The phytomass removed in the crown thinning was the difference in phytomass before and after thinning. The phytomass before thinning was estimated from the diameter distribution and that after thinning was the product of the number of trees (the number in 1975 plus 1% annual mortality) and the estimated phytomass of the mean tree.

The low and crown thinnings removed an average of 34% of the phytomass and ranged from 26 to 40%.

The estimated phytomass accumulation rates after thinning were comparable for all plantations, after adjustment for the intensity and the age at which thinning was done. The estimates for removals by low thinning may be low because some trees above the mean diameter undoubtedly were cut. Also, distribution of the phytomass removed by thinning was assumed to be in the same proportions as the components of the mean tree removed in thinning.

Mortality

Losses were estimated (1) through the first growing season, (2) from the end of the first growing season until the first thinning and (3) after the first thinning. Losses through the first growing season were known for four plantations, and the average of these was used as a proxy for similar losses in the other plantations. Mortality from the end of the first growing season until the time of first thinning was adapted from Krinard and Johnson (1975). An annual mortality rate of 1% of total stems was assumed after thinning was initiated (Unpublished USFS data, T. H. Filer). Mortality after the first thinning was chiefly from windthrow and top breakage and not from competition. Therefore, the death of trees was assumed to be independent of tree size, and the average size of lost trees was assumed to equal that of the mean tree.

Net Primary Productivity

Total net primary productivity was the sum of the standing crop and past losses, which included cumulative foliage production and thinning removals. However, the quantity of branches shed in natural pruning, the production of reproductive material and losses to insects were not included. Only the above ground productivity was estimated. Cumulative foliar production was the sum of annual foliage production through time. Foliar production during the first three years was obtained from young cottonwood plantations at comparable spacings (Unpublished USFS data, J. B. Baker).

Verification

Growth and yield of the eight plantations were compared with those obtained by Williamson (1913), Carter and White (1971a) and Krinard and Johnson (1975). Phytomass of the stem components of Williamson (1913) and Krinard and Johnson (1975) was estimated from their reported volumes and the ASG of trees of similar dimensions in this study. Branches and foliage were estimated from the stem dimensions and regression equations developed from the combined data from this study and that of Carter and White (1971a).

Laboratory Analysis

Tissues, previously dried at 70° C for dry weight determination, were prepared for chemical analysis by grinding in a Wiley mill to pass a 20-mesh sieve. Total nitrogen (N) for the wood tissues was determined by a macro-Kjeldahl procedure, and a semimicro-Kjeldahl procedure was used for the other tissues. The ground tissues were dry ashed at 500° C for four hours. Total phosphorus (P) was determined by the vanadomolybdate procedure (Jackson, 1958), and potassium (K), calcium (Ca) and magnesium (Mg) were determined by atomic absorption spectroscopy (Issac and Kerber, 1971).

Table 5. Equations for predicting the nutrient content of the components of cottonwood trees.

Component	Regression Coefficients* b_0	b_1	r^2	SEE
	NITROGEN			
Stemwood	-3.81956	2.64515	0.96	0.154
Stembark	-4.49783	2.88083	0.95	0.176
Branches	0.29496	1.44710	0.63	0.300
Foliage	1.62171	1.14230	0.69	0.210
	PHOSPHORUS			
Stemwood	-3.76970	2.21495	0.93	0.157
Stembark	-6.96650	2.99055	0.96	0.169
Branches	-1.79107	1.52986	0.82	0.190
Foliage	-0.36057	1.00014	0.61	0.215
	POTASSIUM			
Stemwood	-3.66486	2.78393	0.87	0.299
Stembark	-3.43226	2.59194	0.89	0.240
Branches	1.08970	1.14894	0.53	0.297
Foliage**	—	—	—	—
	CALCIUM			
Stemwood	-5.89380	3.52005	0.96	0.186
Stembark	-4.58973	3.29801	0.97	0.160
Branches	1.50637	1.32045	0.58	0.308
Foliage	1.41642	1.28528	0.57	0.302
	MAGNESIUM			
Stemwood	-7.41378	3.42847	0.96	0.172
Stembark	-7.76693	3.45160	0.92	0.270
Branches	-1.69800	1.56339	0.69	0.278
Foliage **	—	—	—	—

* The equation is:

$$\ln(\text{Nutrient Content}) = b_0 + b_1 \ln(\text{DBH})$$

where the units are: nutrient content in g; DBH in cm.

** See text for explanation of excluded values.

Mean Tree Nutrient Content

Nutrient content of the sample trees (Appendix Tables 2-6) was calculated from the values for phytomass and nutrient concentration. Prediction equations for estimating nutrient content (Table 5) were developed with DBH as a predictor.

Equations could not be developed for the K and Mg content of foliage because soil properties influenced the concentrations of these elements and distorted the relationship with DBH (Shelton et al, 1981). The plantations on the Adler soil series had significantly higher levels of Mg and lower levels of K in the foliage than the plantations on the Commerce and Robinsonville soil series. Since most of the plantations were on the Commerce and Robinsonville soils, emphasis was placed on these plantations. This was done by calculating the foliar K and Mg contents using the phytomass prediction equation for foliage (Table 3) and the average K and Mg foliar concentration of trees growing on these soils (1.50% for K and 0.30% for Mg).

Nutrient accumulation by the mean tree through time was estimated by using equation (1) to obtain tree diameters at various ages and the equations in Table 5 to estimate nutrient content (Appendix Table 14). The annual accumulation of nutrients in the permanent components of the tree was the increase in value from year to year.

The nutrient content of the unmerchantable stemtop was determined by summing the values for bolts smaller than the merchantability limit (i.e., 8 and 10 cm). The content of the fractional portion of bolts was determined by interpolation.

Plantation Nutrient Content

The procedure used to obtain plantation phytomass was also used to expand the nutrient content of sample trees to a plantation basis. Estimation of the annual nutrient accumulation was the same as for phytomass. The estimated removals by thinning included branches, foliage and tops, even if these components were left on the site.

Simulation

The accumulation of phytomass, volume and nutrients in the plantations was simulated by using the generalized development of the mean tree, plantation populations and thinning regimes. Average populations of the plantations were 668 trees/ha at four to six years, 291 at nine years, 214 at 12 years and 142 at 15-16 years. Average age of the plantations at the first, second and third thinning was six, nine and 13 years, respectively, and the average intensity of thinnings was 41, 34 and 33% of total basal area, respectively. These populations and thinning regimes were used to derive a generalized history of the plantations through 16 years of development (Table 6). For the simulation, population values were obtained from Table 6, and properties of the mean tree were estimated by using dimensions from equations (1) and (2), phytomass from Table 3 and nutrient content from Table 5.

Table 6. Generalized history of the studied cottonwood plantations.

Age (yrs)	Initial Stand	Mortality	Thinned	Thinning Type	Thinning Removal-%
	trees/ha				
0 to 3	900	200	—	—	—
4 to 5	700	11	—	—	—
6	689	3	343	Mech.	50
7 to 8	343	7	—	—	—
9	336	3	111	Free	33
10 to 12	222	7	—	—	—
13	215	2	71	Crown	33
14 to 15	142	3	—	—	—
16	139	1	—	—	—

RESULTS AND DISCUSSION

Diameter and Height

Diameter and height of the mean tree had parallel development (Figure 1). Diameter and height at four years were 13 cm and 11 m, respectively, and, by 16 years, these dimensions increased 2.5- and 3.0-fold.

Maximum rates of growth occurred during the first three years, when annual diameter and height growth averaged 3.6 cm and 2.6 m, respectively. Rates of growth declined after four years, and the decline in rate of height growth was more rapid than that of diameter. Height of the mean tree at age 16 years was 85% of the estimated height at 30 years, and low rates of height growth are expected after 16 years. In contrast, the diameter growth was fairly constant after 10 years, maintaining an annual rate of 1.5 cm. The relatively constant rates of diameter growth in this study are attributed to the frequent thinnings of plantations. The average diameters of trees in unthinned plantations and natural stands of comparable ages were about 20% less than the diameter of the mean trees in this study (Carter and White, 1971a; Krinard and Johnson, 1975 and 1980; Williamson, 1913).

The pattern of diameter development was similar at different log heights (Figure 2). Maximum increases in diameter at the top of each log occurred during the first four years of its development, and growth thereafter was linear through time.

The development of upper stem diameter through time can be used to estimate the number of merchantable logs (5 m in length) and the time for their development in the average tree of a plantation. For example, assuming a 20-cm diameter merchantability limit for sawlogs, the average tree in the plantation was estimated to have one log at 11 years, two at 13 to 14 years and three at 16 years (Figure 2).

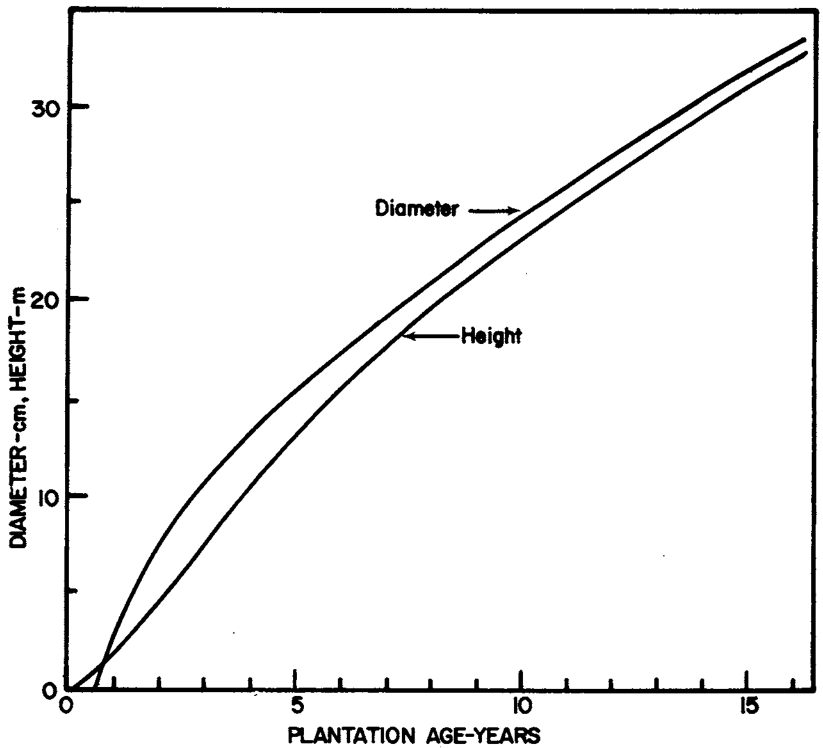

Figure 1. The development of DBH and total height of the mean tree of cottonwood plantations.

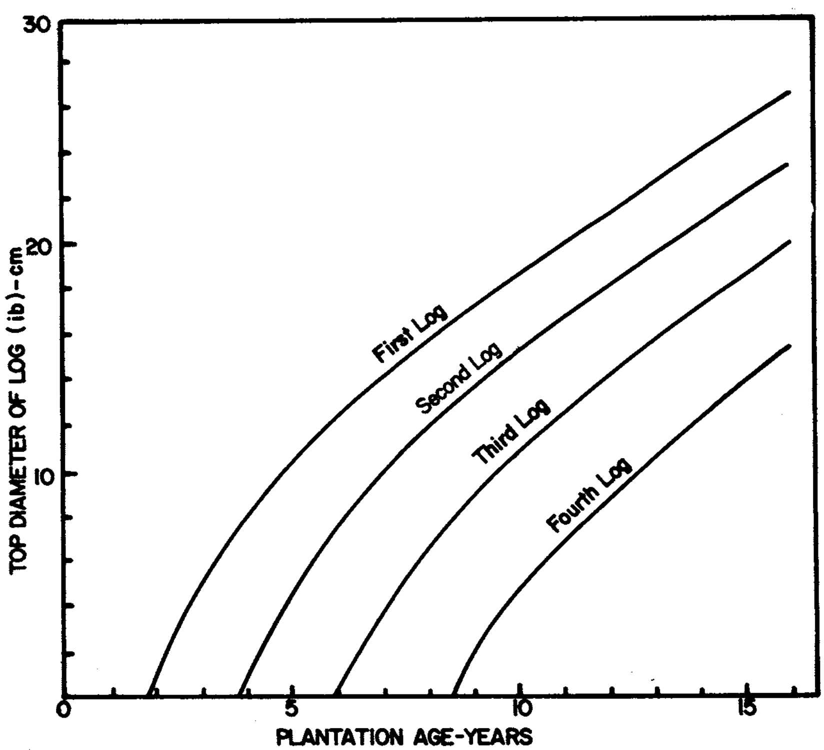

Figure 2. The predicted development of the top diameter of the mean tree of cottonwood plantations at four log heights.

Mean Tree Volume

Development of the inside-and outside-bark volumes of the mean tree was similar (Figure 3), and both of these volumes increased at an annual rate of about 0.1 m^3 after nine years. The development of merchantable volume paralleled that of total volume. For a given merchantability limit, the volume of the unmerchantable top was constant and did not vary significantly with DBH and height. The volume of an unmerchantable top with a basal diameter of 10 cm was 0.02 m^3, and that of an 8 cm top was 0.008 m^3.

The percentage of the total stem volume that was merchantable increased with time. For example, for an 8-cm merchantability limit, 88% of the stem volume was merchantable at four years and 99% at 16 years.

The form factor of the sample trees did not vary significantly with stem dimensions and averaged 0.38 for inside-bark volume and 0.43 for outside bark volume. The standard errors of these means were only about 1% of the mean value. Form factor is an expression of overall taper of a tree-stem. The form factor of the sample trees of this study may be used to calculate a rough estimate of the volume of other plantations of similar densities and sites. The calculation is

$$\text{Volume} = \text{form factor} \times \text{basal area} \times \text{mean total height} \quad (9)$$

Form factor is a ratio; therefore, the volume unit is the product of the basal-area unit and the height unit.

Plantation Volume

The merchantable volume of the standing crop increased rapidly until thinning was initiated (Figure 4). Thinning maintained the volume below 150 m^3/ha, with a mean of 135 m^3/ha. Much of the variation in the standing-crop volume was due to the thinning

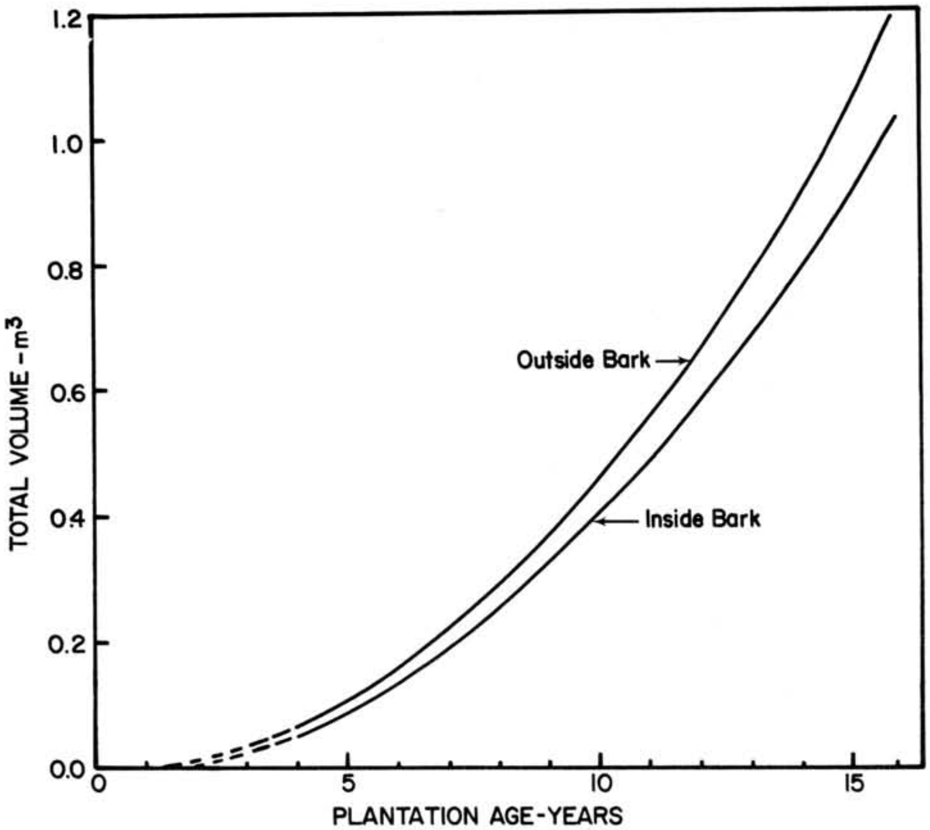

Figure 3. The development of total volume of the mean tree of cottonwood plantations.

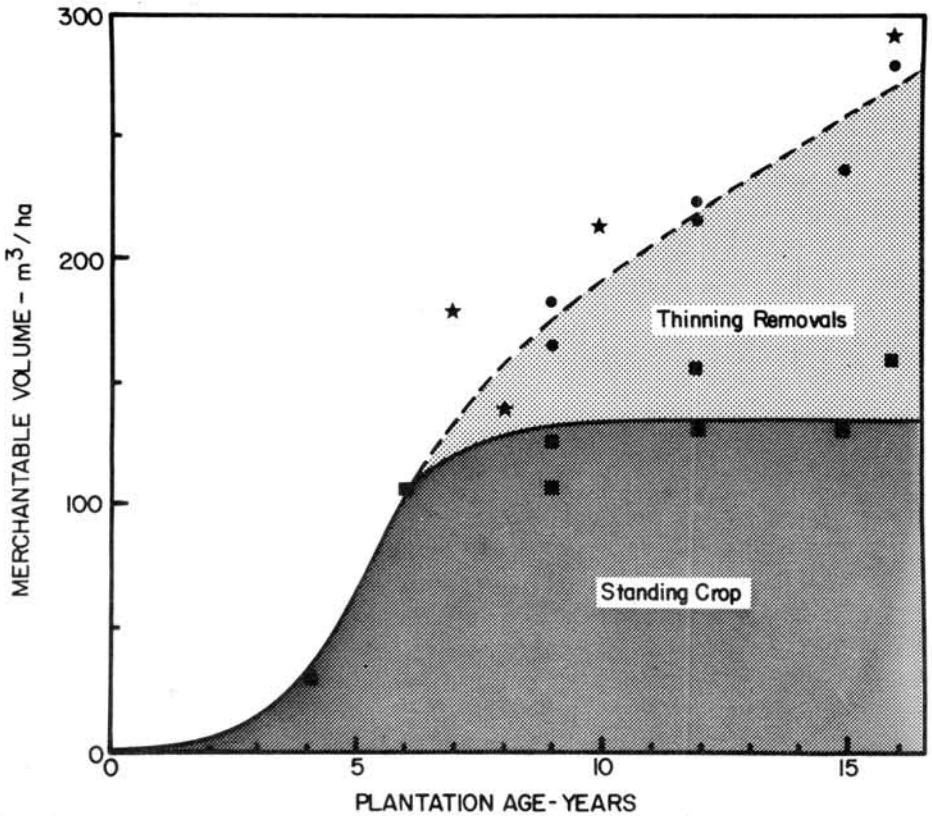

Figure 4. The merchantable volume (outside bark to a 10-cm diameter top) of the standing crop and estimated thinning removals of cottonwood plantations. (■=standing crop; ● = standing crop plus thinning removals; ★ = unthinned plantations and natural stands.)

history of each plantation, because the time lapse since the most recent thinning ranged from two to five years. Average thinning removals through 16 years totaled 140 m^3/ha; therefore, total volume production averaged about 275 m^3/ha.

Total volume production of the plantations was about 8% less than that of the standing crops of unthinned plantations and natural stands reported by Carter and White (1971a), Krinard and Johnson (1975) and Williamson (1913). Apparently, the frequent thinnings of these intensively managed plantations decreased the total volume production, a tendency also noted by Krinard and Johnson (1975) in cottonwood and generally reported in thinning studies with other species. However, the thinnings had a pronounced effect on the distribution of the total volume, with about the same volume carried by fewer stems of larger diameter.

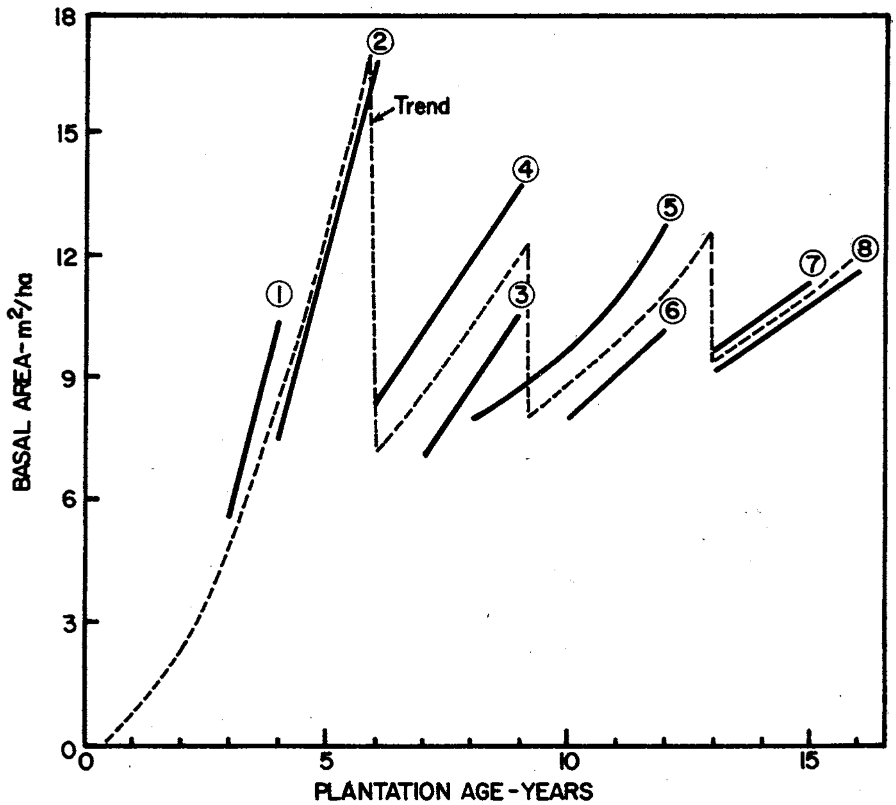

Figure 5. The basal area development of cottonwood plantations after the most recent thinning. (See Table 1 for plantation identity.)

The mean annual increment (MAI) of the plantations reached a maximum of 20 m^3/ha in the eighth year and remained within 90% of the maximum from six to 14 years. Krinard and Johnson (1975) also found that MAI was a maximum at a similar age for unthinned plantations, although Williamson (1913) found that MAI in natural stands maximized at 16 years.

Basal Area

Basal area of the plantations increased rapidly during early development and reached about 13 m^2/ha by five years (Figure 5). Thinnings reduced the basal area to about 8 m^2/ha, and basal area growth after thinning declined as plantation age increased. For example, plantations thinned at seven years grew at an annual rate of 1.6 m^2/ha while those thinned at 13 years grew at the rate of 0.7 m^2/ha.

Wetwood

Wetwood is a common bacterial infection of cottonwood stems (Toole, 1968). The pattern of wetwood distribution is important because it may influence processing and the value of wood products. All sample trees in this study contained wetwood, and the percentage of wetwood in the stem was related to plantation age (Figure 6A). The percentage of wetwood increased with plantation age through nine years and stabilized at 20% thereafter. However, the percentage of wetwood varied widely in plantations of similar ages. For example, wetwood accounted for 30% of the total stemwood volume of the sample trees from the nine-year-old plantation in Issaquena County but only 8% of stemwood volume in the plantation of the same age in Bolivar County. Large variation within a given plantation was also notable; e.g., two-fold differences occurred among the sample trees from the 15-year-old plantation.

The percentage of the stem length infected with wetwood was strongly related to plantation age (Figure 6B). About one third of the stem length contained wetwood at four to six years, but wetwood was found in two thirds of the length nine years. Beyond nine years, the progression of wetwood up the stems was slower.

Wetwood also spreads outward from the stem pith. About 25% of the crosssectional area at the stem base contained wetwood. Only 14%

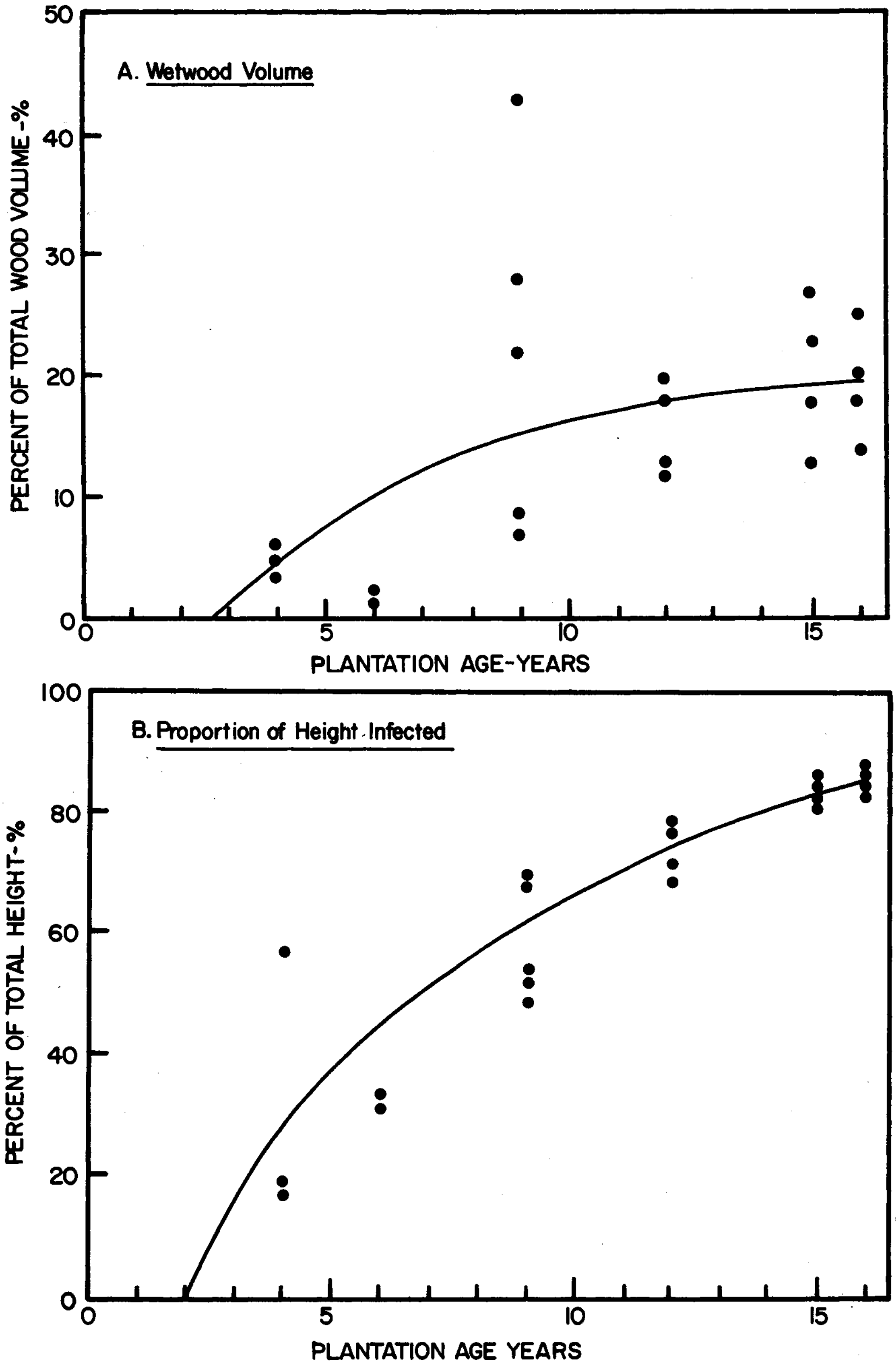

Figure 6. The percentage of total volume and the proportion of total height infected by wetwood in the mean tree of cottonwood plantations.

of the cross-sectional area from the mid-stem contained wetwood, and this declined to 5% at the terminus of the infection.

Apparent Specific Gravity (ASG)

The ASG of stemwood increased from 0.29 at four years and approached 0.37 beyond 12 years (Figure 7). The Forest Products Laboratory (1955) reported a specific gravity of 0.38 for the stemwood of mature cottonwood. The increase in ASG with age was due to the increase in the proportion of mature to juvenile wood in the stem.

The ASG of stembark did not vary significantly with age and averaged 0.38, which was in the range of 0.30 to 0.44 found in nine cottonwood trees by Martin and Crist (1968). The combined ASG of the wood and bark was slightly higher than that of the stemwood.

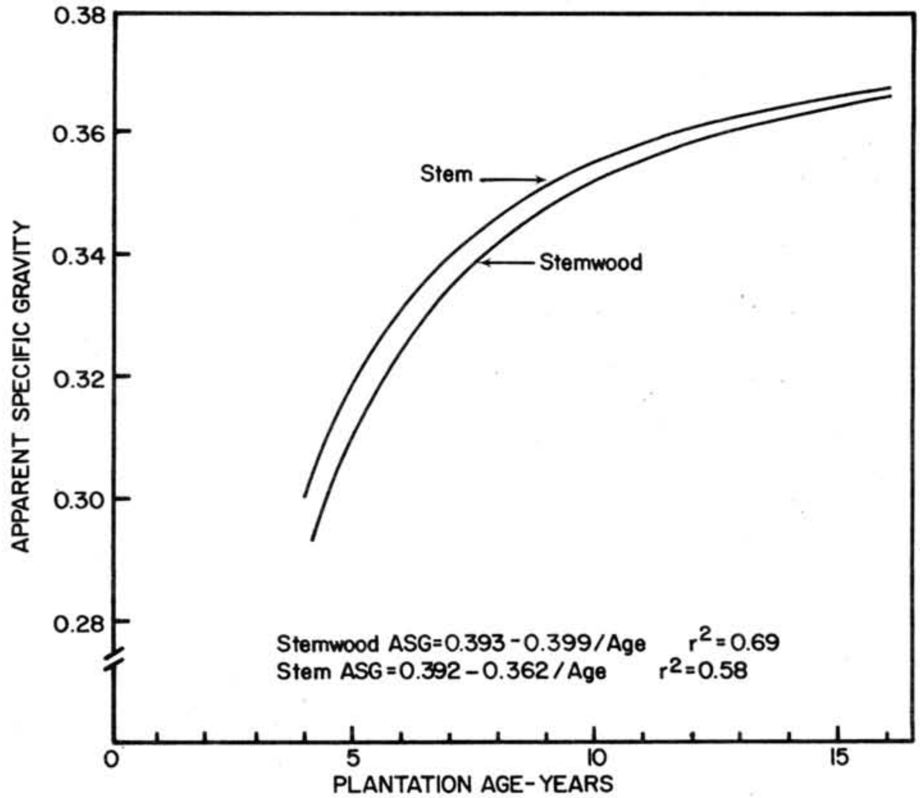

Figure 7. The relationship of apparent specific gravity of the stem and stemwood of the mean tree to the age of cottonwood plantations.

Mean Tree Phytomass

Phytomass of the mean tree and its components accelerated through eight years, and the increase thereafter was essentially linear (Figure 8). The average annual increase in total phytomass from four to eight years was 25 kg, and the increase after eight years averaged 45 kg. The distribution of total phytomass shifted to a higher percentage of stem as age increased. For example, the stem accounted for about 50% of total phytomass at four years and about 90% at 16 years. However, this comparison does not reflect the annual production, because all foliage and some branches are shed each year while stemwood and stembark accumulate.

Ranking of the current annual increment (CAI) of phytomass by component was stemwood

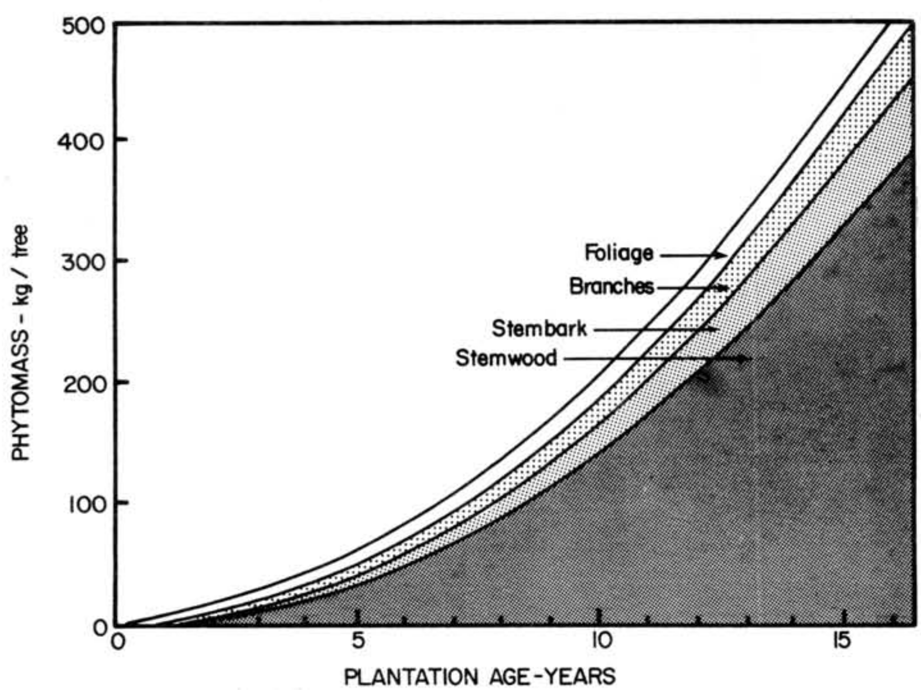

Figure 8. The phytomass development of the components of the mean tree of cottonwood plantations.

>foliage>stembark = branches (Figure 9). Production of the support components of the tree (i.e., stemwood, stembark and branches) was 3.7-fold that of the productive component (i.e., foliage), and this distribution did not change over the age span of this study. The CAI increased through time for all components except branches which remained constant. The apparent constancy of branch production was partially due to the fact that the natural pruning of branches was not quantified.

The quantity of foliage per unit of branches changed with time. This is best illustrated by the pattern of production of current branches and foliage. Only the current branches bear foliage. The current branches averaged 2.6 kg/tree and did not vary significantly with time or tree dimensions. However, the allometric increase in foliage from four to 16 years resulted in a threefold increase in foliage per unit of current branches. This pattern was brought about by the morphology changes in the current branches during this interval. Current branches changed from long, narrow twigs with widely spaced foliage to short twigs with foliage clustered near the apex.

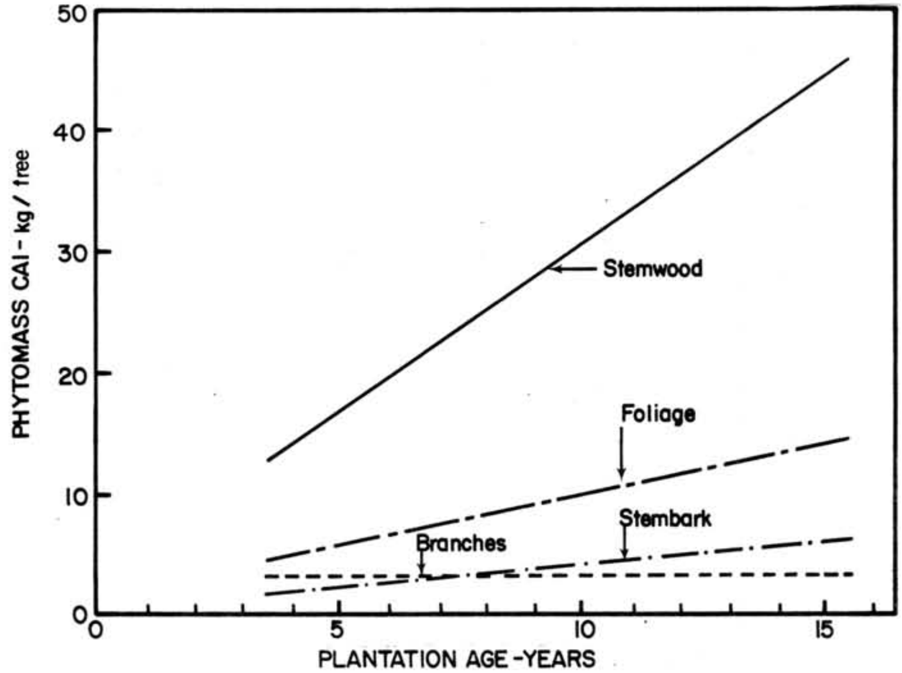

Figure 9. The CAI of phytomass of the mean tree of cottonwood plantations.

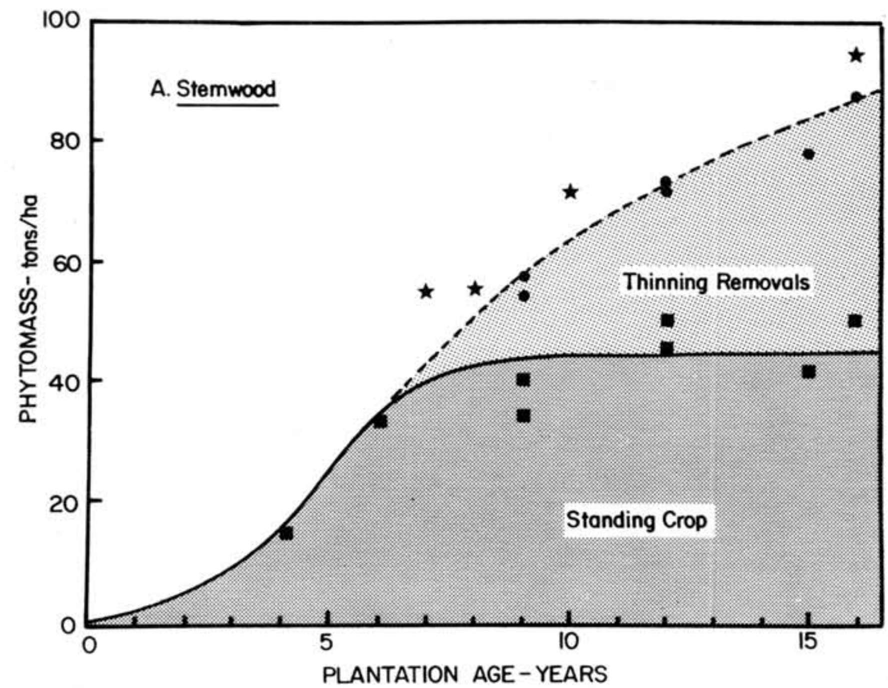

Figure 10A. The phytomass of stemwood of the standing crop and estimated thinning removals for cottonwood plantations. (■=standing crop; ● = standing crop plus thinning removals; ★ = unthinned plantations and natural stands.)

Plantation Phytomass

Stemwood---Plantation development followed the typical sigmoid growth curve; i.e., growth at an increasing rate through four years, growth at a constant rate from four to nine years and growth at a decreasing rate thereafter (Figure 10A). This pattern differed from that of the mean tree, which had no period of declining growth rate. The declining growth rate for plantations was due to reductions from thinning that were not offset by growth of the residual trees.

Average stemwood of the standing crop for the thinned plantations was 45 tons/ha, with a range of 35 to 50 tons/ha. The range was due in part to the time lapse since the most recent thinning, which ranged from two to five years (Table 1). The stemwood removed by thinning through 16 years was about 40 tons/ha; therefore, total production was about 85 tons/ha.

The total stemwood phytomass of the thinned plantations was about 14% less than that of unthinned plantations and natural stands of comparable age (Carter and White, 1971a; Krinard and Johnson, 1975 and 1980; Williamson, 1913). This difference probably resulted from the productivity lost because of the timing and intensity of thinnings; i.e., waiting too long to thin and then thinning too heavily. Also, the 14% reduction in stemwood phytomass was considerably greater than the 8% reduction in volume. This discrepancy may have developed because most thinning was done early in the development of the plantation when ASG was below maximum.

Stembark---Development of stembark was similar to that of stemwood (Figure 10B). The period of acceleration extended through six years and was followed by linear increases from six to 12 years, with declining rates thereafter. The average annual increase was 0.8 tons/ha through six years, 1.2 tons from six to 12 years and 0.5 tons thereafter. Stembark of the standing crop of thinned plantations averaged 6.7 tons/ha, about one half the total produced through 16 years. Values for the studied plantations averaged 13% lower than those reported for unthinned plantations and natural stands.

Branches---Branches of the standing crop increased linearly through six years and declined markedly thereafter (Figure 10C). Total branch production through 16 years was 22 tons/ha, and about 9 tons/ha were carried by the standing crop of thinned plantations. Total branch production was about 5 tons/ha greater than that of unthinned plantations and natural stands. However, the values for total branch production were probably underestimated because branches lost from natural pruning were not accounted for.

Foliage---Foliage of the standing crop reached a maximum of 4

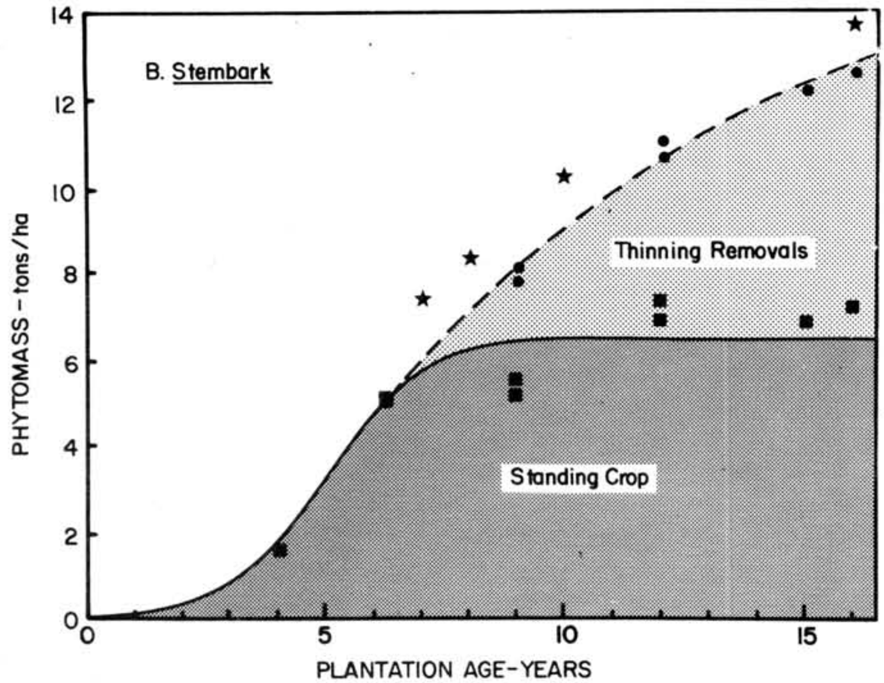

Figure 10B. The phytomass of stembark of the standing crop and estimated thinning removals for cottonwood plantations. (See key, Figure 10A.)

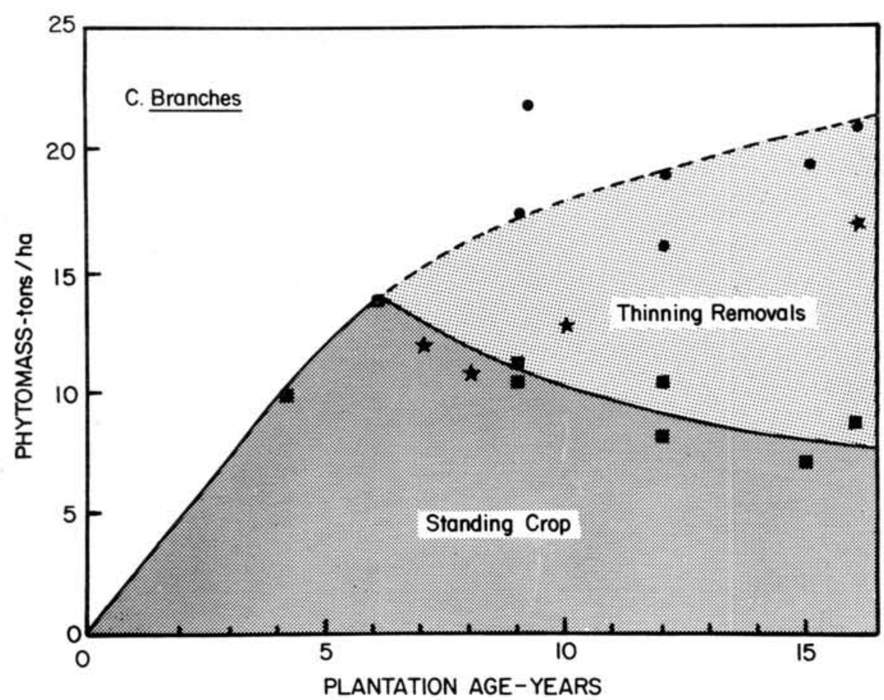

Figure 10C. The phytomass of branches of the standing crop and estimated thinning removals for cottonwood plantations (See key, Figure 10A.)

tons/ha at four years and remained at that level through the ninth year (Figure 10D). Thinnings beyond the ninth year reduced foliage to 2 tons/ha at 16 years. Data from unthinned plantations and natural stands verify a carrying capacity of 4 tons/ha of foliage through 16 years, and this is consistent with findings for a large number of deciduous forests at this latitude (Bray and Gorham, 1964).

The foliage carried by the mean tree increased three-fold from four to 16 years, while the numbers of trees in the plantations were reduced by five-fold during the same period. Thus, thinning reduced the foliar phytomass, and this probably resulted from waiting too long to thin and then thinning too heavily. The effect of thinning was also expressed in the decline in crown coverage, which was 96% before thinning at four years and 45% at 16 years.

Thinnings normally do not have a long-lasting effect on the foliar phytomass of stands (Smith, 1962). However, the crowns of cottonwood trees appear to respond very slowly to the thinning release (Krinard and Johnson, 1975 and 1980; Johnson and Burkhardt, 1976; FAO, 1979).

Mortality---The estimated loss of total tree phytomass through mortality was 8 tons/ha during 16 years, which was 4% of total phytomass production. The frequent thinnings of the plantations reduced losses due to competition to very low levels, and most of the mortality was due to windthrow and stem breakage. Walker (1967) found that second decade mortality losses averaged 38% of the gross volume increment of unthinned natural cottonwood stands, while stands receiving a light low thinning at 12 years lost only 25%.

Total production---Total production of the plantation (mortality excluded) approached 170 tons/ha at 16 years (Figure 11). Distribution of this total at 16 years was 52, 8, 12

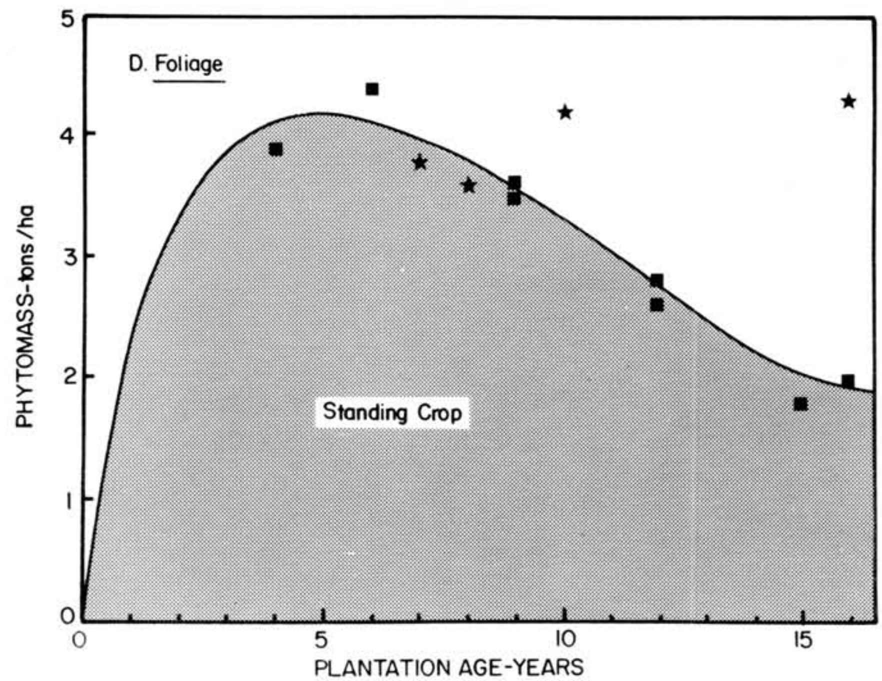

Figure 10D. The phytomass of foliage of the standing crop for cottonwood plantations. (See key, Figure 10A.)

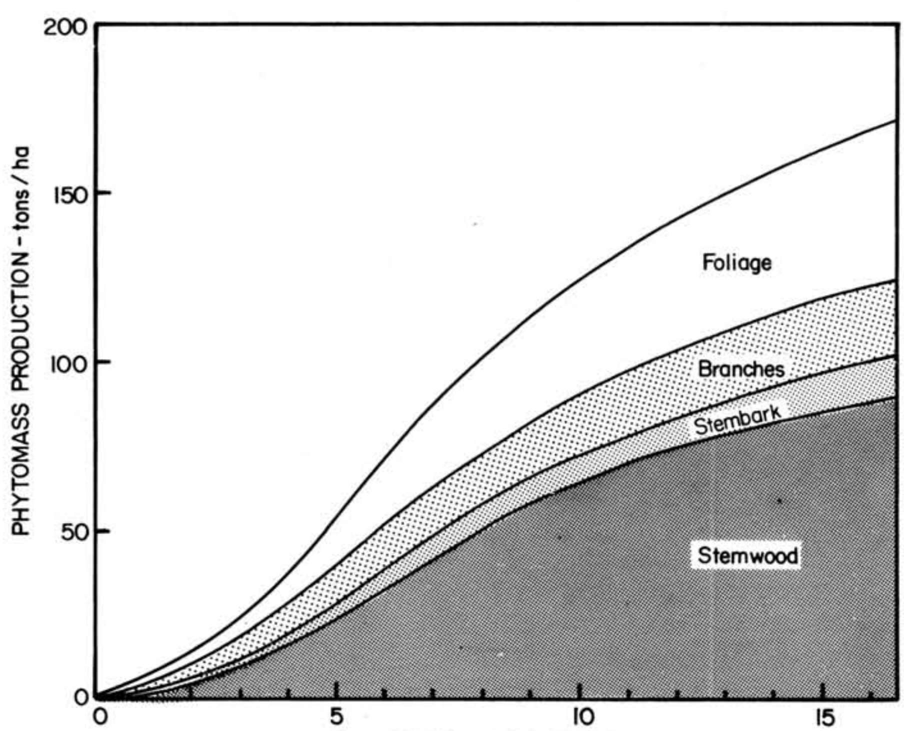

Figure 11. The total production of phytomass in cottonwood plantations through 16 years.

and 28% for stemwood, stembark, branches and foliage, respectively. About one third of the total production was in the standing crop at 16 years, and two thirds had been removed by thinning or lost through the annual shedding of foliage. Cumulative foliage production through 16 years was 45 tons/ha, which was about one half the production of stemwood. The standing crop at 16 years carried only 5% of the total foliar production, but about 50% of the total stem production.

Annual production---The CAI of the stem components reached a maximum at 10 tons/ha from four to seven years and declined to 3 tons/ha at 16 years (Figure 12A). The MAI was maximum from nine to 11 years at 7 tons/ha and was within 90% of the maximum from six to 14 years.

Annual production of the crown components had an earlier and smaller maximum than that of the stem (Figure 12B). The maximum CAI of the crown components occurred before the fourth year at 7 tons/ha. The maximum MAI was 5.5 tons/ha and extended from four to 11 years.

Mean Tree Nutrient Content

Total tree---Nutrient accumulation in the mean tree was in the order of Ca>K>N>Mg>P (Figure 13A), and through 16 years, averaged 160, 70, 60, 20 and 10 g/year, respectively. Content of N, P and K increased five- to six-fold from four to 16 years, while Ca and Mg increased seven- to eight-fold and phytomass increased 13-fold. The difference in phytomass and nutrient accumulation was due to differences in nutrient retention by various tree components. For example, the nutrient content of the annual increment of foliage was greater than that of the annual increment of the stem. However,

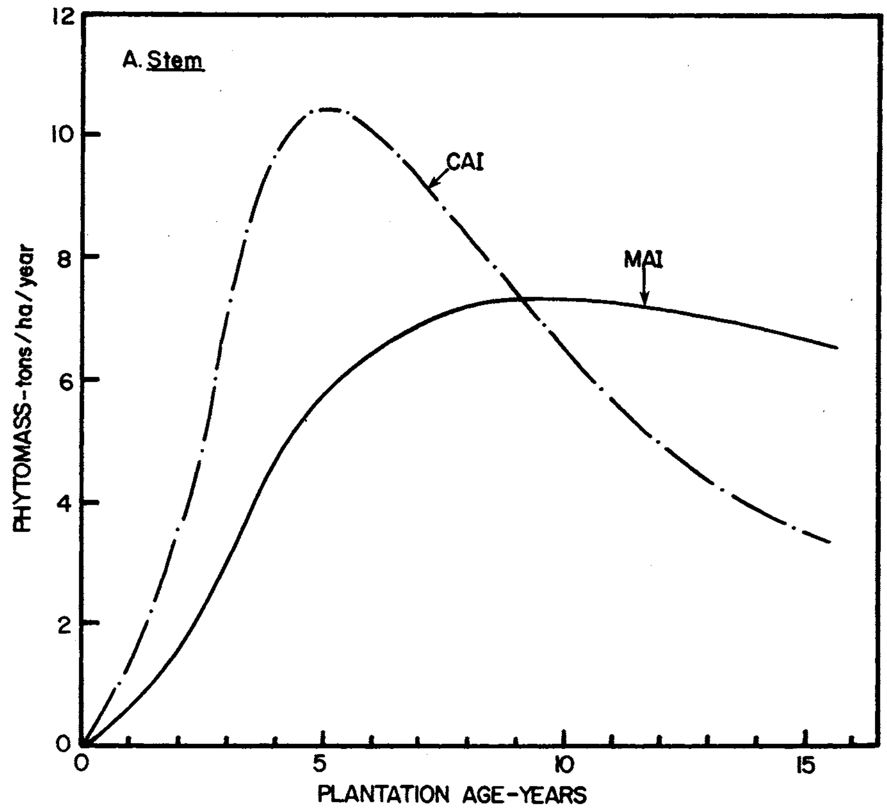

Figure 12A. The CAI and MAI of phytomass for the stem components of cottonwood plantations.

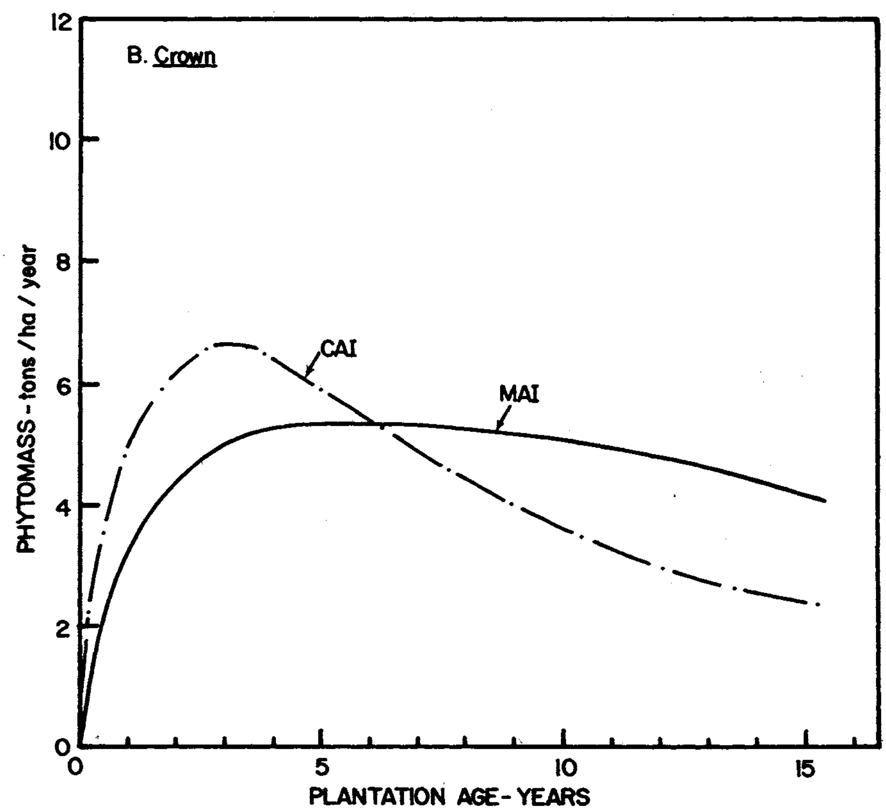

Figure 12B. The CAI and MAI of phytomass for the crown components of cottonwood plantations.

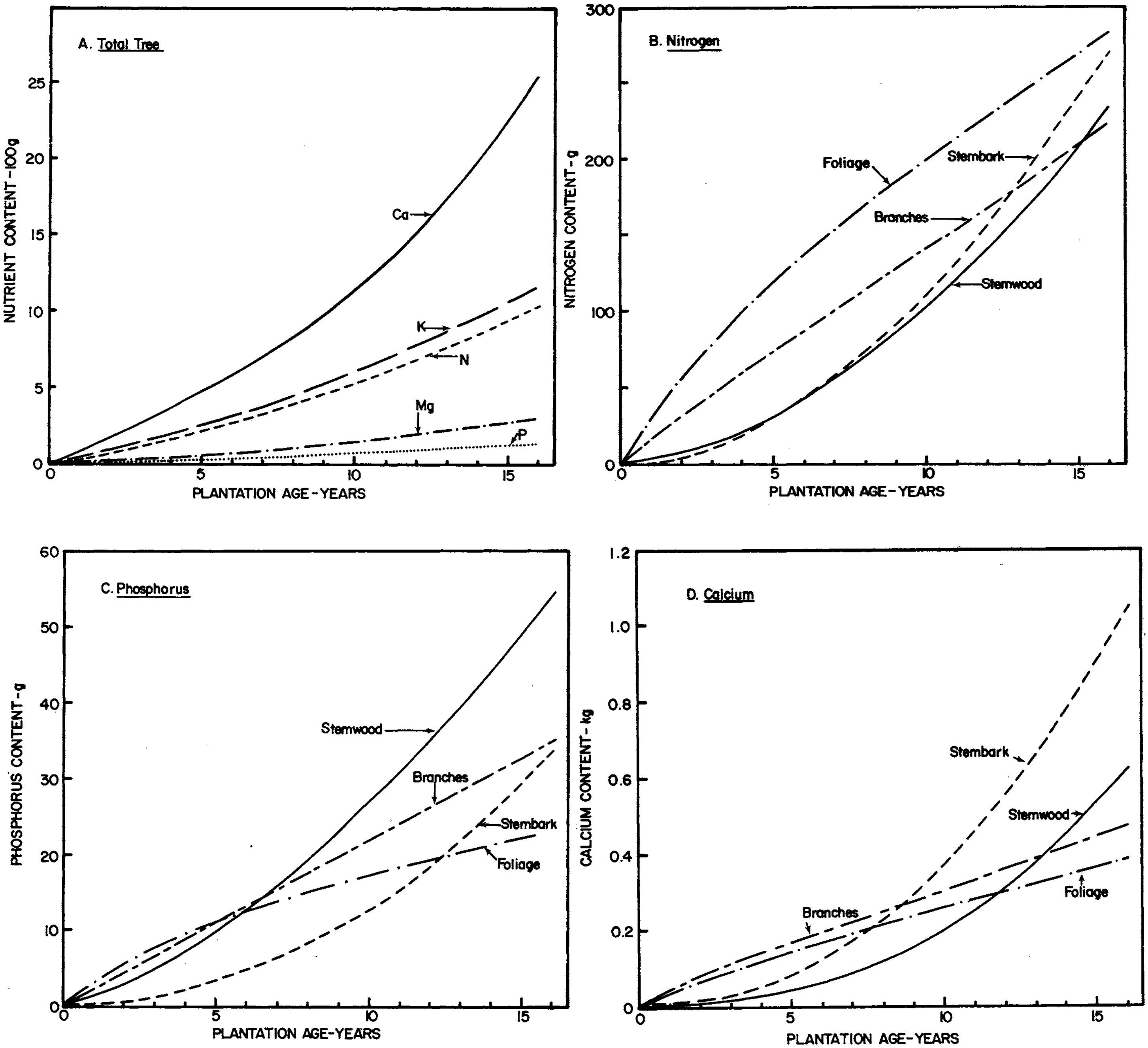

Figure 13. The total nutrient content of the mean tree of cottonwood plantations and the distribution of nutrients among the mean tree's components for N, P and Ca.

foliage was lost annually, while the stem increment was retained and accumulated through time.

Components---Accumulation of N was highest in the foliage (Figure 13B). The maximum accumulation of P, K and Mg was in the stemwood (illustrated by P, Figure 13C), and Ca accumulation was greatest in the stembark (Figure 13D). The different nutrient accumulation patterns resulted from the variation in nutrient concentration among components. The stem components accumulated nutrients exponentially through time, and nutrient accumulation in the crown components generally was linear.

The nutrient content and phytomass of a 10-cm stemtop were about twice those of an 8-cm stemtop (Table 7). These values were constant for all ages and did not vary significantly with DBH and height. The percentage of total stem nutrients in the stemtop decreased through time. For example, an 8-cm stemtop contained 20% of the nutrients in the stem at four years but only 1% 16 years.

Plantation Nutrient Content

The pattern of accumulation of nutrients by the plantation was similar to phytomass. The primary difference was in the distribution among components. N and Ca are considered here as examples of nutrient accumulation (Figures 14 and 15), and the data for all nutrients appear in Appendix Tables 8-12. In this comparison, N typifies the nutrients that are generally greatest in the crown components (i.e., N, P and K), and Ca represents the elements that are greatest in the stem (i.e., Ca and Mg).

Table 7. Average properties of the stemtops of the sample trees from cottonwood plantations.

Property and Unit	Stemtop Diameter Limit-cm	
	8	10
Volume - $10^{-3}m^3$	8.1	19.8
Phytomass - kg	3.5	8.2
Length - m	4.0	5.5
Nutrient Content - g		
N	8.9	18.4
P	1.9	3.9
K	10.0	21.4
Ca	14.4	32.5
Mg	2.0	4.5

Nitrogen---Maximum accumulation of N in stemwood occurred from four to six years at an annual rate of 12 kg/ha (Figure 14A). Thinnings beyond these ages maintained N levels in the standing crop at about 30 kg/ha, and thinnings through 16 years contained 30 kg/ha. Therefore, total

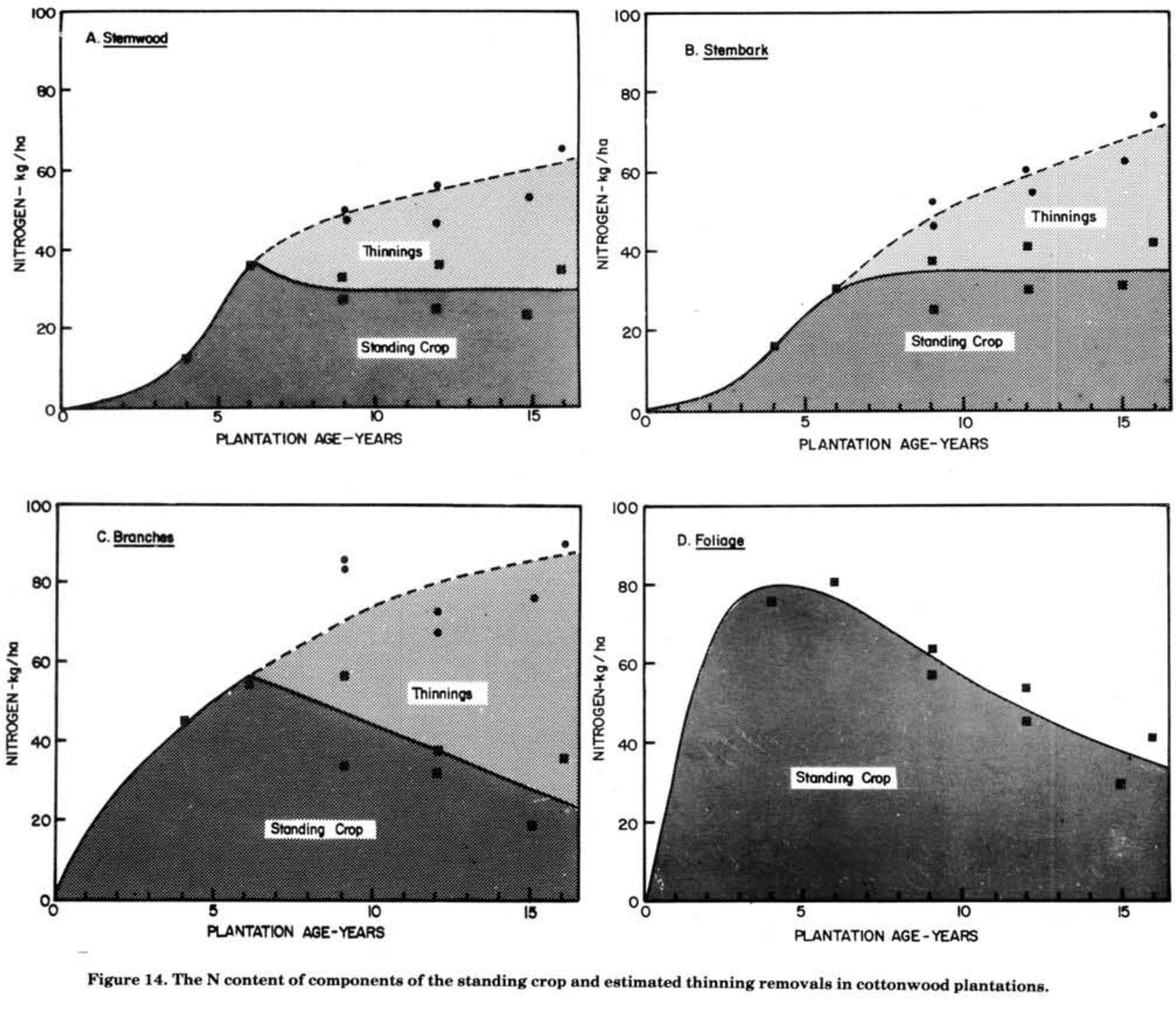

Figure 14. The N content of components of the standing crop and estimated thinning removals in cottonwood plantations.

accumulation of N in stemwood was 60 kg/ha.

Total N accumulation in stembark was about 70 kg/ha at 16 years, and this quantity was distributed equally between the standing crop and thinning removals (Figure 14B). The quantity of N in the stembark and stemwood was about the same, but rates of accumulation differed. For example, the annual rate for stembark was sustained over a long period, while the rate for stemwood peaked sharply and then declined.

Branches accumulated N rapidly, and the maximum rates occurred before four years (Figure 14C). Quantities of N in the standing crop declined after thinning was started, apparently due to the previously noted response of the crowns to thinning. N content of the standing crop was about 30 kg/ha at 16 years, and the quantity contained in thinnings approached 60 kg/ha. However, branches were left on the site after thinning, and their nutrient content will be released gradually by decomposition.

Foliar N content of the standing crop approached 80 kg/ha at four years, but this declined by one half at 16 years (Figure 14D). This decline directly reflected the reduction in foliar phytomass brought about by thinnings. The foliar N has two fates; 60% is translocated to the permanent tissues before abscission, and 40% returns to the forest floor via litterfall (Baker and Blackmon, 1977). The annual return of N via litterfall ranged from 32 kg/ha at four to six years to 16 kg/ha at 16 years. Total N transferred through the litter chain during 16 years was large---approaching 375 kg/ha. However, this total does not represent an actual quantity, because the same unit of N may be repeatedly cycled through the litter chain.

Calcium---Total Ca accumulation in stemwood was 140 kg/ha at 16 years (Figure 15A). About one half of this was removed by thin-

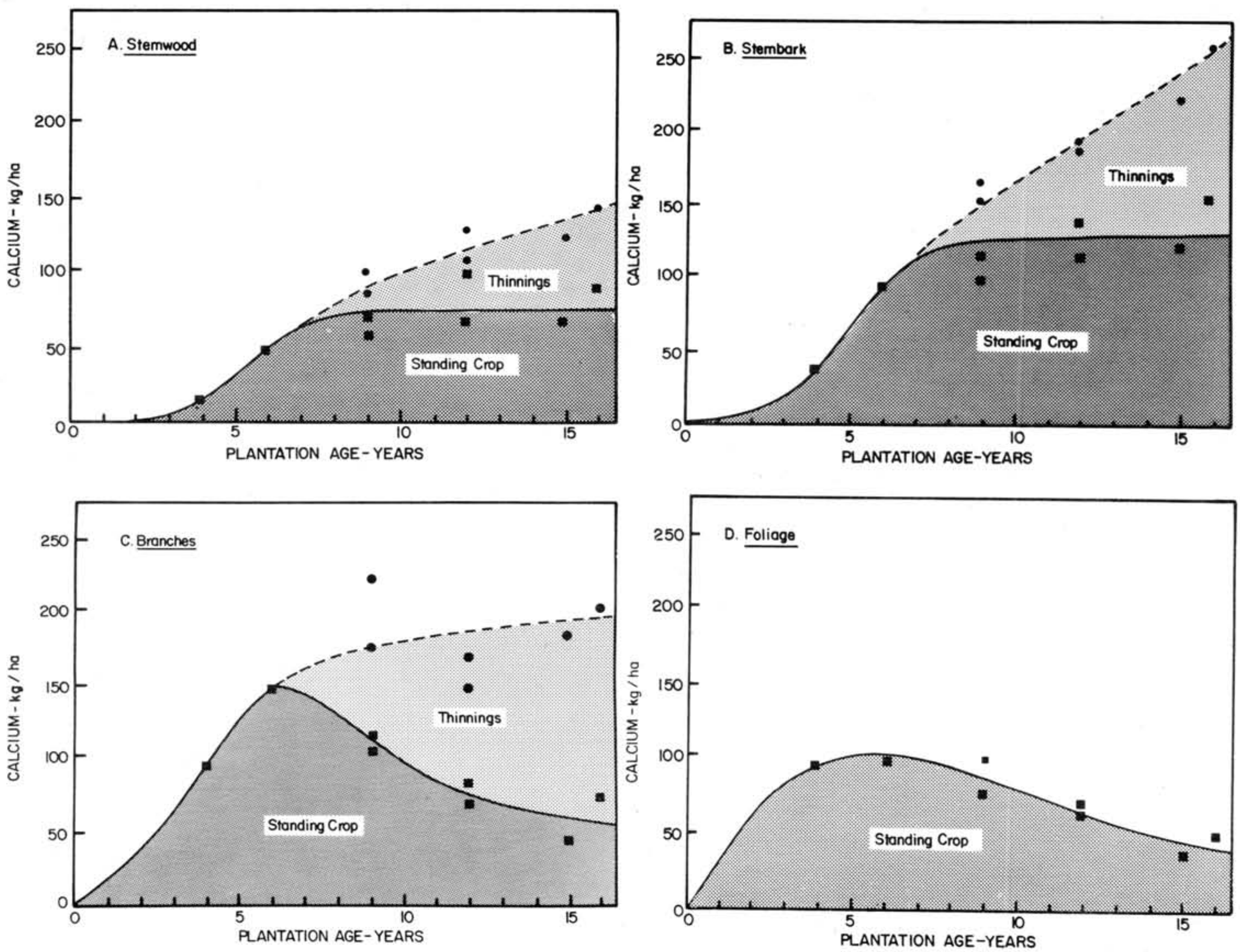

Figure 15. The Ca content of components of the standing crop and estimated thinning removals in cottonwood plantations.

nings, and the remainder was in the standing crop. Total accumulation of Ca in stemwood was more than twice that of N.

The greatest accumulation of Ca occurred in the stembark, where levels in the standing crop were about 130 kg/ha (Figure 15B). Thinning removed about 130 kg/ha; therefore, total accumulation at 16 years was 260 kg/ha. This total was 86% greater than that in the stemwood and more than three times that of stembark N.

Branches accumulated Ca rapidly, and their content (95 kg/ha) exceeded that of stemwood and stembark at four years (Figure 15C). However, Ca in the standing crop was reduced by thinning to 60 kg/ha at 16 years. The branches of trees removed by thinning were left on the site, and their content of 175 kg/ha will be released by decomposition. Total Ca accumulation in branches was three times that of N.

The Ca content of foliage approached 100 kg/ha at four years and then declined by one half at 16 years (Figure 15D). This decline was due to thinning, as previously noted for foliar N and phytomass. The Ca content of foliage was about equal to that of foliar N. Ca is not translocated before abscission (Baker and Blackmon, 1977), and the entire foliar content of the standing crop is transferred each year to the forest floor through litterfall at rates of about 100 kg/ha of Ca at four to six years and 50 kg/ha at 16 years. As with N, large quantities of Ca were transferred in this way during plantation development.

Simulation of Plantation Development

Standing crop---This simulation represents the typical development of a plantation through time under a realistic system of management. Thinnings are at six, nine and 13 years, when the mean DBH is 17, 23 and 29 cm, respectively. The basal area of the standing crop is about 14 m^2/ha before each thinning, which removes 50, 33 and 33% of the basal area, respectively (Figure 16A).

The phytomass of the standing crop has a pattern similar to that of basal area, with recoveries following thinning removals (Figure 16B). The time required for the standing crop to recover from thinning depends on the intensity of thinning and the age of the plantation. Recovery is most rapid at early ages when more trees occupy the site and the annual increments are higher. For example, three years are required for the standing crop to recover from the first thinning, which removes one half of the phytomass. In contrast, only one third of the standing crop is removed by the third thinning, but four years are required for recovery. Phytomass is greatest (70 tons/ha) just before the third thinning.

The largest quantities of N and Ca in the standing crop generally

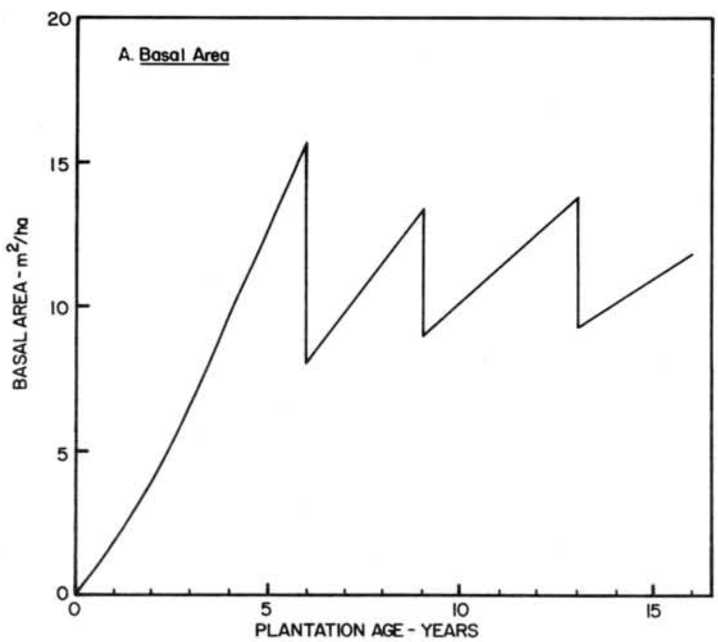

Figure 16A. The basal area of the standing crop of a simulated cottonwood plantation.

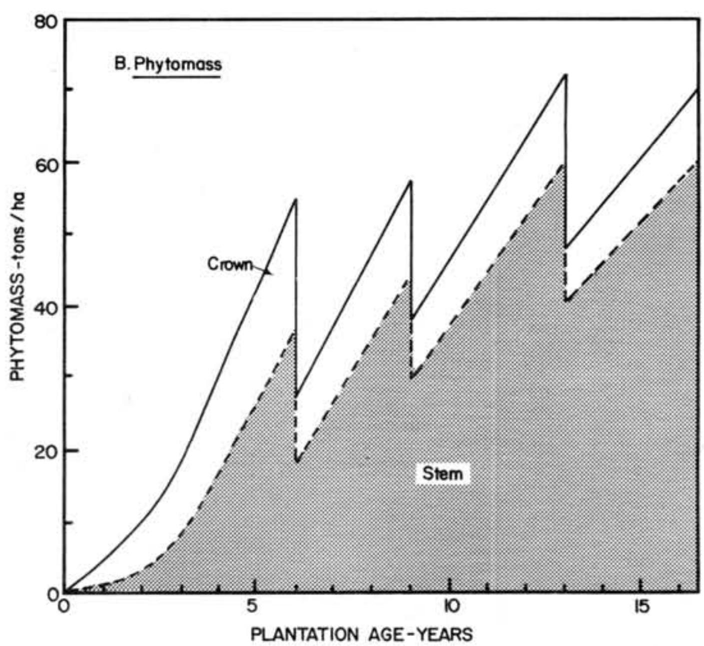

Figure 16B. The phytomass of the standing crop of a simulated cottonwood plantation.

occur before the first thinning (Figures 16C and 16D). This is caused by the greater proportion of crown components early in the development of the plantation. For example, the crown components contain about 75% of the nutrients in the standing crop at four years, but this declines to about 40% at 16 years.

Ca accumulation in the stem components is a direct reflection of the accumulation of stem phytomass. Large increases in Ca occur in the stem components through time, and Ca at 16 years is about twice that at six years. In contrast, the quantity of N increases much more gradually, which is a result of the biochemical cycling within the trees. This internal redistribution of the mobile nutrients decreases concentration through time and is a mechanism for nutrient conservation by the tree (Shelton et al, 1981).

Annual increments---Total CAI of phytomass and nutrients is greatest before the first thinning and declines thereafter (Table 8). The decrease through time is partially due to the fact that the growth of the residual trees does not wholly compensate for the growth of trees removed by thinning. Allocation of the total increment among the components differs for phytomass and nutrients. For example, the annual increment of phytomass is greatest for stemwood, while that for nutrients is greatest in foliage.

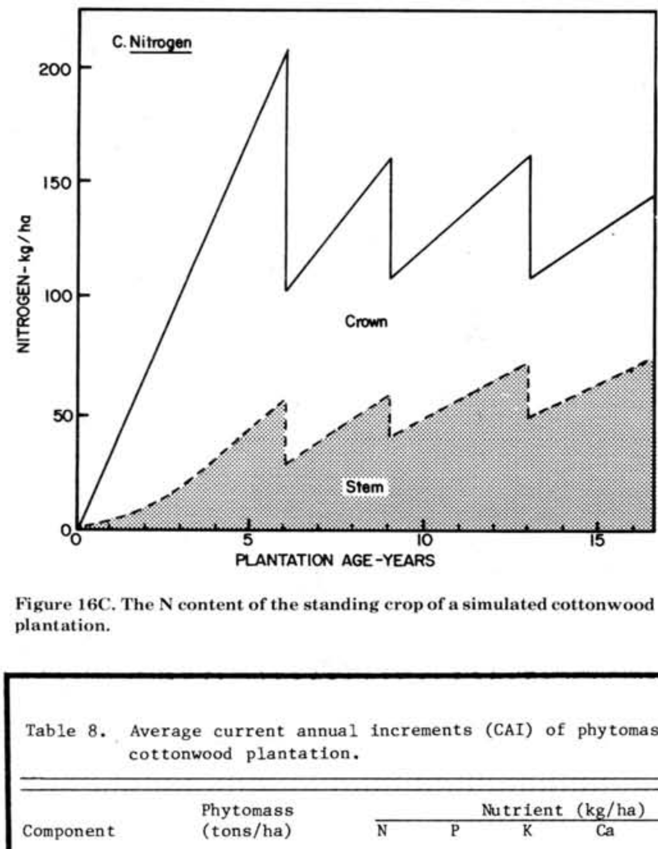

Figure 16C. The N content of the standing crop of a simulated cottonwood plantation.

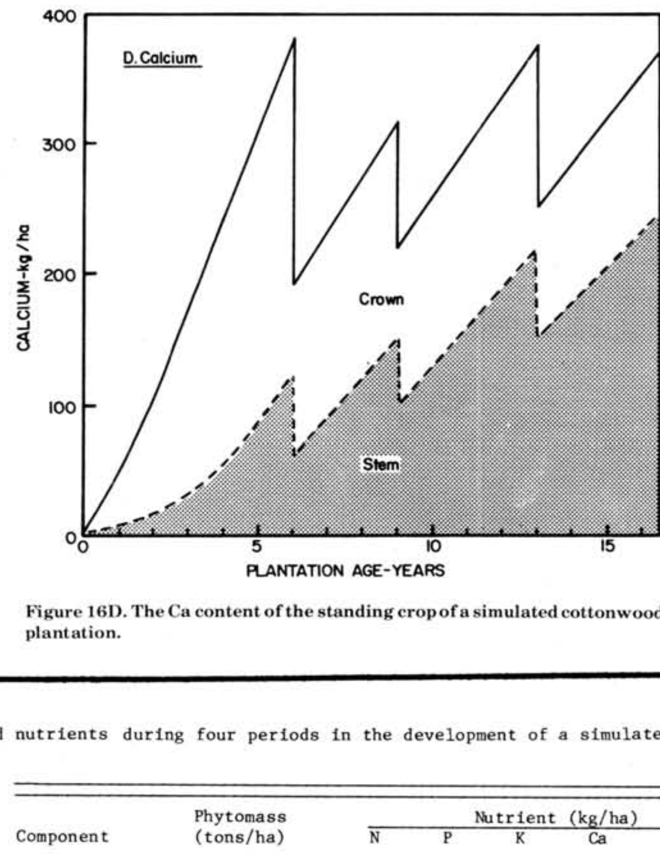

Figure 16D. The Ca content of the standing crop of a simulated cottonwood plantation.

Table 8. Average current annual increments (CAI) of phytomass and nutrients during four periods in the development of a simulated cottonwood plantation.

Component	Phytomass (tons/ha)	Nutrient (kg/ha) N	P	K	Ca	Mg	Component	Phytomass (tons/ha)	Nutrient (kg/ha) N	P	K	Ca	Mg
	4-6 years							10-13 years					
Stemwood	8.7	6	1.8	12	11	1.9	Stemwood	6.7	4	0.8	8	11	1.8
Stembark	1.3	7	0.8	8	21	1.5	Stembark	1.0	5	0.6	5	19	1.4
Branches	2.2	9	1.4	7	20	1.8	Branches	0.7	3	0.4	2	5	0.6
Foliage	4.2	80	7.5	61	99	12.7	Foliage	2.5	47	4.1	36	63	7.6
TOTAL	16.4	102	11.5	88	151	17.9	TOTAL	10.9	59	5.9	51	98	11.4
	7-9 years							14-16 years					
Stemwood	7.4	5	1.2	9	11	1.8	Stemwood	5.2	3	0.6	6	11	1.7
Stembark	1.1	5	0.7	6	19	1.4	Stembark	0.8	4	0.5	4	17	1.3
Branches	1.1	4	0.7	3	9	0.9	Branches	0.4	2	0.3	1	3	0.3
Foliage	2.9	56	5.0	42	72	8.9	Foliage	2.0	37	3.1	29	51	6.0
TOTAL	12.5	70	7.6	60	111	13.0	TOTAL	8.4	46	4.5	40	82	9.3

CAI of nutrients approximates the annual nutrient requirement. Trees have several ways of meeting annual nutrient requirement, and these are illustrated by foliage. A portion of the N and P in foliage is translocated before leaf abscission and stored in the permanent tissues, and only supplemental N and P must be obtained from the soil to meet the requirements of foliage the next year. In contrast, translocation of K, Ca and Mg from foliage is virtually nil, and the annual requirement for these nutrients must be obtained from the soil.

Thinnings---The three thinnings remove 53 tons/ha of phytomass and a volume of 150 m^3/ha (Table 9). Stem phytomass removals in the first and third thinnings are about equal. However, trees are larger in the third thinning and have a greater merchantablility. For example, for an upper stem merchantability limit of 10 cm, 14% of the stem removal is not merchantable in the first thinning, but this declines to only 2% in the third thinning. The bark is about 12% of total stem phytomass and volume in each thinning. The ratio of crown to stem phytomass is 1:2 in the first thinning and 1:5 in the third thinning.

Nutrient content of the felled material also differs with time of thinning. The nutrient content of the first thinning is 1.8-fold greater than that of the second and third thinnings (Table 9). The large nutrient content of the first thinning is mainly due to the greater nutrient content of the crown components. For example, nutrient content of the crown components of the first thinning is about twice that of the second and third thinnings. Nutrient content of stems is more constant among the thinnings than the crowns. The first thinning removes 20% more N, P and K in the stems than the third thinning and 15% less Ca and Mg.

Table 9. Volume, phytomass and nutrient content of the three thinnings of a simulated cottonwood plantation.

Component	Volume (m^3/ha)	Phytomass (tons/ha)	Nutrient (kg/ha) N	P	K	Ca	Mg
			First Thinning				
Stem	55	18.4	29	6.0	44	63	6.4
Crown	---	9.3	76	8.8	64	128	12.8
Total	---	27.7	105	14.8	108	191	19.2
			Second Thinning				
Stem	41	14.6	19	3.8	29	52	5.2
Crown	---	4.4	34	4.0	27	58	6.0
Total	---	19.0	53	7.8	56	110	11.2
			Third Thinning				
Stem	55	19.9	24	4.4	36	75	7.8
Crown	---	4.0	30	3.5	23	51	5.3
Total	---	23.9	54	7.9	59	126	13.1
			Overall Total				
Stem	151	52.9	72	14.2	109	190	19.4
Crown	---	17.7	140	16.3	114	237	24.1
Total	---	70.5	212	30.5	223	427	43.5

MANAGEMENT IMPLICATIONS

Spacing and Thinning

The relationship of spacing to tree and stand characteristics has been reviewed for a number of species by Evert (1971) and for cottonwood by Gascon and Krinard (1976). Spacings in cottonwood plantations in the United States generally range from 140 to 2000 trees/ha, and even wider spacings are used in Europe (FAO, 1979). The closer spacings generally are linked to short rotations for fiber production, and wider spacings are associated with longer rotations for producing sawlogs and veneer. There is no best spacing for all products, but stands of about 750 trees/ha have been suggested as a good compromise in the production of pulpwood, growth of potential crop trees and tree quality (Krinard and Johnson, 1975 and 1980). However, this spacing requires that thinnings are accomplished when required, and thinning problems in Europe necessitate the use of wider spacings (FAO, 1979).

Uniformity was a criterion for selecting the plantations for this study, and the spacings and thinning regimes used were too limited to permit comparisons within this study. However, the system of management used in this study can be evaluated by comparing it with unthinned plantations and natural stands of similar ages and sites.

The general management of the studied plantations was to use relatively close initial spacings (1325 trees/ha) and thin frequently. Thinnings generally were conducted when the basal area exceeded about 14 m^2/ha and reduced the basal area to 8 to 9 m^2/ha. Yields from the thinned plantations were about 10% below yields reported for unthinned plantations and natural stands of similar ages on similar sites (Carter and White, 1971a; Krinard and Johnson, 1975; Williamson, 1913). Krinard and Johnson (1975) found an 18% reduction in yield of merchantable volume of cottonwood plantations managed with a similar spacing and thinning regime. Apparently, stand density maintained by these thinning regimes is below that required for full occupancy of these sites.

The levels of basal area observed in this study (9 to 14 m^2/ha) were below the level of 15 m^2/ha suggested by White (1976) for plantations older than 10 years. In addition, Krinard and Johnson (1975) found no loss in yield of merchantable volume when the residual basal area after thinning was maintained above 15 m^2/ha.

The loss in productivity at basal areas below 15 m^2/ha apparently is related to the slow response of cottonwood after thinning, since the crowns of the residual stand do not promptly utilize the additional growing space. Some growth is sacrificed on an area basis by thinning, but growth of the individual tree is enhanced. Thinnings concentrate the growth of the plantation on fewer trees that may be selected for desired traits (e.g., rate of growth, tree form, quality). Thus, thinnings produce larger trees with more desirable qualities. The mean tree in thinned plantations at 10 years was 24 cm in diameter with a volume of 0.45 m^3, while comparable values for unthinned plantations were 18 cm and 0.18 m^3.

Thinning also reduces mortality within the plantation, which principally is due to lowering levels of competition and harvesting high-risk trees. For example, estimated total mortality from four to 10 years in the thinned plantations was 25 trees/ha, while mortality in unthinned plantations at similar initial spacing was 300 trees/ha for the same period (Krinard and Johnson, 1975).

Rotation Length

Two common rotation lengths with cottonwood are short rotations for fiber production and long rotations for veneer, with fiber production from thinnings. A comparison of two rotation lengths and two levels of utlization was developed from the synthesized plantation. A nine-year rotation with thinning at six years was compared to an 18-year rotation with thinning at six, nine and 13 years.

Mean annual yields of stem-only utilization are about the same for both rotations (Table 10). Yield for

Table 10. Mean annual removals of phytomass (tons/ha) and nutrients (kg/ha) for long and short rotations under two utilizations.

Item	9-Year Rotation		18-Year Rotation	
	Stem-Only	Whole-tree	Stem-Only	Whole-tree
Phytomass	6.9	9.5	6.8	8.4
N	9.6	29.4	8.7	20.0
P	1.9	4.2	1.5	2.9
K	14.7	30.9	12.6	21.9
Ca	24.2	57.9	26.3	46.2
Mg	2.5	5.9	2.8	4.8

whole-tree utilization is 13% higher with short rotations than with long rotations, because crowns constitute a higher percentage of total phytomass in the short rotations.

Rotation length also affects the size of the mean tree. DBH and volume of the mean tree in the final cut of a nine-year rotation are 23 cm and 0.36 m^3, respectively, and are 36 cm and 1.5 m^3 for the mean tree in the final cut of an 18-year rotation.

Nutrient removals for stem-only utilizations do not differ appreciably for the two rotations. Long rotations remove 15% less N, P and K than short rotations and 10% more Ca and Mg. The difference in removal of the mobile and immobile nutrients is partially due to changes in their concentration in the stem as age increases (Shelton et al, 1981). Nutrient removals for whole-tree utilization are less for long than for short rotations, by 30% for N, P and K and 20% for Ca and Mg.

Length of the rotation also determines the frequency of site regeneration and the frequency and extent of disruption of the nutrient cycle. Disruption of the nutrient cycle is far greater with the final cut at the end of the rotation than with thinnings where a residual crop remains. Reestablishment of the nutrient cycle depends on a number of factors, including the promptness and success of regeneration, the degree of utilization and the effect of harvesting on the physical properties of the soil.

Effect of Utilization on Nutrient Removal

Whole-tree utilization yields the most phytomass and removes the most nutrients. More conservative utilizations remove specific portions of the standing crop and remove less nutrients. The general relationship for these plantations is typified by N removal (Figure 17).

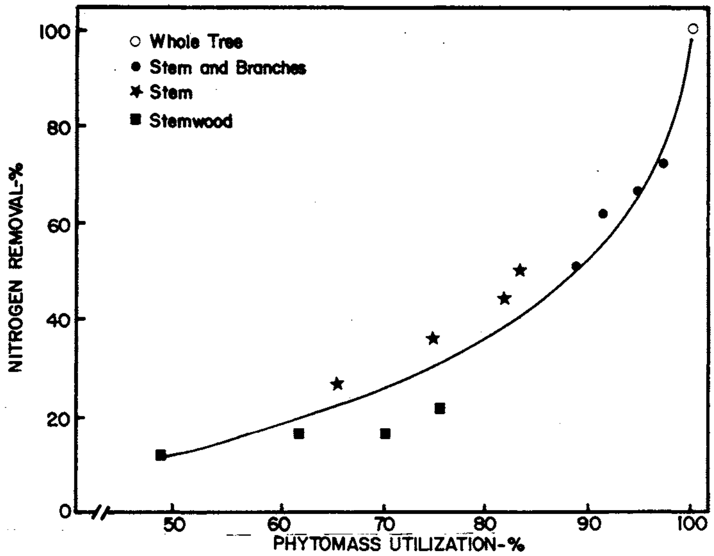

Figure 17. The general relationship between phytomass utilization and N removals in cottonwood plantations, based on thinning removals at six, nine and 13 years and the final harvest at 16 years.

Removal of stemwood provides about two thirds of the total phytomass and removes only one fifth of the total N. This utilization involves debarking the stem on site, which is possible with current harvesting equipment. Utilization of the entire stem removes 80% of the total phytomass and 40% of the total N. Including the branches in the removal increases phytomass yield to 90% of the total, and N removal is 60% of the total. When foliage is included in removal, the phytomass yield increases only 10%, but the removal of N increases by 40%.

Removal of foliage can be avoided in whole-tree utilization by postponing harvest until after defoliation. However, such a delay is only partially effective for N and P, because much of the foliar content is translocated to the permanent tissues before abscission. The use of chemical defoliants for removing foliage before harvest has been suggested (White, 1974), but this approach raises many economic and ecological questions.

Maintenance of Productivity

The ability of a site to sustain nutrient removals from cropping is a basic consideration in evaluating various intensities of utilization. Maintenance of the inherent productivity of the site is more effective than trying to restore a decline in productivity (Bengston, 1978). The resolution of this question involves all compartments of the forest ecosystem and the nutrient fluxes among the compartments. Therefore, the nutrient inputs, losses and reserves of the system must be quantified.

An estimate of the ability to sustain productivity under various cropping systems is obtained from the nutrient requirements determined by this study, the nutrient status of alluvial soils represented by the Commerce and Robinsonville series and the atmospheric nutrient inputs. Total N, available P, exchangeable K, Ca and Mg in these soils to a depth of 120 cm are 13.0, 2.3, 3.5, 46.5 and 10.9 tons/ha, respectively (Lockaby, 1981). These nutrient supplies are supplemented with atmospheric inputs that average 10.0, 1.0, 4.0, 6.0 and 1.5 kg/ha/year for N,P,K,Ca and Mg, respectively (Lockaby, 1981).

Additional gains and losses include erosion, leaching, mineral weathering, deposition from floods and N fixation. Little or no data exist for these quantities for this locale; therefore, these fluxes are ignored in this initial approximation.

The net demand for soil nutrients was assumed to be the difference in the vegetative requirement for nutrients and the atmospheric inputs. This quantity of nutrients must be obtained from the soil if demands of the crop are to be met. The potential for soil depletion was estimated by expressing the net demand per decade as a percentage of the soil nutrients (Table 11).

Table 11. Potential for depleting soil nutrients for stem-only and whole-tree utilizations in long and short rotations

Nutrient	Short Rotations		Long Rotations	
	Stem-only	Whole-tree	Stem-only	Whole-tree
	%/decade			
N	0.0	1.5	0.0	0.8
P	0.4	1.4	0.2	0.8
K	3.0	7.6	2.4	5.1
Ca	0.4	1.1	0.4	0.9
Mg	0.1	0.4	0.1	0.3

The values for potential depletion are lowest for the most conservative management system (stem-only utilization, long rotation) and highest for the most intensive (whole-tree utilization, short rotation). In addition, the values vary among the nutrients, with N and Mg having the lowest values and K the highest. These values, with the possible exception of K, generally indicate no problems with soil depletion over a number of rotations. For example, depletion values for stem-only utilization with either rotation are less than 5% of the soil nutrients per century for N, P, Ca and Mg, while K exceeds 25%.

Thus, K appears to have the highest potential for depletion. However, the chemistry of soil K suggests that the amount of K that can be used by plants is underestimated by standard analytical procedures. K reserves in the soil exist in both readily and slowly available forms. Exchangeable K, the common expression of soil K, does not include the slowly available K.

The slowly available pool of K in the Robinsonville soil series has been estimated to be about 100 times that of the available pool in the surface layers (Gholston and Hoover, 1948), and the size of each pool and the exchange rates between pools must be considered when evaluating the overall K status of the soil under intensive cropping. Studies of the K-release characteristic of some Delta soils indicate that they have high K-supplying ability (Gholston and Hoover, 1948; Turner, 1958). Therefore, the potential for K depletion is not great when the release properties of the soil are considered. Further assurance is gained from the fact that soils similar to those of this study have been under agronomic cropping for long periods without requiring K fertilization.

There appears to be little potential for soil depletion on these fertile soils in the immediate future, especially if conservative utilization practices are employed. However, additional research is needed to provide an overall picture of the relationship of nutrition to productivity. For example, experience with old-field cottonwood plantations indicates that attention should be given to the influence of culture on the physical properties of the soil (Broadfoot and Bonner, 1966; Baker and Blackmon, 1973). Also, the reported response to N fertilization in cottonwood plantations established on old fields indicates that the nutritional status of these soils can be altered by intensive cropping (Blackmon and White, 1972).

Net Primary Productivity

Net primary productivity (NPP) expresses the total phytomass that is produced by the plantation and is the base from which yields of usable materials are realized. As such, it includes all foliage, branches and stem materials that have been produced during the life of the plantation, even if not present in the standing crop. The standing crop and the degree of utilization determine realizable yields.

Total NPP of the plantations is 185 tons/ha through 16 years, and only 37% of this is in the standing crop at 16 years (Table 12). Distribution of the total NPP through 16 years is 60, 11, 25 and 4% for stems, branches, foliage and mortality, respectively. The three thinnings and the final harvest at 16 years account for 60% of total NPP with stem-only utilization and 75% with whole-tree utlization. The portion of NPP not utilized enters the biogeochemical nutrient cycle.

Table 12. Distribution of net primary productivity (NPP) of a simulated cottonwood plantation through 16 years and the associated quantity of nutrients.

Component	Phytomass (tons/ha)	Nutrient (kg/ha) N	P	K	Ca	Mg
	Standing Crop at 16 Years					
Stemwood	50.4	32	7.5	63	87	13.7
Stembark	7.4	37	4.6	40	146	10.7
Branches	7.5	31	5.0	24	66	6.2
Foliage	2.1	39	3.3	30	53	6.2
TOTAL	67.4	139	20.4	157	352	36.8
	Felled in Three Thinnings					
Stemwood	45.9	35	9.8	65	67	10.9
Stembark	7.0	37	4.4	44	123	8.5
Branches	13.4	57	8.8	51	130	10.9
Foliage	4.3	83	7.5	63	107	13.2
TOTAL	70.6	212	30.5	223	427	43.5
	Cumulative Foliage					
Biogeochemical Cycle*	—	461	36.6	549	955	120.1
Biochemical Cycle**	—	295	32.5	0	0	0.0
Total	39.6	756	69.1	549	955	120.1
	Cumulative Mortality					
TOTAL	6.9	21	3.6	24	48	4.2
Overall Total	184.5	1128	123.6	953	1782	204.6

* Total quantity transferred via litterfall to the forest floor through 15 years, excluding that felled in thinning.

**Total quantity internally transferred through 15 years based on Baker and Blackmon (1977).

Plantation Nutrition

The quantity of nutrients associated with the NPP through 16 years is large---almost 2 tons/ha of Ca, about 1 ton/ha of N and K and 200 and 120 kg/ha of Mg and P, respectively (Table 12). However, a large portion of the nutrients is involved in cycling, which is an important mechanism in the annual regeneration of nutrients in forest ecosystems (Switzer and Nelson, 1972). Thus, the plantation functions with a much smaller actual quantity of nutrients, which are periodically reutilized. Cycling also retains nutrients within the plantation and increases the efficiency of their utilization.

The importance of cycling is illustrated by N and Ca. About 500 kg/ha of N and almost 1 ton/ha of Ca are transferred to the forest floor through litterfall (Table 12). Only a portion of this quantity remains in the forest floor, since decomposition releases the nutrients and makes them once again available for plant uptake. Lockaby (1981) found that the steady-state forest floor in unthinned cottonwood plantations contains about 160 kg/ha of N and 250 kg/ha of Ca.

Part of the foliar N is transferred through the biochemical cycle, but no Ca is transferred in this manner. Retention of N through the biochemical cycle increases the efficiency of its use; for example, the total requirement of N at 16 years is 46 kg/ha, about one half of which is supplied by N retained from the foliage of the previous year. Therefore, about one half of the N requirement for the 16th year must be obtained from the soil. In contrast, the entire Ca requirement for the 16th year (82 kg/ha) must be obtained from the soil.

Comparison With Other Forests

The average annual NPP of 12 tons/ha for the studied plantations closely agrees with the average of 13 tons/ha reported by Olson (1975) for warm-deciduous forests on floodplain soils. The maximum rates of NPP are attained early in plantation development and average about 17 tons/ha from four to six years. These rates approach the maximum of 20 ton/ha reported for the warm-temperate forest (Lieth, 1975). The rates decline to 8 tons/ha at 16 years, a value near the minimum of 6 tons/ha reported by Lieth (1975).

The rapid early development of cottonwood is also illustrated by comparison with loblolly pine (*Pinus taeda*). Phytomass of cottonwood at six years is three times that of loblolly pine; however, phytomass of loblolly pine equals that of cottonwood at 15 years (Table 13). Trends beyond 15 years indicate that production of loblolly pine will exceed that of cottonwood. For example, Wells and Jorgensen (1975) reported values for 16-year-old loblolly pine that are 15% greater than values for cottonwood of comparable age (Table 14). The most notable difference in this comparison is for foliage, which is four times greater for loblolly pine.

Accumulation of nutrients is greater in cottonwood plantations than in loblolly pine plantations; e.g., cottonwood accumulation of N, P, K, Ca and Mg, respectively, is 1.0, 1.4, 1.9, 3.6 and 1.5 times that of loblolly pine at 16 years. The greatest differences between the two species are for the bases (K, Ca and Mg). The higher values for Ca are associated primarily with the stembark component, where the quantity in cottonwood is seven times that in loblolly pine.

Table 13. Phytomass of cottonwood and loblolly pine plantations at six, 10, and 15 years.

Age (yrs)	Phytomass: Cottonwood	Phytomass: Loblolly Pine
	tons/ha	
6	55	17
10	90	62
15	126	127

*These data are from sites considered good for each species. The values for cottonwood are for the standing crop plus thinning removals of the stem and branches. The loblolly pine values are for the unthinned standing crop reported by Baker (1971) at six years and unpublished MAFES data at 10 and 15 years.

Table 14. Phytomass and nutrient content of the components of cottonwood and loblolly pine plantations at 16 years.

Component	Phytomass (tons/ha)	Nutrient (kg/ha) N	P	K	Ca	Mg
	Cottonwood*					
Stemwood	96.3	67	17.3	127	153	24.6
Stembark	14.4	74	11.2	84	269	19.2
Branches	20.9	87	13.8	75	197	17.1
Foliage	2.1	39	3.3	30	53	6.2
TOTAL	133.7	267	45.6	316	672	67.1
	Loblolly Pine**					
Stemwood	109.6	79	10.7	65	74	22.7
Stembark	15.2	36	4.2	24	38	6.5
Branches	23.2	60	6.0	28	58	9.1
Foliage	8.0	82	10.0	48	17	7.9
TOTAL	156.0	257	30.9	165	187	46.2

* The standing crop at 16 years plus thinning removals of stemwood, stembark and branches.

**From unthinned plantations (Wells and Jorgensen, 1975).

The difference in nutrient accumulation between the two species illustrates the greater nutrient requirements of cottonwood while performing at about the same productivity level as loblolly pine. This also emphasizes the differences in quality of sites necessary for the two species.

Appendix Table 1. The identity, age, dimensions, phytomass and volume of the 24 cottomwood trees sampled in August 1975.

Identity	Age	Plot	Tree No.	Dimensions DBH	Dimensions Ht	Phytomass Stemwood	Phytomass Stembark	Phytomass Branches	Phytomass Foliage	Volume ib	Volume ob
	-yrs-			-cm-	-m-	kg	kg	kg	kg	$10^{-3} m^3$	$10^{-3} m^3$
Catfish	4	A	1	15.0	12.5	26	4.6	16.6	6.3	89	99
		B	2	16.3	12.8	30	4.9	16.8	6.7	104	117
		C	3	16.7	13.0	30	4.1	21.3	7.0	106	117
Leavenworth	6	A	4	20.1	17.8	67	8.2	31.5	10.3	209	235
		B	5	18.5	17.4	61	8.5	16.6	5.7	178	201
		C	6	17.5	18.0	50	7.0	18.3	4.7	151	174
Catfish	9	A	7	22.6	21.9	108	13.9	29.8	9.3	340	391
		B	8	22.6	22.1	123	17.9	39.6	14.9	354	395
		C	9	22.4	21.5	131	22.6	35.9	10.8	345	397
Fitler	9	A	10	25.6	21.0	145	18.5	35.3	11.9	422	477
		B	11	27.4	23.0	170	22.7	37.3	16.3	452	511
		C	12	24.4	23.8	148	22.5	43.8	9.8	440	506
Fitler North	12	A	13	27.4	27.4	226	36.6	32.5	11.6	650	730
		B	14	27.2	24.2	199	26.0	34.8	11.3	533	620
Fitler South	12	A	15	28.7	27.4	230	36.7	54.9	12.6	599	681
		B	16	27.2	25.4	216	32.1	52.6	14.4	600	679
Warren	15	A	17	33.5	32.2	379	56.6	41.4	13.2	1057	1194
		B	18	31.5	28.8	320	50.3	37.6	11.5	807	901
		C	19	29.7	28.5	253	49.0	45.4	11.4	711	845
		D	20	27.9	27.6	220	35.4	32.5	10.8	641	731
Warren	16	A	21	36.8	34.6	502	70.7	80.4	22.4	1381	1621
		B	22	35.6	31.2	428	62.9	93.9	16.1	1191	1373
		C	23	34.8	30.9	367	48.4	42.2	13.3	1007	1162
		D	24	35.6	32.0	414	57.0	69.4	14.3	1175	1297

Appendix Table 2. The N content of the components of 24 cottonwood trees sampled in August 1975.

Tree No.*	Stemwood	Stembark	Branches	Foliage
	g			
1	25	35	75	137
2	26	34	70	129
3	36	35	98	134
4	70	44	114	184
5	54	51	71	92
6	49	52	75	101
7	88	92	128	189
8	88	74	124	207
9	101	101	116	212
10	119	124	186	176
11	139	176	226	303
12	108	106	209	202
13	178	167	118	204
14	153	120	150	237
15	140	215	254	232
16	123	127	150	274
17	169	367	143	243
18	164	193	117	190
19	168	181	156	199
20	142	122	85	185
21	385	428	315	464
22	286	318	363	270
23	241	314	220	274
24	285	353	297	328

*See Appendix Table 1 for identity, age and dimensions.

Appendix Table 3. The P content of the components of 24 cottonwood trees sampled in August 1975.

Tree No.*	Stemwood	Stembark	Branches	Foliage
	-----------------------	g	-----------------------	
1	9	3	11	14
2	9	4	12	12
3	10	4	14	11
4	17	6	22	23
5	18	7	12	11
6	17	6	12	7
7	19	9	17	14
8	20	12	21	21
9	24	13	19	15
10	30	12	21	18
11	41	17	31	23
12	31	12	23	15
13	47	24	23	17
14	37	17	28	20
15	34	25	40	20
16	42	18	29	22
17	53	46	31	22
18	51	29	26	20
19	40	26	25	17
20	33	20	29	16
21	139	63	65	40
22	69	39	51	31
23	51	28	32	25
24	53	41	51	24

*See Appendix Table 1 for identity, age and dimensions.

Appendix Table 4. The K content of the components of 24 cottonwood trees sampled in August 1975.

Tree No.*	Stemwood	Stembark	Branches	Foliage
	--------	-------- g	--------	--------
1	40	35	71	110
2	52	36	66	109
3	53	27	84	144
4	86	60	110	139
5	81	80	78	90
6	124	59	55	60
7	136	94	131	160
8	129	130	133	193
9	125	124	103	161
10	256	145	148	172
11	490	145	189	199
12	357	159	135	144
13	309	287	115	153
14	230	152	140	172
15	240	258	215	185
16	276	216	150	180
17	456	401	107	145
18	239	207	87	73
19	266	198	109	84
20	342	136	78	92
21	426	377	267	222
22	705	222	262	100
23	415	304	148	109
24	517	281	191	118

*See Appendix Table 1 for identity, age and dimensions.

Appendix Table 5. The Ca content of the components of 24 cottonwood trees sampled in August 1975.

Tree No.*	Stemwood	Stembark	Branches	Foliage
	g			
1	38	85	173	136
2	38	95	143	157
3	42	88	200	184
4	87	205	401	258
5	73	139	156	148
6	80	135	140	74
7	164	251	254	214
8	211	320	432	321
9	206	447	377	288
10	270	443	398	339
11	321	567	414	450
12	222	312	344	258
13	357	632	241	298
14	453	496	324	264
15	357	620	519	274
16	361	671	407	435
17	610	1141	338	297
18	450	881	287	285
19	385	812	298	233
20	418	627	254	213
21	828	1676	760	606
22	701	1413	793	475
23	672	954	414	359
24	622	1078	428	282

*See Appendix Table 1 for identity, age and dimension.

Appendix Table 6. The Mg content of the components of 24 cottonwood trees sampled in August 1975.

Tree No.*	Stemwood	Stembark	Branches	Foliage
	g			
1	7	6	14	23
2	7	7	13	20
3	8	6	20	20
4	14	10	28	37
5	13	10	12	18
6	16	10	12	13
7	23	24	24	33
8	27	18	45	36
9	29	30	26	29
10	42	20	26	38
11	50	31	35	47
12	41	29	28	34
13	60	38	24	30
14	55	22	22	28
15	52	37	35	32
16	52	33	26	38
17	97	94	34	67
18	86	83	41	61
19	76	50	34	50
20	73	63	30	49
21	202	202	104	103
22	131	106	89	110
23	101	125	48	68
24	91	76	50	63

*See Appendix Table 1 for identity, age and dimensions.

Appendix Table 7. The phytomass of the standing crop and estimated thinning removals from cottonwood plantations (tons/ha).

Location	Age (yrs)	Stemwood	Stembark	Branches	Foliage
		STANDING CROP			
Catfish	4	15.8	1.7	9.8	3.9
Leavenworth	6	35.5	4.7	14.0	4.4
Catfish	9	35.1	5.3	10.3	3.5
Fitler	9	40.7	5.5	10.9	3.6
Fitler North	12	51.2	7.5	8.1	2.8
Fitler South	12	45.0	6.9	10.2	2.6
Warren	15	41.9	6.9	5.8	1.8
Warren	16	51.3	7.2	8.8	2.0
		THINNING REMOVALS			
Catfish	4	--	--	--	--
Leavenworth	6	--	--	--	--
Catfish	9	19.5	2.9	11.4	4.2
Fitler	9	17.6	2.6	6.6	2.2
Fitler North	12	21.8	3.3	8.2	2.7
Fitler South	12	28.1	4.2	8.8	2.9
Warren	15	36.0	5.4	13.7	4.9
Warren	16	37.3	5.5	12.6	4.4

Appendix Table 8. The N content of the standing crop and estimated thinning removals from cottonwood plantations (kg/ha).

Identity	Age (yrs)	Stemwood	Stembark	Branches	Foliage
		STANDING CROP			
Catfish	4	12.7	16.0	45.0	77.2
Leavenworth	6	36.1	30.5	55.8	81.2
Catfish	9	26.6	25.6	35.6	58.9
Fitler	9	32.9	36.9	58.1	63.8
Fitler North	12	35.6	40.7	32.5	53.6
Fitler South	12	24.2	31.4	37.1	46.5
Warren	15	23.0	31.2	18.3	30.1
Warren	16	35.6	41.8	36.4	41.2
		THINNING REMOVALS			
Catfish	4	---	---	---	---
Leavenworth	6	---	---	---	---
Catfish	9	20.7	20.0	50.2	81.3
Fitler	9	15.8	15.6	28.3	42.2
Fitler North	12	19.6	19.4	35.1	54.6
Fitler South	12	22.5	23.6	37.0	54.3
Warren	15	30.2	31.2	59.1	93.5
Warren	16	28.6	32.3	54.4	84.9

Appendix Table 9. The P content of the standing crop and estimated thinning removals from cottonwood plantations (kg/ha).

Identity	Age (yrs)	Stemwood	Stembark	Branches	Foliage
		STANDING CROP			
Catfish	4	5.3	1.4	6.6	7.7
Leavenworth	6	11.0	3.9	10.0	8.9
Catfish	9	6.1	3.3	5.6	4.9
Fitler	9	9.3	3.7	6.4	5.6
Fitler North	12	10.2	4.9	6.3	4.6
Fitler South	12	7.0	3.9	6.3	3.9
Warren	15	6.5	4.4	3.8	2.8
Warren	16	7.2	4.5	5.6	3.3
		THINNING REMOVALS			
Catfish	4	---	---	---	---
Leavenworth	6	---	---	---	---
Catfish	9	7.1	3.2	8.0	7.7
Fitler	9	5.3	2.4	4.6	3.7
Fitler North	12	6.5	3.0	5.7	4.7
Fitler South	12	5.6	3.6	6.2	4.9
Warren	15	9.5	4.9	9.6	8.7
Warren	16	9.8	5.0	6.1	7.9

Appendix Table 10. The K content of the standing crop and estimated thinning removals from cottonwood plantations (kg/ha).

Identity	Age (yrs)	Stemwood	Stembark	Branches	Foliage
		STANDING CROP			
Catfish	4	19.7	15.4	41.9	71.7
Leavenworth	6	60.5	41.4	52.1	61.2
Catfish	9	37.6	33.8	35.8	48.5
Fitler	9	102.3	40.7	44.4	51.6
Fitler North	12	65.4	53.4	31.1	39.5
Fitler South	12	47.4	43.6	33.5	35.3
Warren	15	46.4	34.2	23.8	25.0
Warren	16	62.3	35.7	26.8	28.9
		THINNING REMOVALS			
Catfish	4	---	---	---	---
Leavenworth	6	---	---	---	---
Catfish	9	36.2	26.5	49.5	60.8
Fitler	9	28.1	19.5	25.7	31.9
Fitler North	12	34.8	24.3	31.9	39.7
Fitler South	12	40.8	28.7	33.6	41.2
Warren	15	52.2	38.8	57.5	70.7
Warren	16	53.7	38.8	52.3	64.1

Appendix Table 11. The Ca content of the standing crop and estimated thinning removals from cottonwood plantations (kg/ha).

Identity	Age (yrs)	Stemwood	Stembark	Branches	Foliage
		STANDING CROP			
Catfish	4	13.1	36.5	94.7	96.3
Leavenworth	6	46.8	96.4	149.8	103.3
Catfish	9	57.0	99.7	104.2	80.8
Fitler	9	72.5	118.2	110.6	100.3
Fitler North	12	98.4	137.1	68.6	68.2
Fitler South	12	66.0	118.8	85.2	65.3
Warren	15	65.8	123.5	43.5	37.8
Warren	16	85.6	155.5	74.1	53.0
		THINNING REMOVALS			
Catfish	4	---	---	---	---
Leavenworth	6	---	---	---	---
Catfish	9	28.5	57.4	118.9	99.0
Fitler	9	24.6	48.0	65.1	53.5
Fitler North	12	30.5	56.7	80.9	66.6
Fitler South	12	39.3	75.5	85.7	70.0
Warren	15	53.0	100.8	140.2	121.1
Warren	16	57.1	105.8	128.7	105.7

Appendix Table 12. The Mg content of the standing crop and estimated thinning removals from cottonwood plantations (kg/ha).

Identity	Age (yrs)	Stemwood	Stembark	Branches	Foliage
		----STANDING CROP----			
Catfish	4	2.6	2.6	8.6	12.0
Leavenworth	6	8.6	5.8	11.1	14.5
Catfish	9	7.7	7.1	9.3	9.6
Fitler	9	11.9	7.0	8.2	8.8
Fitler North	12	13.9	7.3	5.6	7.1
Fitler South	12	9.6	6.4	5.6	6.3
Warren	15	11.9	10.4	5.1	8.4
Warren	16	13.1	12.4	7.7	9.8
		----THINNING REMOVALS----			
Catfish	4	---	---	---	---
Leavenworth	6	---	---	---	---
Catfish	9	4.9	4.5	9.3	12.8
Fitler	9	4.2	4.2	5.4	6.7
Fitler North	12	5.2	5.2	6.7	8.3
Fitler South	12	6.7	5.1	7.3	8.7
Warren	15	8.7	6.9	12.8	14.7
Warren	16	9.2	7.3	10.3	13.4

Appendix Table 13. The simulated development of dimensions, volume and phytomass of the components of the mean tree of cottonwood plantations.*

Age	DBH	Total Height	Volume (ob)	Component			
				Wood	Bark	Branches	Foliage
-yrs-	-cm-	-m-	$-10^{-3}m^3-$	----------------kg----------------			
3	10.9	7.8	39	7.8	1.9	10.2	4.2
4	13.2	10.7	70	17.6	3.3	13.6	5.2
5	15.3	13.2	111	30.6	5.2	17.1	6.2
6	17.2	15.4	159	46.3	7.4	20.5	7.1
7	19.1	17.6	221	66.0	10.3	24.1	8.0
8	20.9	19.7	292	88.9	13.6	27.7	8.9
9	22.6	21.6	372	114.5	17.3	31.3	9.7
10	24.2	23.3	459	142.3	21.3	34.7	10.6
11	25.8	25.0	558	174.1	25.9	38.3	11.4
12	27.3	26.6	663	207.6	30.8	41.8	12.1
13	28.8	28.2	779	244.8	36.2	45.4	12.9
14	30.3	29.6	904	284.7	42.0	49.1	13.7
15	31.7	31.0	1037	327.2	48.1	52.7	14.4
16	33.1	32.4	1180	373.2	54.7	56.3	15.1

*Values calculated using equations (1), (2), (5), (6) and Table 3.

Appendix Table 14. The simulated accumulation of nutrients (g) by the mean tree of cottonwood plantations.*

Age (yrs)	Stemwood	Stembark	Branches	Foliage
	---NITROGEN---			
4	20	19	59	99
6	41	41	86	133
8	69	72	114	167
10	102	110	141	197
12	140	155	168	226
14	184	210	196	255
16	232	270	222	282
	---PHOSPHORUS---			
4	7	1	9	9
6	13	5	13	12
8	20	8	18	15
10	27	13	22	17
12	35	19	27	20
14	45	26	31	22
16	54	34	36	24
	---POTASSIUM---			
4	35	27	60	74
6	74	53	82	101
8	127	88	102	126
10	191	128	121	150
12	267	176	139	172
14	356	230	156	195
16	456	289	173	216
	---CALCIUM---			
4	25	51	143	119
6	63	122	202	167
8	124	232	262	214
10	208	377	318	259
12	319	561	373	302
14	460	791	428	346
16	628	1058	481	387
	---MAGNESIUM---			
4	4	3	11	16
6	10	8	16	21
8	20	16	22	26
10	34	26	28	32
12	51	40	33	36
14	73	57	39	41
16	99	77	45	45

*Values calculated using equation (1) and Table 5.

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